ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Fakulta dopravní

Ústav letecké dopravy

Metódy hodnotenia psychofyziologickej kondície pilotov v kontexte tréningu založenom na dôkazoch

Habilitačná práca

Akreditovaný obor pro habilitační řízení: Dopravní systémy a technika

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Abstrakt

Habiitačná práca sa zameriava na podporu a vytváraníe podporných ukazovateľov pre tzv. Evidence-Based Training, teda tréning na základe dôkazov. Práca je koncipovaná formou komentovaného súboru publikovaných vedeckých prác autora. Konkrétna orientácia práce je na hodnotenie trénovanosti pilotov, respektíve ich podaného výkonu vo výcviku so súčasným hodnotením vybraných biologických signálov a metód ich hodnotenia, ktoré môžu odrážať psychofyziologckú kondíciu pilota. Prezentovaný a komentovaný súbor publikácií sa vo väčšine prípadov opiera jednotné nastavenie experimentálneho tréningového procesu, ktorý vychádza zo zámeru vytvorenia takého konceptu meraní, ktorý bude reflektovať ako simulátorový tak reálny výcvik s prihliadnutím na faktory, ktoré ho môžu ovplivniť, a zároveň vytvoril možnosti pre komparáciu štúdií. To znamená, že v predloženej habilitačnej práci je výber publikácií zvolený tak, aby mal uniformný charakter a vytváral tak ucelenú štruktúru a komparatibilnosť prezentovaných štúdií.

Kľúčové slová: Tréning, letecký výcvik, biologické signály, telemetrický systém, presnosť pilotáže

Obsah

Zoznam obrázkov

Zoznam tabuliek

Predslov

Tréning pilotov založený na koncepcii Evidence-Based Training (EBT), teda tréning na základe dôkazov, sa zrodil z potreby objektivizovať rámec respektíve štandardy pilotného výcviku. Je nutné poznamenať, že výcvik pilotov sa vo svojej podstate od 60. rokov minulého storočia takmer nezmenil. Čo sa však zmenilo, sú technológie, s ktorými piloti prichádzajú do kontaktu.

Myšlienka na vznik nových výcvikových programov prišla až koncom 80. začiatkom 90. rokov minulého storočia, a to v súvislosti so stúpajúcim počtom leteckých nehôd amerických dopravcov, kde hlavnou príčinou bolo zlyhanie ľudského činiteľa. Najvyšší americký úrad spravujúci oblasť letectva FAA (Federal Aviation Administration), na konci 80. rokov povolil leteckému priemyslu flexibilný tréning s väčšou možnosťou adekvátnej reakcia na vtedajšie hrozby. FAA tento alternatívny koncept výcviku prevzala z vtedy používaného vojenského výcvikového prístupu založeného na analýze letových úloh a spätnom zhodnotení dát. Analýza úloh pritom brala do úvahy všetko, čo sa môže v priebehu letovej akcie stať, do akých situácií sa pilot môže dostať pri vykonávaní manévrov. Tento prevzatý a upravený koncept v obchodnej leteckej doprave bol pomenovaný „Advanced Qualification Program“. Výrazným rysom AQP bolo a je, že účasť v programe je pre dopravcov dobrovoľná a že možno program kedykoľvek opustiť a vrátiť sa k tradičnému výcviku. Pri zavedení programu je nutné aplikovať ho na oblasti výcviku ako analýzu, štruktúru, vývoj, implementáciu, prevádzku a hodnotenie. Získané a spracované dáta musia dopravcovia zdieľať s FAA pre spätnú väzbu. Účasť v programu je síce dobrovoľná, ale sú určité časti výcviku, ktoré sú v právnom poriadku pevne zakotvené a ktoré je potrebné dodržiavať.

Spätná väzba poukazuje na fakt, že dopravcovia čím ďalej častejšie siahajú po dobrovoľnom prístupe k výcviku, pričom veľakrát si sami dvíhajú a prekračujú požiadavky na výcvik, ktoré špecifikuje FAA. Tento prístup sa aj vďaka zvýšeným nárokom stáva oveľa bezpečnejší (safety). Kľúčom k úspešnej implementácii AQP sú v tomto smere inštruktori a hodnotitelia.

Odpoveďou na americký alternatívny prístup k výcviku bolo vytvorenie európskeho programu alternatívneho výcviku a kvalifikácií (ATQP). Základný legislatívny rámec bol opísaný v nariadení JAR-OPS 1.978, ktoré sa neskôr začlenilo pod Part ORO. FC.A.245 v rámci EASA. ATQP je opäť odlišný spôsob vykonávania základných i obnovovacích výcvikov, ktorý dopravcom umožňuje výcvik prispôsobiť svojim špecifickým potrebám, a tým zvýšiť efektivitu.

Na základoch AQP (Advanced Qualification Program) a ATQP (Alternative Training Qualification Programme), ktoré ponúkajú dobrovoľnú alternatívu k tradičnému poňatiu výcviku od pilotov, cez letecký personál až po prevádzkový personál, bol vytvorený program výcviku pilotov - EBT (Evidence-based Training).

Tým, že sa dopravca sústredí na to, čo letecký personál potrebuje a neopakuje to, čo už človek v zácviku môže ovládať, je výcvik flexibilný, kratší a lacnejší.

Aj keď je základá myšlienka EBT jasná, doposiaľ sa nevyužívajú také koncepty, ktoré by dokázali personalizovať výcvik pilotov. Uvedené by bolo možné riešiť napríklad kontinuálnym sledovaním progresu/degresu partikulárnych častí leteckého výcviku jedinca v čase, a tým prispôsobovať tréningový proces jeho potrebám. Pre uvedené účely je možné, okrem iného, využiť sledovanie trénovanosti (napríklad práve prostredníctvom hodnotenia presnosti vykonávaných činností) a hodnotenie fyziologických parametrov ako ukazateľa psychofyziologickej kondície pilota.

Predložená práca je preto orientovaná na hodnotenie trénovanosti pilotov, respektíve ich podaného výkonu vo výcviku so súčasným hodnotením vybraných fyziologických parametrov a metód ich hodnotenia, ktoré môžu odrážať psychofyziologckú kondíciu pilota. Práca je koncipovaná formou komentovaného súboru publikovaných vedeckých prác.

1 Motivácia a definovanie primárneho zamerania vedecko-výskumnej činnosti habilitanta

1.1 Charakteristika EBT

Po rokoch praxe sa prišlo na to, že väčšia efektivita sa nedosiahne len zameraním sa na bežné operácie dopravcu a ich perfektné vykonávanie, ale vytvorením takého konceptu výcviku, ktorý by staval na skúsenostiach leteckého personálu. Prečo nespočetne krát opakovať úkon, ktorý pilot už dávno ovláda, a namiesto toho tento čas v rámci výcviku využiť na precvičenie toho, čo mu ešte nejde a potrebuje zdokonaliť? Preto sa dôraz na stanovovanie programu výcviku postupne prenáša z organizácie ako celku na jednotlivých pilotov, pričom ciele a potreby organizácie zostávajú zachované. EBT koncept stojí na evidencii, teda na dôkazoch, na dátach, či predchádzajúcich meraniach, a postup výcviku sa prispôsobuje potrebám pilota.

Dopravca zavádzajúci koncepciu EBT má zadarmo k dispozícii globálne dáta na rôzne typy lietadiel. Časom je dopravca schopný začleniť vlastné spracované dáta a koncept opäť upraviť na mieru svojim vlastným potrebám.

Podľa definície v Part-ORO, EBT znamená trénovanie a hodnotenie založené na dátach zbieraných v prevádzke. Tieto dáta sú charakteristické vývojom a hodnotením celkových schopností študenta v leteckom výcviku naprieč celým spektrom plnených úloh. Dochádza teda k objektivizácii celkového hodnotenia výcviku namiesto individuálneho hodnotenia jednotlivých manévrov. Základným dokumentom pre dopravcov hľadajúcich informácie pre implementáciu EBT je dokument ICAO Doc 9995, ktorý už zohľadňuje európsky právny rámec EBT. V súčasnej dobe, ak sa dopravca rozhodne pre EBT musí tento koncept aplikovať na celú flotilu, avšak nemusí ho aplikovať na všetky typy výcviku [1].

V európskom právnom rámci je EBT začlenený do Part-ORO (Organization Requirements for Air Operations) čo predstavuje Príloha 3 k nariadeniu Komisie (EÚ) č. 965/2012 z 5. októbra 2012, ktorým sa ustanovujú technické požiadavky a administratívne postupy týkajúce sa letovej prevádzky podľa nariadenia Európskeho parlamentu a Rady (ES) č.

216/2008, inak nazývaného Äir OPS Regulation". Toto začlenenie bolo vykonané v roku 2015 formou rozhodnutia výkonného riaditeľa EASA, rozhodnutím 2015/027 / R zo 16. decembra 2015 s účinnosťou rozhodnutia 20. decembra 2015 [2].

Okrem požiadaviek začlenených do nariadenia č. 965/2012, bola určitá časť požiadaviek začlenená do nariadenia Komisie (EÚ) č. 1178/2011 z 3. novembra 2011, ktorým sa ustanovujú technické požiadavky a administratívne postupy týkajúce sa posádky civilného letectva podľa nariadenia Európskeho parlamentu a Rady (ES) č. 216/2008.

Podľa dokumentu vydávaného EASA "Terms of Reference"RMT.0696 bol vytvorený dočasný Guidance Material (GM). Plné začlenenie EBT podľa ICAO Doc 9995 do GM prišlo až so zmenou RMT dokumentu RMT.0599 [2]. ICAO manuál Doc 9995 je určený pre letecké úrady (CAA), prevádzkovateľa a schválené výcvikové organizácie - ATO (Approved Training Organizations), a to iba na obnovujúci výcvik vykonávaný na simulátoroch - FTSD (Flight Simulation Training Device). Okrem návodu, ako koncept EBT začleniť do svojich výcvikových programov, slúži tento dokument aj ako návod hodnotenia pre inštruktorov vykonávajúcich výcvik podľa EBT. Ďalšie podklady pre implementáciu EBT poskytuje dokument vypracovaný IATA v súčinnosti s IFALPA a ICAO Evidence-based Training Implementation Guide. V roku 2014 IATA organizácia uverejnila dokument s názvom Data Report for Evidence-based Training, ktorý v sebe obsahuje doposiaľ všetky zozbierané, analyzované a zhodnotené dáta. Dokument odráža dlhoročné skúsenosti mnohých aerolínií.

Propagátori myšlienok EBT si uvedomujú, že dnešné technicky veľmi pokročilé simulátory obsahujú množstvo funkcií, ktoré nie sú (efektívne) využívané, pretože legislatíva je nastavená k tzv. Checking, teda striktnému odškrtávaní zoznamov - Checklist, a nikoho už nezaujíma, prečo sa niektoré veci dejú. Cieľom EBT je teda snaha o odstránenie nerovnováhy medzi skutočnou podstatou výcviku a jednoduchou kontrolou (checking-om).

Koncept EBT je určený k rozvoju a hodnoteniu všetkých oblastí schopností (Competency) letovej posádky v obnovovacom výcviku. Za tým účelom bol vytvorený zoznam hrozieb a možných chýb. Zoznam je kategorizovaný podľa generácie lietadla (od najstarších po najnovšie modely) a fáz letu, v ktorej sa uvedené hrozby a chyby môžu vyskytnúť. Aby bolo možné hodnotiť schopnosti, je prvým krokom vytvorenie úplného rámca hodnotených schopností, ich opis, ktoré zahŕňajú technické a netechnické vedomosti, zručnosti a postoje ktoré umožňujú bezpečnú, efektívnu a ekonomickú prevádzku. Druhá časť metodiky vytvorenie EBT výcviku je postavená na prieskume kritických častí výcviku (Training criticality survey) identifikujúce hrozby a možné chyby v rôznych fázach letu. Tieto hrozby a chyby sú rozdelené do 8 kategórií, fáz letu, od predletovej prípravy a rolovanie, cez vzlet, stúpanie, let, klesanie, priblíženie, pristátie a rolovanie a poletový rozbor.

Základným pilierom celého konceptu je zbieranie dát, ktorého zmysel tkvie v tom, že slúži ako referenčný program udalostí založený na spomenutých generáciách lietadiel. Je potrebné zbierať údaje nielen z výcviku zo simulátorov, ale aj dáta z reálnej prevádzky, incidentov a nehôd, lebo neustálou aktualizáciou dát zostane výcvik aktuálny. Za týmto účelom sa dáta zbierajú od prevádzkovateľov, výrobcov, orgánov vyšetrujúci nehody, medzinárodných leteckých organizácií a leteckých úradov.

Kritickou časťou je potom analýza dát po ktorej nasleduje celková (potvrdzujúca) analýza, ktorá kombinuje všetky dátové zdroje. Následne sa vykoná spomínaný prieskum kritických častí výcviku, čiže "Training Criticality Survey", ktorého výsledkom je množstvo matíc hrozieb a chýb zodpovedajúce jednotlivým fázam letu. Neskôr sa vykoná analýza týchto matíc. Na záver sa priradia váhy jednotlivým výsledkom. Ako náhle je proces analýzy matíc hotový, nasleduje tzv. „Evidence Table process". Jedná sa o tabuľku obsahujúcu výsledky z rôznych zdrojov, ktoré sú identifikované a popísané niekoľkými kľúčovými slovami. Ďalej sa stanovia závery, na základe ktorých je určená priorita výcviku.

FAA plne podporuje celý koncept EBT. Zároveň sa podieľa na vývoji programu a podporuje amerických dopravcov, ktorí už praktizujú výcvik podľa AQP, začlenením EBT do výcvikových plánov [2].

Austrálsky úrad kompetentný v oblasti bezpečnosti letectva CASA (Civil Aviation Safety Authority) sa myšlienkou alternatívneho konceptu výcviku zaoberá od roku 2012, kedy bol schválený projekt možnosti alternatívneho výcvikového konceptu. V roku 2016 sa austrálskym dopravcom podali jasné a konzistentné informácie, ako dáta zbierať, hodnotiť a ako získané poznatky aplikovať na vlastné výcvikové programy. V roku 2017 ICAO zdôraznilo potrebu implementácie nového zdravého rámca pre výcvikové programy, ktorý by umožňoval kontinuálne analýzu a hodnotenie schopností pilota. Na základe analýzy zozbieraných dát od dopravcov, Úrad zistil, že existujú významné rozdiely v očakávaniach pilotov, ktoré boli podmienené tým, v akej organizácii vykonávali výcvik. Zároveň sa zistilo, že len niekoľko málo dopravcov zbiera a analyzuje svoje dáta a nakoniec podľa nich aj upravuje výcvikový program. Preto CASA zdôrazňuje potrebu zberu týchto dát, pretože plánuje vývoj takého výcvikového programu, ktorý by odrážal požiadavky dopravcu s meniacim sa vybavením, technológiami, novo vznikajúcimi / vzniknutými hrozbami alebo len zmenami v letových cestách. Tieto dáta by slúžila ako databanka pre inkluzívne EBT výcvikové programy. Spolu s plánmi a víziami [2, 3].

EASA zase každý rok vydáva a aktualizuje predchádzajúci Európsky plán bezpečnosti letectva EPAS (European Plan for Aviation Safety). V súčasnom Pláne vydaného na rok 2018-2022 je cieľom kompletné prepracovanie ustanovení v časti ORO oddiel FC. Z vízie vyplýva, že EBT už nebude dobrovoľnou možnosťou, ale stane sa povinným spôsobom vykonávania výcviku.

Spomínaná časť ORO, oddiel FC (Flight Crew) predstavujúce Prílohu 3 k nariadeniu č. 965/2012 obsahuje všeobecné state o poskytovaní výcviku. Konkrétne časť zaoberajúca sa výcvikom je ORO.FC.145 Poskytovanie výcviku, kde je povedané, že výcvik musí byť v súlade s osnovami výcviku, ktoré si dopravca stanovuje, že vyučovanie poskytujú adekvátne kvalifikovaní pracovníci, že programy základného aj obnovujúci výcviku vrátane osnov schvaľuje príslušný letecký úrad. Zároveň je v časti ORO.FC.145 povedané, že simulátory, čiže FTSD (Flight Simulation Training Devices), sa musia čo najviac zhodovať s lietadlom, ktoré prevádzkovateľ používa a že musí zaviesť systém monitoringu FSTD tak, aby sa zabránilo vzniku vplyvov, ktoré by na program výcviku mali negatívny dopad. Ďalšou časťou, ktorá sa zaoberá výcvikom, je časť ORO.FC.230 Udržiavací výcvik a preskúšanie, ktorá stanovuje, že každý člen posádky musí absolvovať udržiavací výcvik aj preskúšanie na totožný typ lietadla, na ktorom lieta. Pri preskúšaní pilot musí preukázať odbornú spôsobilosť, absolvovať traťové preskúšanie v lietadle a preskúšanie používania núdzového a bezpečnostného vybavenia.

Základným dokumentom pre získanie licencií a kvalifikácií je Part-FCL (Flight Crew Licensing), Príloha 1 k nariadeniu Komisie (EÚ) č. 1178/2011 (z 3. novembra 2011, ktorým sa ustanovujú technické požiadavky a administratívne postupy týkajúce sa posádky v civilnom letectve podľa nariadenia Európskeho parlamentu a Rady (ES) č. 216/2008). Podľa tohto dokumentu ATO (Approved Training Organization), čiže schválené výcvikové organizácie, vytvára vlastné interné postupy výcvikov a preskúšanie za súčasného dodržania miním a postupov stanovených v časti FCL. Základná osnova výcviku podľa časti FCL vyzerá nasledovne:

- Výučba - teoretických vedomostí na úrovni vedomostí pre získanie daného preukazu a požiadavka na určitý počet hodín, ktorých rozsah sa odvíja od daného preukazu.
- Skúška - teoretických vedomostí do požadovanej hĺbky a rozsahu.
- Výcvik v lietaní - opäť podľa požiadaviek daného typu preukazu a počet hodín resp. rozsah.
- Prax - pri niektorých typoch licencie je nevyhnutné absolvovať aj prax do určitého počtu hodín a rozsahu.
- Skúška zručnosti.

Štandardné formy výcvikových programov pracujú iba s dvoma možnými výstupmi hodnotenia, a to prešiel / neprešiel. Inštruktor samozrejme tiež prechádza výcvikom, ktorého súčasťou je zvládnutie metodiky hodnotenia. Okrem prípravy materiálov, vytváranie prostredia pre výcvik, prenosu poznatkov a ďalších odborných znalostí je súčasťou výcviku aj vyškolenie na to, aby inštruktori dokázali správne zhodnotiť výkonnosť účastníka výcviku. (FCL) V šiestej kapitole príručky pre leteckých inštruktorov vydané novozélandským leteckým úradom je opísaný spôsob hodnotenia žiadateľa o preukaz. Tam je hodnotenie popísané slovami: „comprehensive“, „systematic“ a „objective“. Z toho vyplýva, že inštruktor musí k žiadateľovi o preukaz pristupovať s všímavým, systematickým a objektívnym spôsobom, a to pri ústnom pátraniach, písomnom skúšanie či testovanie výkonu v leteckom zariadení. Súčasťou náplne práce leteckého inštruktora je pozorovanie zručností a schopností žiadateľa jeho zaznamenávanie. Toto zaznamenávanie výkonu študenta je známe ako

„anecdotal record“, voľne preložené ako stručný, no výstižný záznam výkonu, ktorý má určitú štruktúru a pravidlá vypĺňania, a ktorý je čisto subjektívneho charakteru. Novozélandská príručka vyzdvihuje pozitíva tohto záznamu, najmä preto, že dokáže zachytiť správanie v prirodzených situáciách. Manuál uvádza príklad študenta, ktorý síce oplýva vynikajúcimi znalosťami miním VFR, ale opakovane a vedome ich porušuje, čo taký záznam môže odhaliť. Pre hodnotenie iných soft parametrov, čo sú zručnosti v oblasti správania, teda predstavujúce sociálnu a emočnú inteligenciu, je lepším záznamom štrukturalizovaný „rating scale“. Novozélandská univerzita Massey vyvinula hodnotiace stupnice, ktoré poskytujú systematický postup zaznamenávania inštruktorových pozorovaní. Stupnica síce má opäť výstup prešiel / neprešiel, ale objavuje sa náznak rozčleneného hodnotenia.

Snaha o detailnejšie hodnotiace kritériá je vidieť v časti FCL pri jazykových schopnostiach. Hodnotenie jazykových schopností je dané úrovňami, keď tri z nich, 4, 5 a 6 a ich slovné ekvivalenty prevádzková, rozšírená a odborná úroveň, dávajú viac možností úspešného zloženia skúšky než len prešiel / neprešiel. Stále však nerieši problém nedostatočnej objektivity.

„Hard skills“, čiže odborné znalosti a zručnosti sa na základe svojej podstaty merajú ľahšie ako mäkké zručnosti. V časti FCL je jasne popísané čo, a akým spôsobom sa pri letových úlohách hodnotí. V súčasnej dobe vo svetle pokročilých výcvikových programov sa ukazuje, že prosté hodnotenie prešiel / neprešiel je nedostatočné.

Všetky príručky sveta žiaka ubezpečujú, že jeho výkon bude hodnotený správne a spravodlivo, lebo inštruktor je popisovaný takmer ako boh. Spravodlivý a vždy objektívny. Ale školenia a manuály pre inštruktorov už takou istotou neoplývajú. Tieto školenia inštruktorov nabádajú k objektívnemu hodnoteniu. To, že inštruktor absolvuje výcvik a získa FI licenciu, ešte nezabezpečuje stopercentnú objektivitu či správnosť jeho rozhodnutí. Existuje tisíc a jeden dôvodov, ktoré môžu narušiť inštruktorovu objektivitu. Medzi také dôvody môžu patriť neovplyvniteľné fyzické príčiny - hlad, smäd, únava či choroby, ktoré znižujú vnímanie pre vykonanie letovej úlohy, psychofyziologické ako stres, alebo psychické od silných emócií až po sympatie či antipatie k žiakovi. Následkom subjektívneho vyhodnotenia, či už cieleného alebo nie, je evalvácia, ktorá nezodpovedá skutočnému výkonu. Z toho vyplýva potreba vytvorenia a používania objektívnych nástrojov pre hodnotenie.

Je ťažké a pravdepodobne aj nemožné prísť s objektívnym prístupom k hodnoteniu soft parametrov. Je úplne nemysliteľné, že by človek bol schopný plne objektívne hodnotiť výkony v oblasti výcviku a veda zatiaľ tiež so žiadnym konceptom neprišla.

Čo však dnes možné je, to je hodnotenie tvrdých zručností pomocou vedy a techniky. Budúcnosťou sa môžu zdať automatické hodnotiace nástroje s implementovanou umelou inteligenciou. Ale obmedzenie umelej inteligencie tkvie v tom, že človek musí softvéru túto inteligenciu dodať. Lenže inteligencia sa skladá zo znalostí, ale aj zo skúseností a ľudských schopností, teda ako z hard parametrov, tak i soft parametrov. Nie je problém stroj naučiť hodnotiť presnosť pilotovania lietadla s preddefinovanými tolerančnými hranicami, napr. že pri vzlete musí pilot držať kurz zhodný s osou dráhy s maximálnou odchýlkou Km$\pm$ 5°, že zatáčať má povolené až v určitej výške alebo držať konštantnú hladinu výšky apod.. Ťažké, ale nie nemožné je naučiť stroj rozoznať napríklad jazykové schopnosti. Ale čo je takmer nemožné, je softvér naprogramovať tak, aby dokázal správne vyhodnotiť problematickú, neprehľadnú či inak náročnú situáciu. V mnohých situáciách, a pritom sa nemusí jednať o kritické situácie, nemusí byť vhodné len jedno možné riešenie. V takýchto situáciách sa totiž prejavia skúsenosti inštruktora. Najcennejšou devízou inštruktorov je ich „know-how“, „knowledge“, alebo inak povedané expertné znalosti.

Východiskom by bolo navrhnúť také riešenie, ktoré by kombinovalo automatický a objektívny spôsob hodnotenia „hard“ parametrov s expertnou znalosťou inštruktora. Objektívne by softvér podporil názor inštruktora a naopak inštruktor by validovali výstup softvéru. Jednalo by sa tak o vhodné komplementárne riešenie.

Hodnotenie na základe analýzy dát je zatiaľ možné a dostupné len pre prevádzkovateľov leteckej dopravy, väčšie aerolínie, a zatiaľ len pre obnovovací alebo typový výcvik. Z popísaných celosvetových trendov v oblasti výcviku vyplýva, že je potrebné nájsť také riešenie, automatický evaluátor, ktorý by v reálnom čase vyhodnocoval výkon pilotov a ktorý by slúžil ako objektívny prvok dopĺňajúci hodnotenie letového inštruktora aj pre menšie podniky, v tomto prípade pre letecké školy. Výstup takéhoto systému založeného na analytických a klasifikačných nástrojoch by mohol odhaliť veľa problémov, od činností, s ktorými študent-pilot má ťažkosti až po také aktivity, ktoré inštruktor nemusí postrehnúť a naopak činnosti, ktoré študent-pilot zvláda natoľko dobre, že je stratou času je neustále opakovať a tento čas venovaný výcviku sa dá efektívnejšie využiť práve na precvičenie problematických úloh. Použitie takéhoto evaluátora by bolo najefektívnejšie, ak by ho bolo možné využívať hneď od začiatku výcviku.

Takýto prostriedok by vyjadroval nielen esenciu EBT, teda výcviku založeného na analýze dát, ale zároveň by naplnil ideu EASA vízie 2022.

Alternatívne metódy hodnotenia výkonu pilota ICAO, IATA, ďalšie medzinárodné organizácie či dopravcovi nezverejňujú spôsob, akým letecké dáta spracúvajú, ani aké parametre sú princípmi evaluácie. V rámci akademickej obce je táto téma riešené len veľmi málo, ale z relatívne mnohých uhlov.

Prínosné sa ukazujú byť výskumy zamerané na meranie psychofyziologických reakcií jedincov na rôzne podnety. Existuje relatívne veľa štúdií, zameraných na meranie reakcií človeka v záťažových a stresových situáciách, ale publikovaných bolo len málo štúdií, ktoré by v týchto situáciách hodnotili psychofyziologický stav lietajúceho personálu. Všeobecne sa reakcia organizmu na záťaž hodnotí na základe rozbor krvi a slín, kedy dochádza k saturácii arteriálnej krvi kyslíkom, mení sa hladina krvného cukru, hladina kortizolu, IL-3 a IL-6. Najčastejšie merané reakcie na stresové podnety sú zmeny frekvencie srdcovej činnosti - EKG, dychovej frekvencie, myopotenciálov - svalového napätia, teploty tela, meranie mozgovej aktivity - EEG, galvanické kožné reakcie, krvný tlak atp. Ukazuje sa, že najspoľahlivejším ukazovateľom hodotenia úrovne stresovej záťaže je tepová frekvencia. Budúcnosť merania biosignálov tkvie v následnej implementácii do leteckých simulátorov. V praxi by to znamenalo, že by inštruktorovi bol k dispozícii ďalší dátový zdroj, z ktorého by bolo vidieť, aké manévre, letové situácie, fázy letu robia pilotovi ťažkosti.

Ďalšia oblasť využitia letových dát je zameranie sa na hodnotenie technického vykonania letu. Najčastejšie vyhodnocovaným parametrom je presnosť techniky pilotáže, v rámci ktorej sú sledované v určitých etapách letu odchýlky letových parametrov od požadovaného režimu letu.

1.2 Základná charakteristika realizovaného výskumu

V konexte vyššie uvedených faktov, bol od roku 2013 uskutočnený kontinuálny zber dát na základe vykonania experimentálnych meraní. Nižšie popísaný koncept opierajúci sa o výber uchádzačov a nastavenie experimentálneho tréningového procesu vychádzal zo zámeru vytvorenia takého konceptu meraní, ktorý bude reflektovať ako simulátorový tak reálny výcvik s prihliadnutím na faktory, ktoré ho môžu ovplivniť, a zároveň vytvoril možnosti pre komparáciu štúdií. To znamená, že v predloženej habilitačnej práci (vo forme súboru publikovaných vedeckých prác) je výber publikácií zvolený tak, aby mal uniformný charakter a vytváral tak ucelenú štruktúru a komparatibilnosť prezentovaných dát.

1.2.1 Výber výskumnej vzorky a realizácia výcviku

Pre zaradenie uchádzačov do výcvikového procesu prebehol výber účastníkov spomedzi študentov Leteckej fakulty Technickej Univerzity v Košiciach. Výber spočíval zo zloženia teoretických testov, psychologických testov a zdravotných kritérií. Všetci záujemci o účasť na experimentálnych meraniach podstúpili záťažový test (tzv. OR-test, ktorý je súčasťou psychologického hodnotenia na Ústave leteckého zdravotníctva), ktorý spočíval zo štyroch častí.

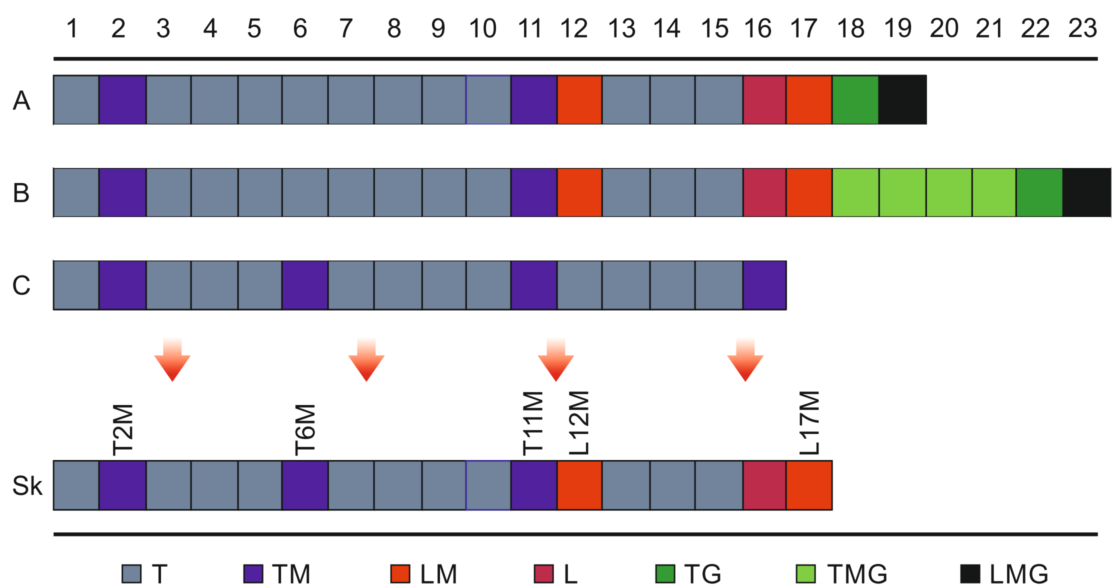
Každý študent dostal dva papiere popísané kombináciou dvoch alebo troch písmen a dvoch čísel. Všetky strany boli rovnaké a každá z nich bola pre jednu zo štyroch špecifických hodnotiacich častí. Študentom bolo postupne nadiktovaných dvadsať kombinácií písmen a čísel, ktoré museli označiť v testovacom hárku. Na vyriešenie jednej úlohy mali tri sekundy. V prvej časti počuli kombináciu písmen a čísel, ktorú museli zaškrtnúť. V druhej časti im boli najprv povedané dve kombinácie písmen a potom dve čísla. Cieľom bolo zaškrtnúť obe spojenia. V tretej časti počuli kombináciu písmen a čísel. Ak bolo číslo nepárne, museli ho zaškrtnúť. V prípade, že išlo o párne číslo, museli ho zakrúžkovať. V štvrtej časti im najskôr boli nadiktované kombinácie dvoch písmen a potom dvoch čísel. Opäť museli zaškrtnúť spojenie s nepárnym číslom a zakrúžkovať spojenie s číslom párnym.

Každá nasledujúca časť testu teda zvyšovala nároky na emočnú stabilitu, pozornosť a mentálne preťaženie, čo sa prejavilo individuálne v počte chybových označení správnych odpovedí v testovacom hárku. Test bol prevzatý z Ústavu leteckého zdravotníctva a upravený pre potreby zaradenia subjektov do testovacej vzorky vzhľadom k účelom tejto práce. Zo všetkých štyroch častí sa stanovilo celkové skóre, na základe ktorého bolo vytvorené poradie jednotlivých záujemcov o účasť na experimentálnom tréningovom procese. Do experimentu bolo zaradených 35 uchádzačov. Okrem vyššie uvedeného museli všetci vybraní uchádzači spĺňať platné požiadavky na zdravotnú spôsobilosť leteckého personálu (JAR-FCL 3.105) a zároveň nesmeli byť držiteľmi licencie pilota (PPL), vzhľadom k zabezpečeniu čo najvyššej úrovne uniformnosti skúmanej vzorky subjektov.

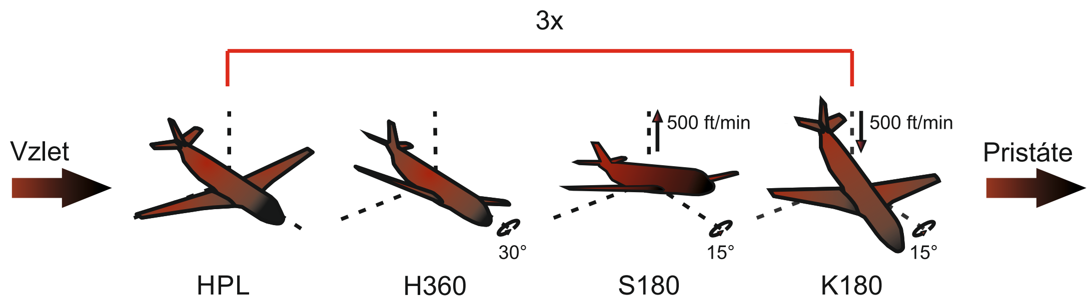
Účastníci boli rozdelení do troch skupín (A, B a C) skupinu A tvorilo 8 mužov a 2 ženy s priemerným vekom 22 ± 5 rokov, skupina B pozostávala z 9 mužov a jednej ženy s priemerným vekom 23 ± 3 roky. Skupinu C tvorilo 10 mužov a 5 žien s priemerným vekom 21 ± 4 roky. Všetci uchádzači v uvedených skupinách mali rozdielnu časť tréningu. Spoločným však bola teoretická príprava zameraná na zvládnutie jednoduchej techniky pilotovania (JTP), a to v rozsahu 2 hodín. Cieľom teoretickej prípravy bolo oboznámenie probandov s ergonómiou pilotnej kabíny, rozmiestnením jednotlivých ovládacích prvkov a prístrojov, ich význam a využitie behom letu. Praktický letový výcvik prebiehal v súlade so stanovenou metodikou výcviku, znázornenou na obrázku 1.1, pod vedením skúseného inštruktora (pilota, respektíve učiteľa lietania).

Ako bolo spomenuté, harmonogram realizácie tréningu sa u jednotlivých skupín mierne líšil. Skupina A najprv absolvovala 11 hodín na trenažéri s analógovým zobrazením letových, navigačných a motorových údajov, kedy druhá a posledná hodina bola meraná (v zmysle merania psychofyziologických parametrov a presnosti pilotovania). Hneď nato nasledoval prvý výcvik v lietadle, pri ktorom bolo meranie taktiež realizované. Následne mali subjekty ďalšie tri cvičenia na trenažéri a dve hodiny výcviku v lietadle, kedy posledný z nich bol opäť meraný. Na záver sa zmenilo zobrazenie letových údajov z analógového na Glasskokpit a prebehlo merané cvičenie na trenažéri a meraný výcvik v lietadle.

Začiatok výcviku skupiny B bol rovnaký ako u skupiny A. Študenti teda absolvovali 11 letových hodín na trenažéri s analógovým zobrazením letových, motorových a navigačných údajov, pričom meranie prebehlo pri 2. a 11. tréningovej hodine. Nasledoval prvý meraný výcvik v lietadle, tri cvičenia na trenažéri a potom dve tréningové hodiny v lietadle (meraná bola práve druhá hodina) s analógovým zobrazením. Pre ďalší výcvik sa zmenil režim zobrazenia na Glasskokpit. Na rozdiel od skupiny A, ale študenti absolvovali 5 cvičení na trenažéri, kedy až posledné z nich bolo merané, a na záver mali meraný výcvik v lietadle pri Glasskokpitovom zobrazení. Skupina C na rozdiel od predchádzajúcich dvoch skupín neabsolvovala výcvik na reálnych lietadlách. Tréningový harmonogram pozostával len zo 16. letov na simulátore s analógovým zobrazením letových, navigačných a motorových údajov. Zber dát bol pritom realizovaný v 2, 6, 11 a 16 hodine tréningu.



Obr. 1.1: Harmonogram tréningu pre skupinu A, B a C (T – trenažér, analóg; TM – meranie na trenažéri, analóg; LM – meraný let, analóg; L – let, analóg; TG – trenažér, glasskokpit; TMG – meranie na trenažéri, glasskokpit; LMG – meraný let, glasskokpit, Sk – zložená skupina zo všetkých subjektov zaradených do výcviku pri splnenej podmienke uniformného výcvikového procesu)



Obr. 1.2: Charakteristická séria manévrov realizovaná pri jednom lete, pozostávajúca z horizontálneho priamočiareho letu (HPL), horizontálnej zatáčky (H360), stúpavej zatáčky (S180) a klesavej zatáčky (K180)

Vzhľadom k rozdielnosti výcvikového procesu v neskorších fázach boli vyššie popísané skupiny zjednotené pre evaluačné účely tejto práce. Zjednotenie skupín teda spočívalo vo výbere spoločnej tréningovej fázy. Pre skupinu A a B sa konkrétne jednalo o zjednotenie do 17 hodiny tréningu. Skupina C bola do výslednej hodnotiacej vzorky zaradená s ohľadom na realizáciu tréningu po 11 tréningovú hodinu. Participanti pôvodne zaradení do skupiny C teda prispeli k rozšíreniu sledovaných parametrov a vymedzeniu medzery medzi prvým a druhým trenažérovým meraním. Celkový prehľad výslednej skupiny pre hodnotenie je znázornený na obrázku 1.1. Na uvedenom obrázku (dole) sú taktiež znázornené skratky jednotlivých realizovaných meraní, ktoré budú vystupovať v ďalších častiach tejto práce. Konkrétne sa jedná o meranie na trenažéri v 2. hodine výcviku T2M (35 subjektov), meranie na trenažéri v 6. hodine tréningu T6M (15 subjektov), meranie na trenažéri v 11. hodine výcviku T11M (35 subjektov), meranie realizované na lietadle v 12. hodine výcviku L12M (20 subjektov) a merania na lietadle v 17.1 hodine výcviku L17M (20 subjektov).

Výcvik prebiehal na leteckom trenažéri typu TRD40, simulujúcom lietadlo typu Cessna 172 a v lietadle typu Diamond DA40. Behom realizácie jednotlivých letov museli probandi vykonávať presne definované letové úkony s cieľom udržania požadovaných letových parametrov letu, a to behom horizontálneho priamočiareho letu (HPL), horizontálnej zatáčky o 360° (H360) pri náklone 30°, stúpavej a klesavej zatáčky (S/K180) o 180° pri náklone 15° a vertikálnej rýchlosti stúpania/klesania 500 ft/min. Uvedené poradie manévrov bolo striktne dodržiavané a jednotlivé série manévrov sa vykonávali trikrát v jednom lete. Okrem vzletu a pristátia boli teda realizované tri série manévrov v poradí HPL, H360, S180, K180, (Obr. 1.2) čo zabezpečilo uniformnosť výcviku a meraní.

1.2.2 Zber dát

Okrem samotných záznamov letu (zo simulátora) a subjektívneho hodnotenia chybovosti inštruktorom v jednotlivých fázach tréningového procesu, bol zber dát (biosignálov) realizovaný pomocou nositeľného telemetrického systému určeného pre snímanie fyziologických a blízkych environmentálnych parametrov subjektu.

Meranie fyziologických dát prebiehalo s využitím systému FlexiGuard vyvinutom na spoločnom pracovisku biomedicínskeho inžinierstva FBMI ČVUT a 1. LF UK. Systém bol primárne určený pre meranie psychofyziologickeho stavu a environmentálnych parametrov u členov integrovaného záchranného systému. Vďaka modularite, neinvazivite a konceptu, ktorý neobmedzuje meraný subjekt vo vykonávaní jeho činností, bol tento merací system využitý aj pri meraniach realizovaných pri výcviku pilotov.

Základný popis tohto systému na hardvérovej a softvérovej úrovni, je bližšie popísaný v publikáciach uvedených v Prílohe A a B.

Schlenker, J., Socha, V., Smrcka, P., Hana, K., Begera, V., Kutilek, P. et al. (2015). FlexiGuard: Modular biotelemetry system for military applications. In International Conference on Military Technologies (ICMT) 2015. IEEE.

Príloha A

Kliment, R., Smrčka, P., Hána, K., Schlenker, J., Socha, V., Socha, L., & Kutílek, P. (2017). Wearable Modular Telemetry System for the Integrated Rescue System Operational Use. Journal of Sensors, 2017, 1–12.

Príloha B

2 Presnosť pilotáže ako indikátor výkonnosti

Vo všeobecnosti sa výcvik pre získanie tzv. Personal pilot license (PPL) respektíve Ultralight pilot licence (ULL) opiera o zvládnutie teoretickej prípravy obsahujúcej pravidlá lietania, technické znalosti letúna, plánovanie a vykonanie letu, meteorológiu, navigáciu, prevádzkové postupy, základy letu atp. Pri tomto type výcviku sa posudzujú schopnosti, skúsenosti, zručnosti a návyky pilota-žiaka. Výcvik je považovaný za ukončený ak sú splnené minimálne požiadavky na výcvik a žiak je pripravený preukázať schopnosť ako veliteľ letúna, vykonávať postupy a manévre so stupňom zručností zodpovedajúcim oprávneniam PPL a ďalej preukázať schopnosť riadiť letún v rozsahu jeho obmedzení, vykonávať všetky manévre plynule a presne, prejaviť dobrý úsudok a vyvinutý zmysel pre let, uplatňovať teoretické znalosti v praxi, riadiť letún takým spôsobom, že nikdy nevznikne vážna pochybnosť o úspešnom výsledku vykonávaného postupu, alebo manévru. Z uvedeného vyplýva, že v rámci tréningu pri tomto type výcviku, ktorý je vo väčšine prípadov prvotný, je potrebné objektívne sledovať a hodnotiť výcvikový progres. V tomto smere je určite užitočné sledovanie praktického zvládnutia jednoduchej techniky pilotáže. Hodnotenie presnosti pilotáže patrí medzi základné hodnotiace kritéria využívané inštruktormi, sledovanie progresu - nie vždy.

Možnosti hodnotenia presnosti pilotáže sú zrejmé, avšak toto hodnotenie sa odvíja od dostupnosti dát a charakteru vykonávanej letovej úlohy. V podstate existujú dve prístupy k takémuto hodnoteniu a to expertý (hodnotenie inštruktorom) alebo komplexná post-hoc analýza letového záznamu.

V rámci realizovaných štúdií orientovaných na hodnotenie presnosti pilotáže boli publikované dva články ktoré sú predmetom Prílohy C a D. V prvom z predložených publikácií je, okrem iného, vykonaná analýza závyslosti medzi exaktným určovaním presnosti vo vykonávaní konkrétnych manévrov (využívajúc spracovanie dát z letovéh zapisovača) a hodnotením na základe inštruktora. Výsledky poukazujú na fakt, že hodnotenie inštruktorom je v podstate totožné s hodnotením na základe reálnych dát. Taktiež je však povšimnuteľná relatívne vysoká variabilita pri odhadovaní presnosti vykonávaného manévru na základe subjektívneho hodnotenia inštruktorom.

Socha, V., Kutilek, P., Stefek, A., Socha, L., Schlenker, J., Hana, K., et al. (2014). Evaluation of relationship between the activity of upper limb and the piloting precision. In Proceedings of the 16th International Conference on Mechatronics - Mechatronika 2014. IEEE.

Príloha C

Okrem vyššie uvedeného sa článok taktiež zaoberá vplyvom aktivity hornej končatiny na presnosť pilotáže. Tu výsledky ukazujú že piloti, bez osvojených návykov základnej techniky pilotovania vykazujú zvýšenú aktivitu pri riadení (tzv. vyšívanie), čo má za následok neustálu snahu korigovať trajektórie letu. Takéto chyby spôsobené napríklad nedodržaním stanovenej vertikálnej rýchlosti stúpania alebo klesania spôsobujú skrátenie alebo predĺženie času dosiahnutia požadovanej hladiny alebo výšky letu lietadla. Tieto chyby môžu mať za následok zníženie bezpečnosti letu u menej skúsených pilotov najmä vo fáze priblíženia lietadla na pristátie, hustej letovej prevádzke apod.

Druhý publikovaný článok hodnotiaci presnosť pilotáže sumarizuje celkový priebeh výcviku u skupiny subjektov zaradenej do experimentálneho tréningového procesu. Okrem samotného hodnotenia presnosti pilotáže, článok pojednáva o využiteľnosti simulátorov pre výuku základnej techniky pilotáže a osvojovaní si návykov spojených so samotným riadením lietadla. Táto potreba vychádzala z faktu, že kritické využitie leteckých simulátorov predstavuje ich začlenenie do tréningového procesu pilotov a to hlavne pri prihliadnutí na základnú pilotnú licenciu vo forme personal pilot licence (PPL) prípadne ultralight pilot licencie (ULL). Pri typovom výcviku pre obdŕžanie PPL, za predpísaného náletu 45 hodín je pritom možné využiť 5 hodín na certifikovanom simulátore. Simulátori tu však nie sú využívané pre oboznámenie sa s pilotážou.

Vzhľadom k vyššie uvedenému sa predkladaný článok konkrétne zaoberá hodnotením výcviku pilotov s využitím leteckého simulátora, pričom hlavný ohľad je braný práve na jednuduchú techniku pilotáže. Cieľom štúdie bolo vyhodnotiť vyhodnotiť využiteľnosť leteckého simulátora pri nácviku jednoduchej techniky pilotovania a to prostredníctvom hodnotenia chybovosti vo vykonávaní predpísaných manévrov, ktorá je jedným zo základných kritérií pre obdŕžanie licencie pilota. Ďalším cieľom, ktorý vychádza z analýzy súčasného stavu, prezentovanej v publikácií, je zhodnotenie vplyvu prestupu zo simulovaných letov na lety reálne a to vzhľadom na progres/degres v presnosti vykonávaných manévrov.

Socha, V., Socha, L., Hanakova, L., Lalis, A., Koblen, I., Kusmirek, S. et al. (2016). Basic Piloting Technique Error Rate as an Indicator of Flight Simulators Usability for Pilot Training. International Review of Aerospace Engineering (IREASE), 9(5), 162–172.

Príloha D

Ako je zo štúdije zrejmé, letecké simulátori už v súčasnej dobe majú a aj v budúcnosti budú mať svoje nezastupitelné miesto vo výcviku pilotov. Ich význam spočíva najmä v získavaní správnych návykov, eliminácii chýb, tréningu predpísaných postupov, riešení krízových situácií apod.

Parciálne výsledky vyššie prezentovaných štúdií slúžili ako dobrý ukazovateľ výkonnosti/trénovanosti pilota a zároveň poskytovali predstavu o priebeu výcviku u sledovaných subjektov, ktorá bola využitá aj pri hodnotení fyziologických funkcií.

3 Sledovanie fyziologických funkcií u pilotov

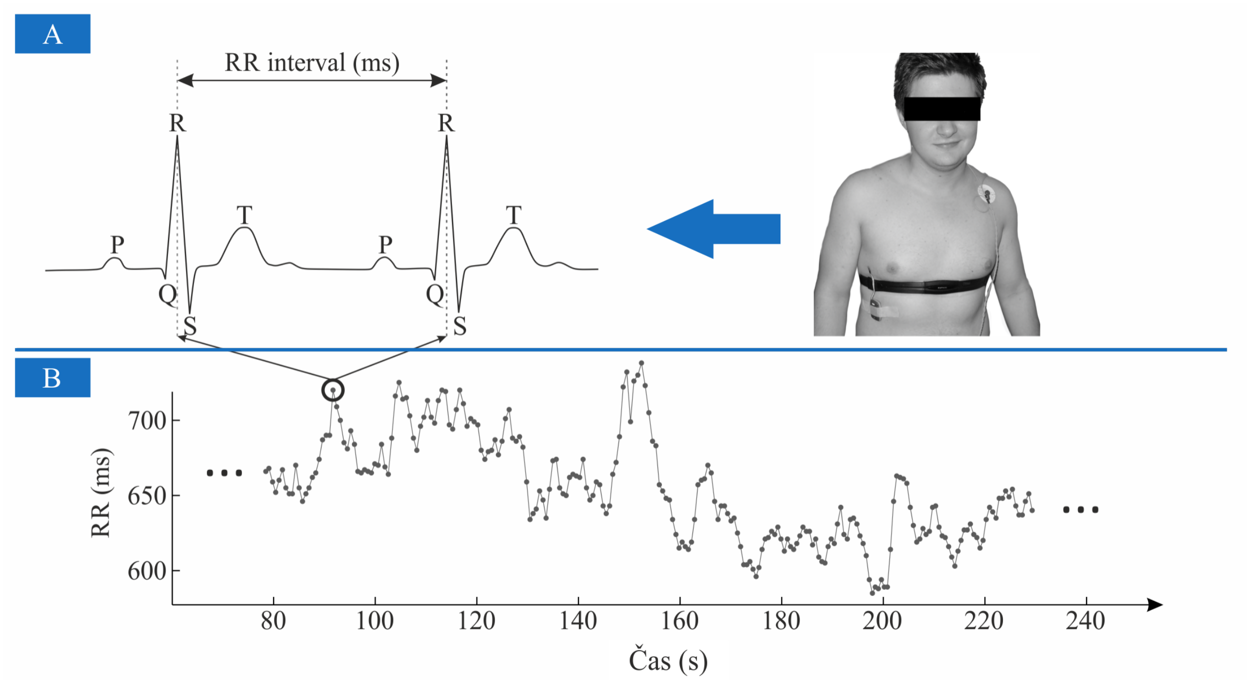
Pomocou fyziologických funkcií ako je srdcová frekvencia a dychová frekvencia je možné hodnotiť záťaž človeka pri plnení určitých úloh. V klasickej medicíne sa tieto metódy využívají pri zvýšenej fyzickej aktivite k zisťovaniu výkonnosti organizmu. V kabíne pilota však k veľkej fyzickej aktivite nedochádza, no napriek tomu sa výkon pilotov pri pilotáži može meniť. V tomto prípade to ovplyvňuje nie fyzická ale psychická záťaž (únava, psychické poruchy, lieky a pod.), ktorá je taktiež regulovaná fyziologickými mechanizmami organizmu.

Srdcová frekvencia a dychová frekvencia patria medzi najjednoduchšie merateľné parametre v kabíne pilota, ktoré možu indikovať zmenu záťaže. Funkcia srdca a dýchanie je ovplyvňované autonómnym nervovým systémom, ktorý je súčasťou periferného nervového systému, a to jeho dvoma zložkami sympatikus a parasympatikus. Tieto dve zložky v organizme pracujú antagonisticky, ale nie absolútne protichodne, pretože sa navzájom doplňujú. Dynamicky reagujú na zmeny vonkajšieho a vnútorného prostredia organizmu a podľa týchto zmien regulujú životné funkcie orgánov k dosiahnutiu homeostázy. Sympatikus sa zúčastňuje hlavne dejov, ktoré vyžadujú okamžitú reakciu, je s ním preto spojené heslo bojuj, uteč, na druhej strane parasympatikus sa aktivuje viac pri celkovom telesnom kľude s heslom odpočívaj a prežívaj. Tieto dve zložky veľmi citlivo reagujú už na malé vychýlenia z rovnováhy prostredia a práve preto je ich sledovanie prostredníctvom fyziologických parametrov dobrým indikátorom fyzického a psychického stavu organizmu človeka. Najčastejšie merané parametre sú práve tepová frekvencia, krvný tlak, dychová frekvencia, telesná teplota, elektromyopotenciály svalstva, odpor kože. Doposiaľ je odpublikovaných veľa štúdií, ktoré práve pomocou týchto fyziologických parametrov boli schopné zhodnotiť úroveň stresovej záťaže človeka, či už v reálnych alebo simulovaných záťažových situáciách [4, **?**].

Všetky psychofyziologické funkcie človeka odzrkadľujú jeho aktuálny psychický a fyzický stav v akýchkoľvek životných situáciách, ktoré ovplyvňujú jeho konečné správanie a napokon aj subjektívne rozhodovanie. Práve tento aspekt je doležité sledovať v oblasti letectva k zamedzeniu vzniku možných chýb v technike pilotovania, čo následne vedie k zvýšeniu bezpečnosti v leteckej doprave. Problematika ľudského faktora v bezpečnosti leteckekej dopravy totižto stále zohráva rozhodujúcu úlohu, až 70-80% leteckých incidentov bolo sposobených práve zlyhaním ľudského faktora, z toho až 50% priamo lietajúcim personálom [5]. Plnenie jednotlivých úloh piloti musia vykonávať s presnosťou a maximálnou koncentráciou, akákoľvek nová informácia musí byť spracovaná v čo najkratšom intervale. Tieto podmienky možu vytvoriť určitú hladinu mentálnej a emocionálnej záťaže, ktorá može následne vyvolať neadekvátnu reakciu pilota.

Psychická záťaž cez autonómny nervový systém ovplyvňuje činnosť srdca, čo sa prejaví zmenou srdcovej frekvencie. Vplyvom sympatika dochádza k zvyšovaniu srdcovej činnosti s kontraktility srdca, antagonisticky na tieto funkcie posobí parasympatikus. Samozrejme, okrem tejto neurálnej modulácie na činnosť srdca vplývajú aj humorálne vplyvy (hormón thyroxin alebo pomer adrenalín/noradrenalín), a napokon aj okolité prostredie (teplota prostredia, nadmorská výška a pod.). Práve sledovanie neurálnej modulácie funkcie srdca sa ale javí ako najvhodnejší pre jeho hodnotenie. Základnou charakteristikou srdcovej frekvencie je R-R interval, t.j. Interval medzi dvoma po sebe nasledujúcimi QRS komplexmi elektrokardiogramu (Obr. 3.1). Zmeny v tepovej frekvencii sú vyvolané zmenami medzi jednotlivými kontrakciami srdcového svalu. Tieto zmeny sú popisované ako variabilita srdca rytmu (HRV). Práve pomocou tejto variability je možné odvodzovať informácie o regulovaní homeostázy organizmu autonómnym nervovým systémom. Viaceré štúdie už potvrdili, že HRV je podstatným ukazovateľom schopnosti človeka prisposobovať sa zmenám a požiadavkám okolitého prostredia [6, 7].

Dychová frekvencia ako ďalší fyziologický ukazovateľ zmeny psychického stavu človeka je taktiež regulovaný autonómnym nervovým systémom. V stresových situáciách dochádza k nárastu dychovej frekvencie. Dychová frekvencia ovplyvňuje aj činnosť srdca, srdcovú frekvenciu, práve preto pri hodnotení záťaže človeka môže byť meranie tohto parametra dôležité.



Obr. 3.1: Príklad EKG krivky (A) a príklad signálu srdcovej aktivity vo forme R-R intervalov.

3.1 Analýza dychovej frekvencie

Pre neinvazívne snímanie dychovej frekvencie bol využitý piezoelektrický senzor vyvinutý na spločnom pracovisku biomedicínskeho inžinierstva ČVUT v Prahe a 1. Lekárskej fakulty Univerzity Karlovej. Piezoelektrická jednotka pre snímanie dychovej frekvencie bola umiestnená v stredovej čiare pod processus xiphoideus (mečovitý výbežok kosti hrudnej) cca 7 cm ventrálne v oblasti epigastria s pásom obopínajúcim telo v tejto úrovni. Umiestnenie senzoru bolo zvolené kvôli väčšej objemovej zmene spôsobenej respiráciou a minimalizácii pohybových artefaktov, z čoho vyplývala presnejšia identifikácia nádychov [8]. Dychová frekvencia bola vypočítaná z periódy medzi identifikovanými nádychmi. Dáta reprezentujúce počet dychov za minútu (bpm) boli zasielané do zbernej jednotky s odosielacou frekvenciou 5 Hz prostredníctvom rádio frekvenčného rozhrania.

Hodnotenie dychovej frekvencie je založené na podobných princípoch ako hodnotenie HRV, ktoré sú popísané v kapitolách nižšie (väčšinou sa jedná o hodnotenie v časovej oblasti). Problémom pri meraní dychovej frekvencie pilotov bol veľké zašumenie dosiahnutého signálu, vzhľadom k pohybovým artefaktom. Tento senzor sa nezdal vhodný pre dosiahnutie presných meraní a v neskorších fázach zberu dát prestal byť využívaný.

Namerané dáta, po odstránení extrémov a predspracovaní preukázali, že dychová frekvencia môže byť reflektovať sympato-vagálny balanc podľa teórie popísanej vyššie. Tieto zistenia boli prezentované v publikácií umiestnenej v Prílohe E.

Socha, V., Szabo, S., Socha, L., Kutilek, P. & V. Nemec (2014). Evaluation of the variability of respiratory rate as a marker of stress changes. In Proceedings of the 18th International Scientific Conference Transport Means. Kaunas University of Technology.

Príloha E

3.2 Analýza HRV vo frekvenčnej obasti

Frekvenčná analýza je široko používaná metóda analýzy srdcovej činnosti. Ide o spektrálnu analýzu RR intervalov srdcovej frekvencie, pomocou Fourierovej transformácie (FT), ktorá rozkladá komplexnú funkciu do rôznych frekvencií oscilujúcich funkcií ako sú sínus a kosínus. Príklad rozdelenia jednotlivých pásiem je znázornený na Obr. 3.2. Spektrálna analýza využíva FT pre finálne grafické prerozdelenie jednotlivých frekvenčných pásiem, nachádzajúcich sa v analyzovanom signále. V prípade srdcovej činnosti ide o tri frekvenčné pásma:

- VLF – pásmo veľmi nízkych frekvencií v rozsahu 0,01 – 0,04 Hz. Je všeobecne známe, že toto pásmo opisuje činnosť pomalých mechanizmov sympatikového systému. Jednotkou sú ms^2.

- LF – pásmo nízkych frekvencií v rozsahu 0,04 – 0,15 Hz charakterizuje oba, sympatikový aj parasympatikový systém, no vo všeobecnosti je silným indikátorom sympatikovej aktivity. LF opisuje vplyv parasympatika, ak je frekvencia dýchania nižšia ako 7 dychov za minútu alebo počas hlbokého dýchania. Ak je teda subjekt v pokoji s pomalým a rovnomerným dýchaním, hodnoty LF môžu byť veľmi vysoké ukazujúc skôr zvýšenú parasympatikovú aktivitu, než zvýšenie sympatikovej regulácie. LF má rovnakú jednotku, a to milisekundy štvorcové.

- HF – pásmo vysokých frekvencií s rozsahom 0,15 - 0,4 Hz odráža parasympatikovú aktivitu, a je tiež známe ako dýchacie pásmo, pretože odpovedá variáciám NN intervalov spôsobených dýchaním (RSA). Srdcová frekvencia sa zvyšuje počas vdychovania a klesá pri výdychu. Jednotkou sú ms^2.

Ďalším parametrom charakterizujúcim spektrálnu analýzu je celkový výkon (TP) a je to odhad celkového spektrálneho výkonu, t.j. všetky pásma 0 – 0,4 Hz. Prirodzene, má rovnaké jednotky ako frekvenčné pásma a indikuje celkovú autonómnu aktivitu, kde je sympatiková činnosť hlavným aktérom. Východzím parametrom je však pomer nízkych a vysokých pásiem (LF/HF), pretože hovorí o celkovej rovnováhe medzi symatikovým a parasympatikovým systémom. Vyššie hodnoty znamenajú dominanciu sympatika, zatiaľ čo nízke hodnoty dominanciu parasypatika. Tento podiel môže byť použitý práve pre kvantifikovanie spomínanej rovnováhy autonómnych systémov. Okrem týchto parametrov existuje aj upravená forma nízkych a vysokých frekvenčných pásiem. Ide o takzvané normalizované hodnoty:

- Normalizovaná LF (nLF) – normalizovaná hodnota LF, je to podiel absolútnej hodnoty LF a rozdielu celkového výkonu a VLF (3.1). Táto transformácia pôvodnej hodnoty LF na normalizovanú má za úlohu minimalizovať vplyvy zmien nízkofrekvenčnej zložky a zdôrazňuje zmeny sympatikovej regulácie.

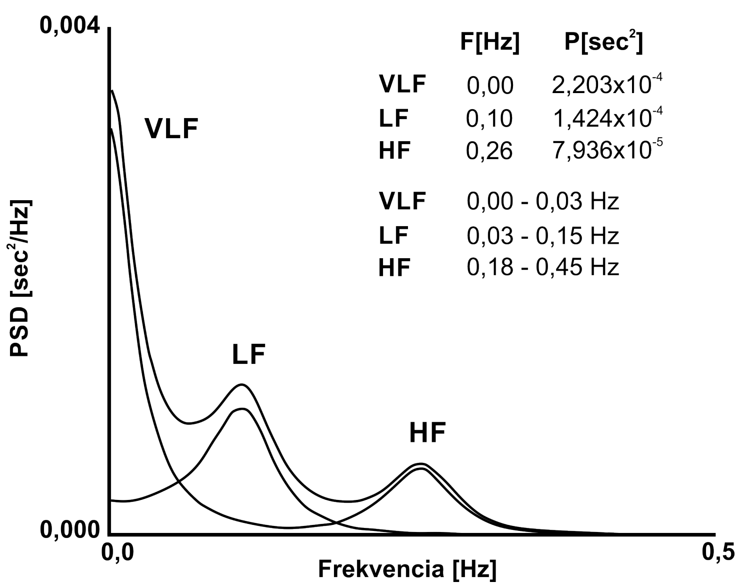
$$nLF = \frac{LF}{TP - VLF} = \frac{LF}{HF + LF} \tag{3.1}$$

- Normalizovaná HF (nHF) – analogicky ide o pomer hodnoty HF a rozdielu TP a VLF (3.2). Normalizovaná hodnota redukuje vplyvy zmien vysokofrekvenčnej zložky a vyzdvihuje zmeny spôsobené parasympatikom. nLF aj nHF sa uvádzajú v percentilových jednotkách [9].

$$nHF = \frac{HF}{TP - VLF} = \frac{HF}{HF + LF} \tag{3.2}$$

Vo viacerých štúdiách bolo dokázané, že frekvenčná analýza srdcovej aktivity na základe frekvenčných pasiem HF, LF a LF/HF podielu – podiel sympatikus/parasympatikus, je vhodná pre charakterizovanie funkcie ANS, srdcovej činnosti, a teda aj psychického stresu [10, 11]. HF je teda hlavným indikátorom parasympatikovej a LF indikátorom sympatikovej aktivity. Podiel LF/HF predstavuje ich rovnováhu a môže byť použitý ako komplexný ukazovateľ úrovne psychického zaťaženia. Podľa publikácie [12] sú stresory alebo stres spojené so zvýšenou aktivitou sympatikového systému riadenia srdcovej činnosti a zníženou aktivitou parasympatika. Tieto situácie spojené s psychickým vypätím sú v spojení s ANS charakterizované zvýšením nízkofrekvenčného pásma LF a zvýšením HF.

Berúc do úvahy vyššie popísaný princíp, tento bol využitý pri hodnotení pilotov v definovanom tréningovom procese, berúc do úvahy prestup z analógového zobrazania letových, motorových a navigačných údajov (tzv. analog cockpit) na zobrazenie digitálne (tzv. Glass cockpit). V čase publikovania týchto článkov totiž legislatíva nebola uspôsobená na to, aby usmerňovala tréning pri prestupe z jedného typu zobrazenia na druhý. V súčasnosti je



Obr. 3.2: Rozloženie výkonu jednotlivých frekvenčných pásiem HRV

oprávnenie pre pilotáž na Glass cockpit v podstate automatické a nieje potrebný transférový tréning z analógového zobrazenia na digitálne. Je ale nutné podotknúť, že vice versa to neplatí.

Článok, ktorý je obsahom Prílohy F bol publikovaný v podstate pre poukázanie na túto problematiku. Zistenia z tejto štúdie však viedli k vytvoreniu ďalšieho výskumného konceptu.

Regula, M., Socha, V., Kutilek, P., Socha, L., Hana, K., Hanakova, L., & Szabo, S. (2014). Study of heart rate as the main stress indicator in aircraft pilots. In Proceedings of the 16th International Conference on Mechatronics - Mechatronika 2014. IEEE. https://doi.org/10.1109/mechatronika.2014.7018334

Príloha F

V prípade realizácie tohto výskumu bolo pozoruhodné, že faktor akým je zmena zobrazenia letových, motorových a navigačných údajov prispieva k diskomfortu počas tréningového procesu a taktiež k nepriaznivej zmene psychofyziologického stavu.

Otázkou ostávalo, či zmena v tréningovom procese, akou je pridanie simulovaných letov do výcviku dokáže prispieť k zlepšeniu psychofyziologického stavu pilotov. Pre tieto účely bola nameraná druhá skupina uchádzčov, ktorý absolvovali doplňujúci teoretický a praktický výcvik.

Socha, V., Schlenker, J., Kalavksy, P., Kutilek, P., Socha, L., Szabo, S., & Smrcka, P. (2015). Effect of the change of flight, navigation and motor data visualization on psychophysiological state of pilots. In 2015 IEEE 13th International Symposium on Applied Machine Intelligence and Informatics (SAMI). IEEE. https://doi.org/10.1109/sami.2015.7061900

Príloha G

Výsledky prezentované v publikácií, ktorá je predmetom Prílohy G poukázali na to, že krátky transférový tréning má zmysel pre vyladenie tréningového procesu. Okrem iného je možné taktiež vidieť princípy data-driven tréningu, s využitím bio-telemetrie, nehovoriac o možnostiach analýzy presnosti pilotovania. Táto problematika sa však k publikovaniu nedostala vzhľadom k zavedeniu transférového tréningu a tým pádom je mimo tému. V súčasnosti sa však realizujú výskumné aktivity pre hodnotenie prestupu analog-glass v porovnaní s glass-analog, kde bude možné výsledky presnosti pilotáže z prezentovaných meraní aplikovať.

3.3 Analýza HRV pomocou nelineárnych metód

Batéria štandardných parametrov, ktoré môžu kvantifikovať nepredvídateľnosť časové rady sú zhrnuté v Tab. 3.1). Nelineárne merania ukazujú nepredvídateľnosť časovej rady, ktorá vyplýva zo zložitosti mechanizmov, ktoré regulujú HRV. Nelineárne parametre súvisia so špecifickými meraniami vo frekvenčnej aj časovej oblasti. Všetky tieto parametre sú bližšie popísané v [13]. Uvedené parametre neboli predmetom publikovania orientovaného na pilotov vo výcviku, pretože tieto nevykazovali štatisticky významné rozdiely pri komparácií jednotlivých realizovaných meraní.

Najmä v oblasti medicínskeho výskumu sa však čoraz viac rozširuje využitie nelineárnej analýzy signálov, ktorá je založená na rekonštrukcii trajektórie vo fázovom priestore. Metódy založené na rekonštrukcii fázového priestoru sú pomerne mladé - ich vývoj začal až po objavení teorému vnorenia matematikom F. Takensem v 80. rokoch 20. storočia. Jednou z metód nelineárnej analýzy je rekurentná analýza, ktorá vychádza z teórie chaosu.

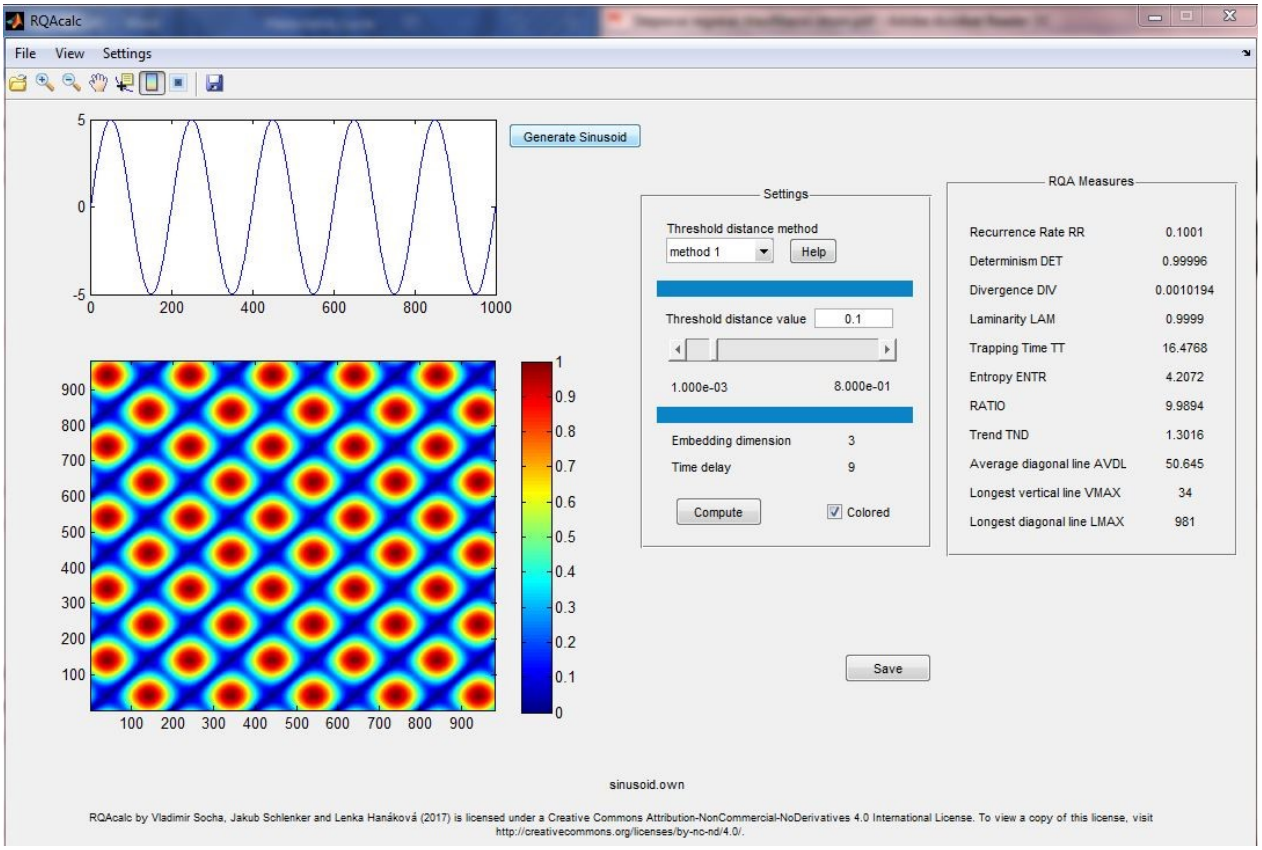
Rekurentná analýza umožňuje vizualizovať rekurenciu (opakovanie) dynamických systémov. K tejto vizualizácii je potrebná jedna časová rada dát, na ktorú nie sú kladené požiadavky ohľadne dĺžky, stacionarity alebo rozdelenia. Jedná sa o multidimenzionánu metódu, vďaka ktorej je možné sledovať dynamiku celého systému.

Tento druh analýzy sa začína experimentálne využívať aj pri spracovaní biologických signálov, kde je väčšina štúdií orientovaná práve na hodnotenie variability srdcového rytmu. Dôvodom je, že autonómny nervový systém sa javý ako dobrý príklad nelineárneho deterministického systému [14, 15], ktorý ovplyvňuje srdcovú frekvenciu a krvný tlak tak, Tabuľka 3.1: Štandardné parametre nelineárnych metód hodnotenia HRV

Parameter	Jednotka	Definícia
S	ms	Plocha elipsy, ktorá predstavuje celkovú HRV.
SD1	ms	Poincaré plot smerodajná odchýlka kolmá na riadok identity.
SD2	ms	Poincaré plot smerodajná odchýlka pozdĺž linie identity.
SD1/SD2	%	Pomĕr SD1 / SD2.
ApEn		Približná entropia, ktorá meria pravideľnosť a zložitosť časovej rady.
SampEn		Vzorka entropie, ktorá meria pravideľnosť a zložitostť časových radov.
DFA $\alpha1$		Odtrendovaná fluktuačná analýza, ktorá popisuje krátkodobé výkyvy (fluktuácie).
DFA $\alpha2$		Odtrendovaná fluktuačná analýza, ktorá popisuje dlhodobé výkyvy (fluktuácie).
D2		Korelačná dimenzia, ktorá odhaduje minimálny počet premenných potrebných pre konštrukciu modelu dynamiky systému.

aby zabezpečil správne fungovanie všetkých orgánov na základe aktuálneho fyziologického stavu.

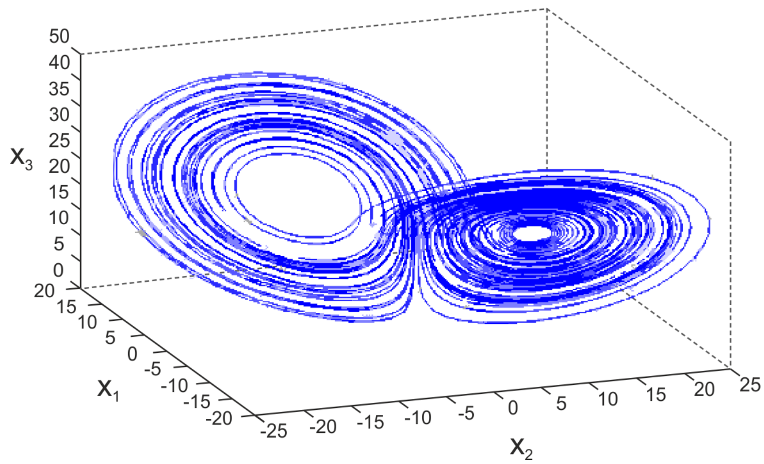
Keďže sa rekurentná kvantifikačná analýza javila ako sľubná metóda pre hodnotenie psychofyziologickej kondície pilotov, bolo v prvom kroku vytvorené softvérové riešenie pre spracovanie signálu touto metódou (Obr. 3.3). Dôvodom taktiež bolo, že okrem dostatočne popísanej teórie, neexistoval (neexistuje) voľne dostupný softvérový nástroj, prípadne knižnica, pre aplikačné účely. Na základe teoretického popisu uvedeného nižšie, bolo teda vytvorené grafické užívateľské prostredie v prostredí Matlab 2014. Prvým krokom je vytvorenie viacedimenzionálního systému, ktorý sa vzťahuje k pôvodnému fázovému systému. Ide teda o rekonštrukciu fázového priestoru a zostrojenie vzdialenostnej matice



Obr. 3.3: Ukážka grafického používateľského prostredia pre hodnotenie dát pomocou rekurentnej analýzy

(distance matrix, DM). Následne sú identifikované body, ktoré nie sú vzdialené v čase, ale sú priestorovímy susedmi na určitom rádiuse, čím je vytvorený rekurentný graf (tzv. Reccurence plot, RP). Posledným krokom je kvantitatívne zhodnotenie RP - rekurentná kvantifikačná analýza (Recurrent quantification analysis, RQA) [16].

Socha, V., Schlenker, J. & Hanáková, L. (2017) RQAcalc. [Autorizovaný Software], Dostupné z: http://uld.fd.cvut.cz/cs/veda-a-vyzkum/vedecke-vystupy/



Obr. 3.4: Fázový priestor Lorenzovho systému

3.3.1 Rekonštrukcia fázového priestoru

Trajektória vo fázovom priestore predstavuje časový vývoj a dynamiku systému. Každý systém je možné popísať pomocou jeho stanovených premenných. Tieto premenné tvoria v čase trajektóriu v n-dimenzionálnom priestore, respektíve vo fázovom priestore [17].

V mnohých prípadoch nieje možné zaznamenať alebo zmerať všetky stavové premenné systému. Fázový priestor však môže byť zrekonštuovaný aj z jedinej stavovej veličiny. Najpoužívanejšou metódou je metóda nizozemského matematika Florisa Takensa, jedná sa o metódu vnorenia dimenzie a časového oneskorenia, viď vzťah (3.3) [17].

$$x_i = (u_i, u_{i+\tau}, ..., u_{i+(m-1)\tau})^T \tag{3.3}$$

kde u je pozorovaná stavová veličina, τ je časové oneskorenie a m je vkladaná dimenzia.

Zrekonštruovaný fázový priestor nie je presne zhodný s originálnym fázovým priestorom, ale jeho topologické vlastnosti sú zachované v prípade, že je vkladaná dimenzia dostatočne veľká [17]. V praxi by vkladaná dimenzia mala byť minimálne dva-krát väčšia ako dimenzia atraktora, presnejšie potom $m > 2d + 1$ [18, 17]. Existujú rôzne názory na nastavenia vstupných parametrov (dimenzia, časové oneskorenie). Optimálne nastavenie týchto parametrov je dôležité pre rekonštrukciu fázového priestoru, ktorý bude plne popisovať dynamiku systému.

Časové oneskorenie nám udáva vzdialenosť medzi susednými elementmi, pre malú hodnotu časového oneskorenia je rozdiel medzi jednotlivými stavmi rekonštruovaného fázového priestoru nepatrný. Naopak, pokiaľ bude hodnota časového oneskorenia príliš veľká, môžu byť stavy vnímané ako nezávislé a rekonštruovaná trajektória sa bude javiť ako náhodný proces.

Jednou zo starších metód voľby časového oneskorenia bolo použitie autokorelačnej funkcie. Bohužiaľ, táto metóda nezohľadňovala možnosť nelineárnych procesov [18]. Posledné štúdie ukazujú, že vhodnou metódou pre voľbu optimálneho časového oneskorenia je miera vzájomnej informácie [18, 19]. Miera vzájomnej informácie predstavuje informáciu o vzájomnej závislosti dvoch závislých veličín, čím sú veličiny závislejšie, tým je ich vzájomná informácia väčšia. Ako najvhodnejšia dĺžka časového oneskorenia je následne uvádzané prvé minimum vzájomnej informácie. Prvé minimum, pre pozorovanie $x(t_i + \tau)$ v čase $t_i + \tau$, nám v priemere prináša najvyšší informačný príspevok k informácii z pozorovania $x(t_i)$ v čase t_i. Vzájomná informácia dvoch premenných A a B môže byť definovaná pomocou entropie ako:

$$I(A, B) = H(A) + H(B) - H(A, B) \tag{3.4}$$

kde $H(A)$ a $H(B)$ sú entropie a $H(A, B)$ je združená entropia A a B.

Po voľbe optimálneho časového oneskorenia je potrebné zvoliť optimálnu dimenziu vnorenia. Jednou z najbežnejšie používaných metód pre voľbu oprimálnej dimenzie vnorenia je metóda najbližších falošných susedov. Podstatou metódy je fakt, že pri projekcii trajektórie systému z originálneho fázového priestoru do priestoru s nižšou dimenziou dochádza k prekríženiu trajektórie so sebou samou. Vďaka tomuto prekríženiu vznikajú takzvaní falošní susedia, ktorých počet sa pri zvyšovaní dimezie znižuje. Nevýhodou metódy môže byť fakt, že musí byť určená prahová hodnota, pre ktorú budú už susedia považovaní za falošných. Zaujímavú modifikáciu metódy falošných najbližších susedov, ktorá túto nevýhodu odstraňuje, popísal vo svojej práci [20], ktorý použil podiel Eukleidovských vzdialeností dvoch susedných stavov v dimenzii m a dimenzii $m + 1$, viď vzťah (3.5).

$$a(i,m) = \frac{||y_i(m+1) - y_{n(i,m)}(m+1)||}{||y_i(m) - y_{n(i,m)}(m)||} \tag{3.5}$$

kde || je Eukleidovská vzdialenosť, $y_i(m)$ je i-ty rekonštruovaný vektor s dimenziou m a $y_{n(i,m)}$ je najbližší sused $y_i(m)$.

Ďalej potom zavádza veličinu nazvanú ako priemer všetkých hodnôt $E(m)$ [20]:

$$E(m) = \frac{1}{N - m\tau} \sum_{i=1}^{N-m\tau} a(i,m) \tag{3.6}$$

Priemer $E(m)$ je závislý len od dimenzie m a oneskorení τ. Aby bolo možné zistiť odchýlky m od $m+1$, definujú sa ešte pomery priemerov z dimenzie m a dimenzie $m+1$, viď vzťah (3.7) [20].

$$E1(m) = \frac{E(m+1)}{E(m)} \tag{3.7}$$

Hodnota premennej $E1(m)$ sa prestane meniť keď je dimenzia m väčšia ako hodnota dimezie atraktora m_0. Minimálna hodnota vkladanej dimenzie je následne rovná $m_0 + 1$ [20].

3.3.2 Rekurentný graf

Vizualizácia trajektórie vo fázovom priestore, ktorá má viac ako tri dimenzie je náročná, preto Eckmann [21] predstavili tzv. rekurentné grafy. Tieto grafy sú základným nástrojom rekurentnej analýzy a umožňujú vizualizáciu viacrozmerného fázového priestoru pomocou dvojrozmerného grafu. Rekurentné stavy sú v grafe zaznamenávané v maticovom formáte "jedničkou", stavy ktoré naopak rekurentné nie sú "nulou". Rekurentný stav je možné určiť pomocou prahovej vzdialenosti ϵ, (vzťah 3.9). Podľa [17] je možné rekurentný graf matematicky zapísať ako:

$$R_{i,j} = \Theta(\epsilon - ||x_i - x_j||), \text{ pre } i,j = 1,2,...,N, \tag{3.8}$$

kde je Θ Heavisidova funkcia, ktorá nadobúda hodnoty 1 a 0 podľa vzťahu 3.9:

$$R_{i,j} = 0 \text{ pre } ||x_i - x_j|| > \epsilon; \text{ a } R_{i,j} = 1 \text{ pre } ||x_i - x_j|| \leq \epsilon, \tag{3.9}$$

kde $R_{i,j}$ označuje bod v matici R v čase i a inom čase j, x_i a x_j sú jednotlive stavy systému, N je celkový počet stavov, $||.||$ je vzdialenosť dvoch stavov vo fázovom priestore a ϵ je prahová vzdialenosť [17].

Grafické znázornenie matice R je rekurentný graf, body v grafe predstavujú rekurentné stavy, ktoré majú v matici hodnotu 1. Je možné sa stretnúť aj s nie binárnou verziou (kolorovanou) verziou rekurentného grafu, kedy sú v matici uvedené vzdialenosti medzi jednotlivými stavmi (bodmi) vo fázovom priestore a nie je použitá Heavisidova funkcia. Vďaka tomuto postupu je možné vyhnúť sa zadávaniu prahovej vzdialenosti. V legende grafu je uvedená tzv. mapa grafu, ktorá definuje aká farba odpovedá akej vzdialenosti.

Určitou nevýhodou rekurentných grafov je ich matematická náročnosť kvôli párovému testu všetkých stavov. Pre N stavy sa počíta N^2 testov. Rekurentný graf je vo svojej podstate vždy symetrický podľa hlavnej diagonály a objavujú sa v ňom základné štruktúry. Medzi tieto štruktúry patria samostatné body, diagonálne čiary, zvislé a vodorovné čiary. Každá z týchto štruktúr má svoj význam [17].

Osamotené body značia jedinečné stavy vo fázovom priestore, v ktorých systém nezotrváva dlho. Diagonálne čiary označujú, že trajektória vo fázovom priestore prebieha rovnakou oblasťou v rôznych časoch. Diagonálne čiary sú charakteristické pre determinizmus. Zvislé a vodorovné čiary označujú, že systém pretrváva v jednom bode, prípadne sa mení len veľmi pomaly [18]. Topológia rekurentného grafu je znázornená na Obr. 3.3.

Najdôležitejšou fázou pri tvorbe rekurentného grafu je voľba vhodnej prahovej vzdialenosti. V súčasnosti je voľba optimálnej prahovej vzdialenosti predmetom diskusií [22, 23, 24], pretože už malá zmena prahovej vzdialenosti môže dramaticky ovplyvniť výsledky [23]. Medzi často používané metódy nastavenia prahovej vzialenosti patrí nastavenie prahovej vzdialenosti percentuálne z maximálnej vzdialenosti vo fázovom priestore. Ďalej je to nastavenie takej hodnoty, ktorá by nemala prekročiť 10% priemernej alebo maximálnej vzdialenosti vo fázovom priestore [22]. Pomerne často používanou metódou je nastavenie tzv. fixného percenta rekurentných bodov. Znamená to, že sa nastaví taká hodnota prahovej vzdialenosti, aby zaručovala presné percento rekurentných bodov [22]. Často býva táto hodnota 1% [22, 23], je možné sa stretnúť aj s iným nastavením, napr. 5% [14].

Medzi ďalšie doporučované nastavenia patrí hodnota prahovej vzdialenosti $\epsilon = 0.1\sigma$ (σ je štandardná odchýlka vstupného signálu). Toto nastavenie určil prof. Marwan experimentálne [24].

3.3.3 Kvantitatívna analýza rekurentných grafov

Aby rekurentné grafy neboli len vizuálnym nástrojom, ale dokázali prispieť aj svojím evaluačným aparátom, je potrebné ich lepšie popísať a kvatifikovať. Pre tento účel slúži tzv. kvantitatívna analýza rekurentných grafov (Recurrence Quatification Analysis - RQA), ktorú predstavili Zbilut a Webber [25, 26] a rozšíril ju prof. Marwan [27]. Jedná sa o sadu parametrov, ktoré štatisticky popisujú rekurentný graf.

Percento rekurentných bodov RR je percento rekurentných bodov, ktoré tvoria graf. Tento parameter zodpovedá pravdepodobnosti, že sa konkrétny stav bude opakovať. Vyššia rekurencia znamená nižšiu variabilitu systému a naopak [18, 14]:

$$RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{i,j}. \tag{3.10}$$

Determinizmus DET je parameter, ktorý predstavuje percento rekurentných bodov, ktoré tvoria diagonálne čiary. Diagonálne čiary označujú, že sa systém vracia k predchádzajúcim stavom v inom čase. Parameter determinizmus súvisí s predvídateľnosťou dynamického systému:

$$DET = \frac{\sum_{l=l_{min}}^{N} l P(l)}{\sum_{i,j}^{N} R_{i,j}} \tag{3.11}$$

kde $P(l)$ je histogram dĺžok l diagonálnych čiar.

Laminarita LAM označuje percento bodov, ktoré tvoria zvislé čiary. Tento parameter slúži na detekciu laminárnych stavov, teda stavov kedy sa systém nemení alebo sa mení len veľmi málo:

$$LAM = \frac{\sum_{v=v_{min}}^{N} v\ P(v)}{\sum_{v=1}^{N} v\ P(v)}, \tag{3.12}$$

kde $P(v)$ je histogram dĺžok v zvislých čiar.

Rekurentný čas (Trapping Time) TT je parameter, ktorým je označená priemerná dĺžka zvislých čiar. Parameter teda označuje, ako dlho zostáva sysém v konkrétnom stave a obsahuje informáciu o frekvencii a dĺžke laminárnych stavov:

$$TT = \frac{\sum_{v=v_{min}}^{N} v\ P(v)}{\sum_{v=v_{min}}^{N} P(v)}. \tag{3.13}$$

Nízka hodnota LAM a TT označuje značnú komplexitu systému. Systém sa totiž vracia do predchádzajúcich stavov len na veľmi krátku dobu [14].

Medzi ďalšie parametre RQA patria maximálna dĺžka diagonálnej čiary $Lmax$, divergencia DIV (prevrátená hodnota $Lmax$), priemerná dĺžka diagonálnej čiary $AVDL$, pomer $RATIO$ (pomer medzi DET a RR), Shannonova entropia $ENTR$ a maximálna dĺžka zvislej čiary $Vmax$.

Pomocou popísanej analýzy a pomocou vytvoreného softvérového nástroja boli v počiatku vytvorené štúdie orientujúce sa na klinické hodnotenie variability srdcového rytmu u pacientov s vazovagálnymi synkopami a u pacientov s atriálnou fibriláciou indikovaných na kardioverziou.

Schlenker, J., Socha, V., Riedlbauchová, L., Nedělka, T., Schlenker, A., Potočková, V. et al. (2016). Recurrence plot of heart rate variability signal in patients with vasovagal syncopes. Biomedical Signal Processing and Control, 25, 1–11.

Príloha H

Socha, V., Schlenker, J., Hana, K., Smrcka, P., Hanakova, L., Prucha, J. et al (2016). Prediction of atrial fibrillation and its successful termination based on recurrence quantification analysis of ECG. In 2016 39th International Conference on Telecommunications and Signal Processing (TSP). IEEE.

Príloha I

Aj keď uvedené publikácie priamo nesúvia s evaluáciou pilotov a ich psychofyziologickej kondície v priebehu tréningu, poukazujú na fakt, že metóda RQA je schopná popísať behavioralitu regulácie srdcovej činnosti. V týchto dvoch publikáciách bolo uvedené potvrdené na základe testu aktívneho stánia a ortostatického testu (bližšie popísané a referované v Prílohe H a I).

Prvotná aplikácia RQA pre určenie a popis psychofyziologickej kondície pilotov bola realizovaná v publikácií v Prílohe J. Vzhľadom k možnéu rozsahu tejto publikácie bolo hodnotenie orientované na prestup z leteckého simulátora na prvý realny let, ktorý bol sledovanými subjektmi absolvovaný. Ako v predchadzajúcich prípadtoch tak aj v prípade využitia tejto partikulárnej metódy bola potvrdená jej vhodnosť a popísané možnosti ďalších applikácií.

Socha, V., Socha, L., Schlenker, J., Hana, K., Hanakova, L., Lalis, A. et al. (2016). Evaluation of pilots' psychophysiological condition using recurrence quantification analysis of heart rate variability. In 2016 20th International Scientific Conference Transport Means. Kaunas University of Technology.

Príloha J

3.4 Analýza HRV v časovej oblasti

Možno sa bude zdať umiestnenie tejto sekcie na koniec, oproti predchádzajúcim, nelogické, avšak využitie analýzy HRV v časovej oblsti bolo aplikované až pri publikovaní posledného z ucelenej batérie publikácií. Parametre hodnotenia HRV v časovej oblasti boli použité pre klasifikáciu úrovní záťaže podľa úrovne trénovanosti, respektíve výkonnosti v priebehu tréningového procesu.

Parametre v časovej oblasti sú najjednoduchšie a vyplývajú z nameraných hodnôt intervalov RR alebo okamžitej srdcovej frekvencie. Parametre získané pomocou štatistických metód vyskytujúcich sa v časovej oblasti sú závislé na presnosti označenia jednotlivých RR intervalov. Smerodajná odchýlka a podobné štatistické vzorce sú totižto ovplyvnené hodnotami, ktoré sa líšia od priemeru analyzovanej sekvencie. Ukazovatele časovej domény

HRV kvantifikujú množstvo variability pri meraní behom daných období (pohybujúcich sa v rozmedzí < 1 minúta až > 24 hodín) medzi po sebe idúcimi údermi srdca, tzv. interbeat interval (IBI). Premenné SDNN, SDANN a SDNN index popisujú globálnu autonómnu reguláciu srdca, ale premenné RMSSD a pNN50 sa vzťahuje k beat to beat variáciám odrážajúcich ústup parasympatiku. Tieto hodnoty môžu byť vyjadrené v pôvodných jednotkách alebo ako prirodzený logaritmus pôvodných jednotiek, aby sa podľa potreby dosiahlo normálne rozdelenie. [28, 29, 13]

SDNN (Standard Deviation of All NN Intervals) popisuje celkovú smerodajnú odchýlku dĺžok všetkých NN intervalov v segmente. Odráža teda všetky cyklické zložky zodpovedné za variabilitu v dobe merania. Vo viacerých štúdiách sa SDNN počíta v priebehu 24 hodinového záznamu pomocou monitoru Holter a tým zahrňuje krátkodobé a dlhodobé zmeny srdcového rytmu. Popri kardiorespiračnej regulácie sa dajú merať reakcie srdca na meniacu sa pracovnú záťaž, anticipačná centrálna nervová aktivita a cirkadiánne procesy vrátane cyklov spánku/bdenia. 24 hodinové nahrávky odhaľujú vplyv sympatikovej sústavy na HRV. Pre krátkodobé merania je daný štandardný časový úsek 5 min, vedci ale taktiež navrhli ultra krátke obdobie pohybujúce sa od 60 do 240 s. SDNN je ovplyvnená činnosťou sympatiku a parasympatiku, respektíve výkonmi pásiem ULF, VLF, LF a celkovým výkonom. Pokiaľ bude energia týchto pásiem vyššia ako v HF pásme, tak dochádza ku zvýšeniu SDNN. Tento vzťah avšak závisí na podmienkach pri meraní. SDNN patrí k najjednoduchším a najčastejšie používaným štatistickým parametrom a jeho meranie je presnejšie, pokiaľ sa vypočíta z 24 hodinového záznamu, ako z kratších období sledovania. Napríklad sa využíva v lekárstve pre klasifikáciu rizík srdcových ochorení – predpovedá morbiditu a mortalitu. Na základe 24 hodín sledovania sú pacienti s hodnotami SDNN nižšími ako 50 ms klasifikovaní ako nezdraví, 50-100 ms ako pacienti s ohrozeným zdravým a pokiaľ majú viac ako 100 ms tak sú zdraví. [30, 11, 31, 13]

SDRR (Standard Deviation of All RR Intervals). Jedná sa o strednú odchýlku medzipulzného intervalu (IBI) pre všetky sínusové údery vrátane abnormálnych alebo falošných úderov, ktoré môžu odrážať srdcovú dysfunkciu alebo šum vyzerajúci ako HRV. Rovnako ako SDNN tak aj SDRR sa časom spresňuje. Pri meraní behom 24 hodín sa lepšie popisujú pomalšie procesy a reakcie kardiovaskulárneho systému na rôznorodé enviromentálne podnety a na pracovnú záťaž. [13]

SDANN (Standard Deviation of the Average NN (RR) Interval). Jedná sa o smerodajnú odchýlku priemerov NN (RR) intervalov počítanú behom všetkých stanovených úsekov z celého 24 hodinového záznamu. Stanovený segment môže byť dlhý od niekoľkých sekúnd do obvyklých 5 minút. Táto doba je závislá na odhade zmien srdcovej frekvencie v sekvenciách dlhších ako 5 minút. Tento parameter sa javí ako SDNN, ale nedajú sa zameniť kvôli dĺžke záznamu. [11, 32, 13]

SDNNi – SDNN index je priemer smerodajnej odchýlky všetkých po sebe idúcich NN (RR) intervalov s minimálnym 24 hodinovým záznamom HRV. Popisuje zmenu variability behom krátkeho 5 minútového úseku. Vypočíta sa tak, že najskôr dôjde k rozdeleniu 24 hodinového záznamu na 255 päťminútových segmentov a následne sa vypočíta smerodajná odchýlka všetkých intervalov NN (RR) obsiahnutých v každom jednotlivom segmente. SDNNi je teda priemer týchto 288 hodnôt. SDNNi primárne odráža autonomný vplyv na HRV. [30, 11, 32, 13]

NNx (Number of Adjacent NN (RR) Intervals). Ide o počet po sebe idúcich NN (RR) intervalov, ktoré sa líšia o viac ako x ms. Najčastejšia hodnota je 50 ms (teda potom NN50), ktorá vyžaduje 2 minútový záznam. Sú možné tri varianty výpočtu, teda počítanie všetkých týchto párov intervalov NN (RR) alebo počítanie iba párov, v ktorých je prvý interval dlhší, alebo iba dvojíc, v ktorých je druhý interval dlhší. [13]

pNNx (NNx Count Value Divided by the Total Numbers of All NN (RR) Intervals). Jedná sa o relatívný počet susediacich NN (RR) intervalov navzájom sa odlišujúcich o x ms (najčastejšie 50 ms) vzťahujúci sa k celkovému počtu NN (RR) intervalov v postupnosti (môže byť taktiež vzťahujúce sa k celkovému počtu RR intervalov v segmente). Presnejšie je to percentuálna hodnota intervalu NNx (NN50). pNNx úzko súvisí s aktivitou parasympatika a je často využívaný ako spoľahlivejší index ako SDNN zmeraný v krátkom úseku. Avšak poskytuje horšie hodnotenie RSA ako parameter RMSSD. [30, 32, 13]

HR Max – HR min. Priemerný rozdiel medzi najvyššou a najnižšou tepovou frekvenciou behom každého respiračného cyklu je obzvlášť citlivý na účinky respiračnej frekvencie a nie je závislý na vagových nervoch. Pre výpočet HR Max – HR Min je požadovaný minimálne 2 minútový záznam merania [13].

RMSSD (Root Mean Square of the Successive Differences). Kvadratický priemer dĺžok po sebe idúcich NN (RR) intervalov sa získa vypočítaním všetkých časových rozdielov medzi srdcovými pulzmi, tieto hodnoty sa následne spriemerujú a tým získame druhú odmocninu rozdielu štvorcov priemerných hodnôt dĺžok NN (RR) intervalov. Klasická doba záznamu je 5 minút, ale taktiež bola navrhnutá aj kratšia doba záznamu (10s, 30s, 60s). Tento parameter je ideálny pre zisťovanie zapojenia vagálnej sústavy do zmien v HRV a je totožný s parametrom SD1, ktorý avšak odráža krátkodobú variabilitu. [30, 11, 13]

NN50, pNN50 a RMSSD sa vypočítajú za použitia rozdielov medzi po sebe idúcimi intervalmi NN (RR) a vďaka tomu sú z veľkej časti ovplyvnené trendami v rozšírenej časovej rade. Parametre získané geometrickými metódami z analýzy v časovej oblasti sú založené na popise určitých geometrických tvarov (napr. Histogramov) a tým pádom sú oveľa menej ovplyvňované artefaktmi v analyzovanom signále EKG. Zároveň ich nevýhodou je potrebné získanie dostatočného počtu NN (RR) intervalov pre rozbor daného geometrického tvaru. [13]

HRVTi (HRV Triangular index). HRV trojuholníkový index je určený z integrálu hustoty histogramu RR intervalov behom 24 hodinového záznamu delený výškou daného histogramu. Jedná sa o najjednoduchšiu metódu analýzy variability srdcového rytmu, ktorá popisuje celkové HRV ako relatívny počet najviac zastúpených intervalov NN. Presnejšie povedané, ide o integrálne rozloženie hustoty, teda podiel celkového počtu intervalov NN (RR) a maximálneho počtu intervalov NN (RR) rovnakého trvania. Spoločne s RMSSD môžu spoločne odlišovať normálne srdcové rytmy a arytmie. Pri HRVTi < 20.42 a RMSSD < 0.068 je srdcový rytmus normálny a pokiaľ je HRVTi > 20.42, jedná sa o arytmiu. [28, 11, 13]

TINN (The Triangular Interpolation of NN (RR) interval Histogram). Trojuholníková interpolácia histogramu intervalov NN (RR) sa vypočíta pomocou približnosti distribúcie NN (RR) intervalov do trojuholníka a meraním šírky základne, kde sa vyjadruje HRV. K nájdeniu takého trojuholníka sa používa minimálny rozdiel štvorcov. Ide teda o základnú šírku histogramu zobrazujúcu intervaly NN (RR). [28, 11, 13]

Nie všetky vyššie poísané parametre sú vhodné pre analýzu HRV pri relatívne krátkych meraniach (1h), ako je popísané vyššie. Základné a najviac využívané parametre HRV z časovej oblasti boli využité pri návrhu klasifikátora prezentovaného v článku umiestnenom v Prílohe K.

Hanakova, L., Socha, V., Socha, L., Szabo, S., Kozuba, J., Lalis, A., et al (2017). Determining importance of physiological parameters and methods of their evaluation for classification of pilots psychophysiological condition. In 2017 International Conference on Military Technologies (ICMT). IEEE.

Príloha K

4 Záver

Cieľom predstaveného výskumu je zvýšenie efektivity výcviku leteckého personálu s primárnym zameraním na pilotov formou Evidence-Based Tréningu. Takýto typ tréningu by mal byť postavený na dôkazoch získaných počas výcviku daného subjektu. Aktuálne je tento typ tréningu všeobecne podporovaný, avšak dostupné metódy sú založené najmä na subjektívnom hodnotení priebehu výcviku inštruktorom. Hoci je expertná znalosť inštruktora nevyhnutná pre daný typ výcviku, efektivitu EBT je možné ďalej podporiť nameranými dátami získanými počas výcviku, čím môže byť hodnotenie čiastočne objektivizované. Takéto dáta teda môžu podporiť inštruktorove rozhodnutie o ďalšom priebehu výcviku, príp. poukázať na situáciu, ktorú inštruktor prehliadol. Medzi získané dáta možno radiť letové parametre získané v priebehu simulátorového výcviku, slúžiace pre hodnotenie presnosti pilotáže a ďalej dáta objektivizujúce psychofyziologický stav meraného subjektu. Z výskumu vyplýva, že ako vhodné dáta pre tieto účely sú údaje získané sledovaním srdcovej aktivity subjektu, HRV.

V priebehu realizácie predstaveného výskumu došlo ku kontinuálnemu zberu uvedených dát v priebehu výcviku pilotov podľa stanovenej metodiky. Výber výskumného vzorky prebehol s ohľadom na porovnateľnosť veku, zdravotného stavu, skúseností s lietaním a ďalej bol podporený psychologickým testovaním subjektov. Týmto spôsobom bola zaistená čo možno najväčšiu uniformnosť súboru skúmaných subjektov. Vybrané subjekty absolvovali presne predpísaný výcvik, pri ktorom prebiehal uniformné lety v každej letovej hodine. Týmto spôsobom bolo možné získať informáciu o progrese v priebehu výcviku podloženou nameranými dátami. Snímaná boli fyziologické údaje primárne pokrývajúce informácie o srdcovej a dychovej aktivite subjektu, jeho fyzickej aktivite hornej končatiny, a ďalej dáta z leteckého simulátora slúžiace pre hodnotenie presnosti pilotáže počas celého výkonu presne definovaných manévrov.

S ohľadom na merané dáta došlo k hodnoteniu na dvoch úrovniach - hodnotenie presnosti pilotáže a hodnotenie fyziologických dát. V prípade fyziologických dát prebiehalo hodnotenie pomocou štandardných a experimentálnych metód, ktoré zahŕňali hodnotenie v časovej a frekvenčnej oblasti a ďalej metódu založenú na zisťovaní rekurencie chaotických signálov (rekurentná kvantifikačný analýza), pre ktorú bol v priebehu realizácie výskumu navrhnutý samostatný licencovaný softvér. Na základe analýzy meraných biosignálov boli následne vybrané najviac relevantné psychofyziologické parametre a importancia jednotlivých parametrov pomocou metód multilineárnej regresie a klasifikácie.

Prezentovaný výskum ukázal, že je možné sledovať a objektivizovať psychickú záťaž, resp. jej zmenu, a to najmä na základe srdcovej aktivity, resp. tepovej frekvencie, ktorej sledovanie je výhodné aj s ohľadom na jednoduchú a pre subjekt pohodlnú možnosť jej snímania. Ďalej potom, že v priebehu výcviku dochádza k zmenám v presnosti pilotáže, ktorá môže byť sledovaná samotným inštruktorom a ďalej s využitím letových dát získaných v priebehu simulátorového výcviku. Takéto dáta teda môžu poslúžiť inštruktorovi počas EBT pre nastavenie ďalšieho priebehu ďalšieho výcviku, napr. Neopakovať úkony, ktoré subjekt zvláda a sústrediť sa na úkony pre subjekt problematické. Ďalším benefitom je, že týmto spôsobom je možné sledovať subjekt od začiatku jeho výcviku, tj. inštruktor má kvalitné a detailné podklady pre EBT takmer okamžite.

Všetky analýzy vykonané pre účely prezentovaného výskumu prebehli post-hoc, teda až po nameraní kompletných dát z priebehu letu. Práve v tomto smere sa aktuálne nachádza významná príležitosť pre posunutie výskumu na ďalšiu úroveň formou online monitorovania a hodnotenia stavu pilota a priebehu jeho letu. V takom prípade by mal inštruktor dostupné informácie o zmene psychologického stavu a o priebehu letu okamžite, v priebehu vykonávaného letu, čo by mohlo poslúžiť pre okamžitú reakciu inštruktora. Možnosť online sledovania je podporená tiež vykonaným výskumom, a to najmä s ohľadom na fakt, že ako najvhodnejšie metódy monitorovania psychologického stavu sa ukázali metódy založené na ľahko merateľných dátach hodnotených pomocou jednoduchých matematických metód s nízkou výpočtovou náročnosťou, teda možnosťou neustálej aktualizácie informácií o stave pilota.

Predstavený výskum prináša ďalšie možnosti pre vývoj výcviku pilotov a rozvoj Evidence-Based Tréningu. Môže teda slúžiť ako podklad pre zefektívnenie výcviku, čo prináša benefity v podobe zníženia nákladov na samotný výcvik a prispôsobenie výcviku pre každý subjekt individuálne na základe objektívneho (i subjektívneho) hodnotenia jeho schopností.

Dáta získané z EBT by v globále mohli vytvoriť platformu podobnú safety, prípade poznatkami vychadzajúcimi z EBT prispievať k popisu behaviorality celkovej leteckej bezpečnoti. Samozrejme, uvedené by bolo viazané na ochotu poskytovania takýchto dát, ktoré by museli byť uniformné a centralizované pre účely ďalšieho hodnotenia. Podobná problématika je, okrem iného, rozoberaná v publikácií prezentovanj v Prílohe L.

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Prílohy

A Článok 1

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FlexiGuard: Modular Biotelemetry System for Military Applications

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***Abstract*—The article presents a FlexiGuard modular biotelemetric system for real-time monitoring of special military units. The main focus of the system is on automated monitoring of special forces via parallel monitoring of each member of the special team individually, witch includes collecting sets of physiologic (or environmental) parameters. The systems consists of a set of sensors (for monitoring temperature, heart rate, acceleration, humidity etc.) and modular sensing unit, which records the measured data and sends them to the visualization unit. The measured values (i.e. heart rate, surface temperature of the body and so on) are then visualized in the graphic user interface of the visualization unit. Testing of the functionality of the system took place in both laboratory and real environment. In the case of carrying out the measurements on 34 soldiers at series of 4 probands at the same time, the sensor networks worked without any loss of signal. During the data transfer to the visualization unit, a loss of approx 0.2% of packets occurred. The system thus can offer information to the commander, which may prove essential for the optimalization of operational strategies, taking the state of wellbeing of the team members into account.**

Keywords*—biomedical telemetry; military equipment; assistive devices; wireless sensor networks

I. Introduction

The selection and training of the members of military forces and the integrated rescue system is vital for the future employment in emergency situations. Similarly, own safety of the members of special forces must not be overlooked in particular actions. Currently, there are several support systems designed (see also [1]) for enhancing safety and protection based on monitoring of the physical variables of the environment and physical state of the crew members. For instance, there is FireNet system [2] for sending sensor data during rescue operations of firefighters, also for the localization of firefighters operating inside buildings [3], [4] or MaD-WiSe [5] platform for wireless communication with the sensor network. None of the above-mentioned solutions, however, offers a tool for automated monitoring of the members of the crew, with enhanced resistance, able to work in extreme conditions, and an ability to provide information on the physiological state, location and parameters of the environment surrounding the monitored member of the team, or does not provide for parallel monitoring of all team members in the above-mentioned conditions. The stated circumstances point out to the necessity for creation of a complex modular telemetric system for the evaluation of the psychophysiologic state of the squad members. Such approach and technical solution might be essential in monitoring health and psychical condition by a real intervention, or by the recruitment and training of cadets.

The main object of this article is to present the new modular telemetric system offering relevant information on the physiological state of a member of special forces. The main orientation of the system (as opposed to other systems) is primarily based on monitoring the whole special team, which might provide for a detail information on psychophysiological state of each crew member while carrying out particular tasks. The system was designed as modular telemetric platform enabling flexible and individual configuration with regard to a particular person.

II. Materials and Methods

The proposed system is aimed on the creation of sensor network providing for a wireless telecommunication of physiological variables measured on the body of the user, or in their close proximity (e.g in their clothes). The wireless solution has been chosen taking into consideration the possibilities of the system's integration into the gear and the resistance against physical damage connected with the wiring used to carry the signal. FlexiGuard telemetric system is based on a modular platform, which physically consists of three basic units (layers). These represent a set of sensors accounting for wireless body area network (WBAN), modular sensing unit (MSU) and concentration-visualisation unit (Fig.1).

A. First Layer Design (WBAN System)

The sensing unit consists of three basic modules: sensor module, main module and power source module. The sensor module consist of a sensor of its own (Fig.2-A) and supporting circuits such as low-pass filter, anti-aliasing filter etc. (Fig.2-B). The main module contains

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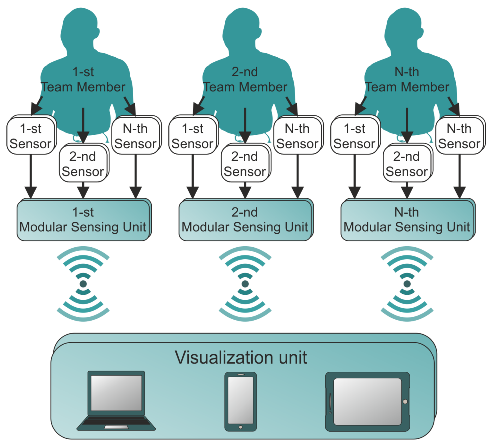

Figure 1. Concept of the designed telemetric system.

microcontroller unit (MCU) (Fig.2-C), which processes the signal from the sensor and provides a transition of signal from analog to digital if needed. MCU also provides for the data creation and communication with the wireless interface circuit (Fig.2-D). The charging module connects the battery (Fig.2-E). In case of the use of LiPol battery, a circuit for the control of the recharging process, or contactless recharging module can be involved.

As for the actual concept, sensors, computer logic and wireless transmitter are integrated to a commercial encasing with dimensions of $4 \times 2 \times 1$ cm. Each sensor is powered by its own replaceable CR2032 battery type (lasting up to four weeks). Computing power is provided for by MCU by NXP (Eidhoven, Netherlands) company with ARM Cortex-M0 core. Sensor layer enables for sensing of the requested variables and their wireless transmission through WBAN network based on ANT+ protocol in 2.4 GHz band. The ANT technology was chosen considering that it focuses on extremely low power consumption and meets the requirements for the range and data transmission efficiency. Compatibility with commercially available sensors (e.g ANT+ heart rate monitors) is also an advantage.

Currently, the system uses commercial sensors for monitoring heart rate (HMR-G1, Garmin Inc.), temperature (TMP112, Texas Instruments, Inc), relative humidity (SHT21, Sensirion, Inc) and activity sensors (MMA8452Q, 12b, FreeScale Semi Conductor, Inc). Modularity of the system provides for employing different types of sensors (as is required), which was used in the design of own sensory units for respiratory rate and myopotential.

The firmware of WBAN modules extensively uses power saving modes, which makes it possible to reduce power consumption to approx 400 microamperes in active mode (during measuring and transmitting via ANT interface). Furthermore, a possibility of configuration of an already programmed device through serial communication port (i.e. to choose the functionality of the motherboard according to the connected sensor, control the period of the transmission of the measured data, set up of the wireless transmission etc.) has been made a part of the firmware.

B. Second Layer Design (MSU System)

The second layer is based on a four-layer printed circuit board (PCB) with inner charging layers. Its shape has been chosen with respect to the used enclosing (an OKW box, Minitec series, size L). An NXP (Eidhoven, Netherlnds) LPC1769 chip with ARM Cortex-M3 core was used as a microcontroller. The controller's crystal works with tact frequency of 12 MHz, the real time circuit is controlled by a crystal of 23.768 kHz. An XB24CZ7UIS-004 module by Digi (based on ZigBee protocol) serves as a communicator with the visualization unit. It is connected to the microcontroller via UART interface and further using a line for the control of power consumption and sleep mode. An AP281M4IB module provides wireless communication with the sensors in the ANT network. It is connected to the microcontroller via UART interface as well, and by several lines for controlling sleep mode, baud rate, and power consumption. PCB is also equipped with μSD card docking which serves as storage medium. An SPI type interface provides for communication with the card. Charging lines of wireless modules and cards are equipped with MOSFETs switched by the microcontroller. This allows a complete disconnection of the power supply from the respective modules and thus reducing the power consumption to minimum if needed.

A Li-Pol battery with the capacity of 1050 mAh and an LTC3530 DC/DC converter, which is set to an output voltage of 3.3 V is responsible for powering of the microcontroller. The range of its input voltage covers the whole range of the voltage used by the Li-Pol battery charger without any problems. The batter charger is recharged using and integrated LTC4054 circuit. As for the input voltage for charging, 5 V from an USB connector is used. The unit is also ready for inductive charging of Qi standard. This functionality has not been implemented in the training module, however shall be used in strike monitors, which is one of the application requirements of the end users. The state of the battery charger is measured by a simple circuit, which is again switched by MOSFET.

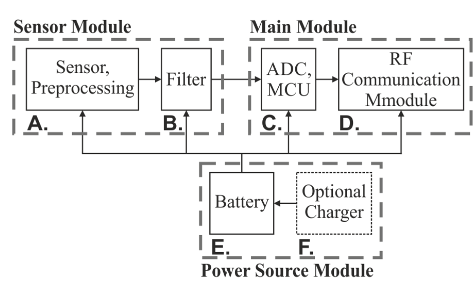

Figure 2. Scheme of sensor layer design.

This avoids self-inflicted loss of power in case MSU has been not used for a longer period of time. An MCP111T circuit watches out for a critical loss of power in the battery charger, which would lead to its destruction. This device switches the DC/DC converter completely off in case low voltage is detected and thus protects the battery charger from further loss of power. Apart from the above mentioned battery charger, the unit is also equipped with CR1216/CR1220 button cell holders. This primary cell provides for the powering of the microcontroller's real time circuit in case of absence or a complete loss of power in the battery charger.

Firmware of the sensing unit is written in C programming language and translated by GNU GDC v. 4.7.1 complier. Its concept is designed with respect to minimal power consumption and uses advanced power saving methods implemented in the ARM Cortex M3 microcontroller's core itself, which represent sleeping modes, options of powering respective peripherals and underclocking of the core. Core of the firmware is a μSystem providing for a selected range of OS functions. This system takes care of the control of the microcontroller's peripherals and the management of file system, and thanks to its versatility it is moveable between platforms, which provides for its swift employment on other microcontrollers

After restarting the microcontroller, all available drivers for the peripherals and other drivers (and later all peripherals) are registered to the system. Then the initialization of microcontrollers take place by switching all peripherals off and set all input pins so that microcontroller consumpts minimum power. Program then jumps to the main loop in main function, where the user code takes place. Here it is checked whether the unit is connected to the PC by an USB connector. If so, the unit will be recognized as USB Mass Storage Device accessing its μSD card, which can be worked with as an external memory device. In this mode, the unit is also charged. If the USB is disconnected, or the unit is disconnected from the USB mode, the program switches to measuring mode, in which the microcontroller is first underclocked, and then a protective timer (so called watchdog) is turned on, which avoids getting the program stuck in a loop by restarting it. Then loading UART interface, AD convertor, GPIO, timer, real time circuit and others take place using μSystem. At the same time, wireless modules get set. Subsequently, microcontroller is set to sleeping mode in an infinite loop due to power saving. All the rest of the code is then processed during interruptions by peripherals.

During an interruption by the AD converter, voltage on the battery charger is measured, which prevents its complete loss of power, and at the same time the value of the voltage is sent out using Xbee module. In case of an interruption by the timer, the system finds out whether or not the device has been connected to PC and if so, the program switches to the USB Mass Storage Device mode, mentioned above. The protective timer is also set to zero to avoid reset of the program. The data from the sensing modules are also loaded and stored into a file on the memory card.

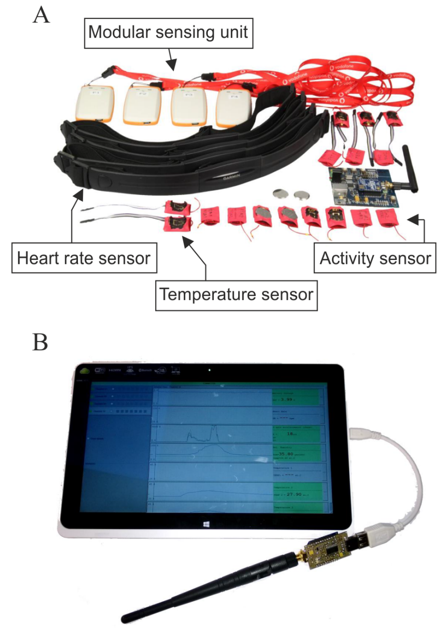

Figure 3. Modular sensing units with sensors (A) and setting screen of the visualization unit of the telemetry system during measurement, on a Tablet PC using Windows 8 OS (B).

At the same time, the concept of interruptions allows for the communication and configuration of sensing modules depending on their availability. For a precise record of the time of the incoming data, the real time circuit and another timer are used. These two timers thus offer the date and time for the recording of the incoming data with accuracy within milliseconds. Interruption operation of the UART interface connected to the ANT module accounts for a correct decoding of the incoming data from the sensing modules and their alternating storing into two storages so that no data get lost during the storing process.

C. Third Layer Design (Software and Visualisation Unit)

This layer (visualization layer) offers an overview of the measured values of the actual psychophysiological state including values of physical parameters of the environment for the commander, superordinate, or any person responsible. This layer is characterised by a multiplatform application including algorithms for the calculations of e.g energy outlay, stress etc. The data are stored on the memory card and sent to the visualization unit via format. Each data packet (on line of the CSV format) contains central unit identifier, sensor identifier, measured data and the real time of moment data were measured. Fig.3 demonstrates a sample of the screen of the visualization unit.

III. Functional Design Verification

FlexiGuard telemetric system has undergone a series of testing experiments aimed at its key features. Especially those connected to power consumption in various modes, data transmission quality check, the effect of interference and least, but not last, resistance against extreme temperatures and climate conditions.

A. Testing WBAN System Functionality

Sensor units of the WBAN system were tested in following steps: power consumption, resistance against extreme temperatures, data transmission capacity, functionality check by simultaneous MSU or VHF/UHF radio station activity. The average power consumption was measured in standard laboratory conditions using a calibrated measurement device (Gossen Metrawatt METRAHIT, M249A digital multimeter) over 200 sec. period (Tab. I). Testing resistance against extreme temperatures was carried out by observing the functions of the device when in environment with temperatures -15°C or, +80°C. Temperature change did not have any effect on the functionality of the device. Transmission capacity and cooperation with the central recording unit (2.4 GHz band, Zigbee) and UHF/VHF radio station (145 MHz and 433 MHz band, 5 W, 50 % changing) was observed in the configuration set:

- Garmin HRM-1G heart rate sensor (approx 4 Hz data period),
- Temperature sensor (approx 1 Hz data period),
- Actigraphy sensor (approx 1 Hz data period).

Sensors were mounted on the proband's body (Fig.4), the receiving part was about a meter away, radio station was always held in hand. During the comparative measurement, no effect of the sensing unit, nor the radiostation on the quality of the transmitted data was found. WBAN solution is therefore fully applicable for the use as monitoring device during special operations.

B. Testing MSU System

Key features of the MSU system were tested. These comprise especially wireless networks features and power consumption. The consumption and modular sensing unit battery life depends on the mode in which it operates. Unit working in the mode of full power and non-stop data transmission by Xbee radiocommunications shows consumption of about 80 mAh, while by underclocking the processor to 10 MHz and reduced dataflow in Xbee networks, the value drops under 20 mAh while mainaining sufficient power necessary for keeping a reliable dataflow. This allows for a battery life of 15, or 72 hours respectively.

TABLE I. Average Power Consumption in Normal Mode and in Lowered Power Consumption Mode

Sensing Unit	Data Transmission Frequency	Average Power Consumption	Power Consumption in Power Saving Mode
Actigraphy	1 Hz	5.61 mA	0.43 mA
Temperature	0.5 Hz	4.88 mA	0.372 mA
Humiditiy	0.5 Hz	4.88 mA	0.372 mA

TABLE II. Average Values of Dataflows from 5 Measurements

WiFi Intereference	Number of MSU	Dataflow [Byte/s]
Screened room 0 WiFi networks	1	6000 ± 5%
	2	4000 ± 5%
	4	4000 ± 5%
Village 1–2 WiFi networks	1	5000 ± 5%
	2	4000 ± 5%
	4	4000 ± 5%
City (extrem case) 15–20 WiFi networks	1	1600 ± 5%
	2	1500 ± 5%
	4	1000 ± 5%

Testing Zigbee data transmission efficiency took place using Xbee SMT modules by Digi company (Digi International Inc., Minnetonka, Minnesota, USA), which MSU is equipped with. The tested devices were in a proximity ranging in metres within the same room, to minimalize the interference of antennae and the reach of wireless modules. MSU firmware was adjusted so that it sends a continuous data stream with precise, adjustable dataflow. Data were received by a module connected to PC equipped with a software designed for recording the incoming bytes.

ZigBee data transmission efficiency is stated to 250 kb/s [6]. It is the data transmission efficiency as a whole, not two modules communicating with each other (especially in the typical FlexiGuard system mode in which data are sent from several units to a single visualization point). This value however can not be physically reached [7]. It changes depending on various modes in which networks operate. Dependance on the number of units in the system was found. Furthermore, a relatively significant dependance on the presence of WiFi networks was found as well. Tab. II demonstrates the results of the ZigBee network data transmission efficiency testing. The measured values are completely suitable for the use in the scope of FlexiGuard telemetric system. Xbee module range testing took place using the same hardware configuration. Therefore, modular sensing units send data periodically in CSV format to the receiver connected to PC. To minimalize the effect of the network's data transmission efficiency, units were set to transmit one data packet per second, which equals 30 b/s for one central unit.

Several types of antennae were used during the tests. Testing revealed the effect of the type of antenna on the range in so called direct visibility, while range over obstructions (buildings, or their parts, walls between rooms) was nearly independent from the type of antenna used. From these results, and from the dimensional requirements of the respective antenna types, Flexi Antenna

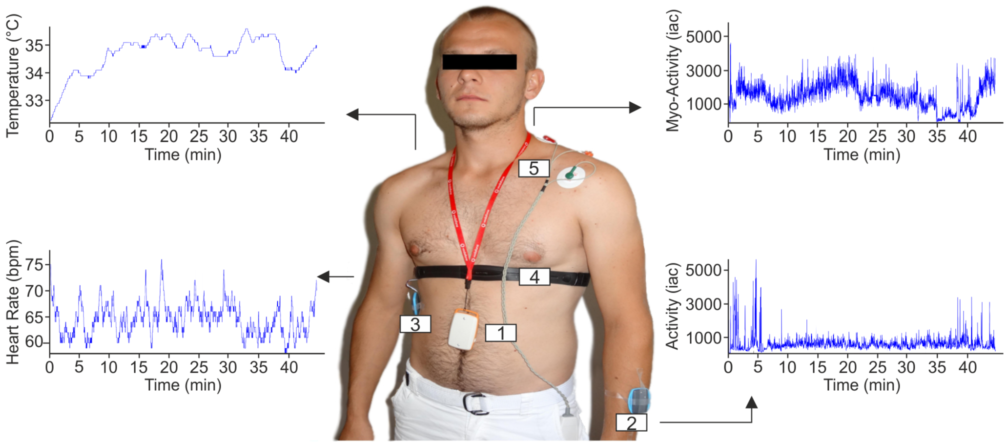

Figure 4. An example of the measured signal using a specific set of sensors and its placement (MSU (1), accelerometer (2), temperature sensor (3), heart rate sensor (4), electromyographic sensor (5)).

located inside MSU and a classic dipolar half wave 2.4 GHz antenna located on the receiver of the visualization unit were chosen as the best solution. The resulting range always depends on particular conditions. In our case, the range may vary from hundreds to thousands of meters in open space without any major obstructions. In case of urbanized areas, the range can be tens of meters, or through several (2–5) concrete walls.

IV. Discussion

The results show, that the resulting range of the FlexiGuard system, if it is used as training monitor, is fully sufficient. In case of the utilization of the system during special operations monitor, it would be possible to enhance the range of the WiFi network. This can be done in terms of Xbee network by installing so called repeaters, or by using different types of communication modules (due to the modular architecture of FlexiGuard, this modification is easy to perform).

Testing experiments of the training monitor on probands took place in military center in Olomouc. The aim was to examine the functionality of the technical solution of the training monitor and gain more data required for the optimalization of the system's ergonomics. Measurements were done on 34 probands from among professional soldiers aged 19–38. These took place in series including 4 probands equipped with training monitors at the same time. Wireless sensor networks WBAN worked without any blackouts during measurements, during the transmission to the visualization unit, an estimated amount of approx 0.2% lost packets was found, which is given by the features of the Xbee wireless network and communication protocol takes these into account (packets are sent redundantly). Experiments fully proven the capability of the training monitor to measure-transmit and archive all required data. Example of the measured signals from specific sensors and telemetric system equipment is shown in Fig.4.

The system optimalized for military objectives serves to obtain physiological and environmental parameters from a soldier for the sake of enhancing their safety during a military operation. The obtained data are transmitted to the commander, where they are very illustratively visualized. Based on these data, the further course of the operation can be optimalized by the commander in regard to the state of his squad members.

V. Conclusion

The designed telemetric monitoring device is conceptualized as modular with the possibility of a simple upgrade using hardware or software modules according to the requirements of end users. Based on the requirements it is possible e.g to add a sensor watching out for the presence of selected dangerous substances, or use a software to modify outputs from the measured data to fit the requirements of the end user.

The module can be used during observation and quantification of the course of training of respective team members in real time, to detect immediate reaction to various situations, to archive the course of training and subsequent long-term observation of trends in parameters during the training process. Based on the stated facts, a telemetric monitoring device with enhanced resistance has been developed, enabling for localization of team members, monitoring their physiological parameters (heart rate, blood pressure, skin resistance sweating, temperature), automatic detection and signalization of emergency state such as exhaustion, stress, hypothermia etc., in real time and in extreme conditions. The systems allows for distinguishing of the nature and intensity of movement including monitoring environmental parameters (temperature, smoke etc.) and other conditions based on real requirements of special forces.

Quality of the evaluation of the state can be improved with "personal safety profile" of a soldier (a set of parameters obtained during training and previous operations).

This profile allows for the creation of a relatively accurate estimation of an immediate state for each soldier. All acquired parameters would be updated automatically with the acquisition of new data during each use of the system.

The commander could thus have an option of securing safety of a soldier (exhaustion prevention, immediate information on being wounded, or a change in the state of a soldier), and optimally use the state of his squad during an operation (based on the information on the state of strain, an immediate strategy can be chosen), and improve the efficiency of trainings (finding optimal and safe strategy during training). The system has been used on various occasions to monitor psychophysiological state of soldiers, members of integrated rescue system and during training of pilots in both simulated and real conditions [8]–[11].

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B Článok 2

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Research Article

Wearable Modular Telemetry System for the Integrated Rescue System Operational Use

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The article summarizes the development of the FlexiGuard modular telemetry system designed for enhancing safety of the Integrated Rescue System team members in solving crisis situations and for improving training processes. Further framework solutions, which lead to the development of automatic modular telemetry system allowing for real time monitoring of physiological parameters, are provided as well. The system provides for the signalization of critical states such as exhaustion, mental stress, and overheating. It further provides differentiation between the nature and intensity of movement, including actual and overall energy output, monitoring environmental parameters, and analysis of an intervention or training. The system has been tested in laboratories as well as in the terrain under real circumstances, and the eventual end users participated in its optimization process. Following the theory of games, a model of a transmission system was also created which demonstrates higher transmission efficiency when using higher number of nodes.

1. Introduction

In the recent years, the field of wearable telemetry systems for physiological parameters monitoring is developing owing to the development of modern technologies. These are uses mainly by sportsmen, who may choose from a range of the so-called sport testers designed to monitor physical activity [1], heart rate, sleep, and other parameters. Similarly doctors, who are now capable of more precise diagnosing [2] or prescribing medication and/or adjusting treatment for the patient, are also interested in the field [3]. Telemetric systems monitoring health are also expanding to fields such as car industry [4, 5] or housing. One may also come across with so-called smart homes, capable of monitoring health of their tenants [6, 7], or with commercial products designed for monitoring health of the elderly [8].

Besides generally known applications in sports and medicine, the above concept of remote monitoring of psychophysiological condition is starting to find its use also with professions requiring mental or physical resistance. It is therefore currently possible to see the utilization of telemetry systems for monitoring physiological and environmental parameters [9] in professions by which monitoring of people performing highly demanding and responsible tasks appears well-grounded. The basic requirement for such applications is to limit the obstruction of carrying out the tasks to the highest possible extent. It is thus vital to opt for compact wearable telemetry systems. An example of such application would be monitoring of pilots [10–12], in situations when it is impossible to measure physiological signals using standard medical devices due to their dimensions (e.g., ECG) in a plane cockpit. The importance of wearable telemetry systems capable of measuring and evaluating physiological condition and environmental parameters of the close surroundings of the user may be clearly seen with members of IRS (Integrates Rescue System). Excessive stress and fatigue threatens their health and may have negative effects on their momentary ability to react promptly and appropriately to crisis situations.

As a result of this, consequences ranging from material to health damages may take place. One of the alternatives to avoid such scenarios is offered by the discussed systems. The primary interest is therefore in surveillance systems capable of providing the status on the condition and close surroundings of the members of IRS in real time [13].

Currently, there is a number of available systems and concepts which may find use with members of Integrated Rescue Systems and their localization in urban spaces, obtaining data from the team members, monitoring physiological signals, and so forth. Most of these systems, however, provide only a limited number of useful features (e.g., measures only a limited number of specialized parameters) and are not open to customization or further development.

LifeNEt [14], designed for localization of firefighters inside complex buildings, is one of the already applied systems. The general idea of LifeNEt evolves around a device worn by a firefighter, capable of deploying a certain number of lifeline beacons. These then serve as so-called access points which detect particular team members in their close proximity as well as their distance from and position towards the beacon using an ultrasound receiver. This allows for locating firefighters inside complex buildings. Miniature monitors can be attached to the device allowing for a firefighter to see his position as well as positions of other firefighters towards beacons. Localization of firefighters using beacons takes place in cooperation with a device which is mounted to their boots. This device also contains a temperature sensor and is furthermore compatible with other devices, for example, accelerometers via I2C interface. Among other applications of LifeNEt [15] there is also monitoring of various physical activities (e.g., cycling, jogging, and walking). Besides the fire brigade, the system has also been implemented for use in military fields with soldiers required to perform mentally and physically demanding tasks in their surrounding environments. From among medical applications of the system, continuous monitoring of physiological parameters in patients with Parkinson's disease or epilepsy [15], helping doctors adjust medications would be worth mentioning.

Another system designed for IRS applications is the MiTag system (Medical information Tag) [16], designed to collect information on the condition of a number of impacted persons. The system is based on the MiTag platform, which includes two wireless interfaces. One interface provides for communication with sensors and creates so-called body area network (BAN) and a wide range network of MESH type allowing for communication with screener. A part of the system are also repeaters which may be deployed along the way between the screening unit and a patient should it be the scenario that there is no direct reach of the signal from the platform on the patient to the screening unit. The MESH network protocol then automatically redirects the data flow through the repeaters which offers virtually unlimited range that the data can be sent over. The platform can be extended by a considerable number of various sensors such as GPS, pulse oximeter, blood pressure sensor, and temperature sensor [16].

The architecture of the wireless network designed directly for the needs of broadcasting the sensor measured data in the case of fire brigade interventions is represented by the FireNet system [17]. It can reconfigure itself automatically as needed and provide data flow to the desired location. Sensors of various types are connected to the network either on the fire fighters themselves or on some of their equipment, such as vehicles. A GPS receiver is attached to a vehicle enabling their localization, and then by using the network itself it makes it possible to partially locate relative distances between points. The obtained data are transmitted to screening unit of the intervention commander and the using internet sent further to the fire brigade headquarters [17].

Among fairly perspective systems, there is also Zephyr Bioharness [18] or ProeTex [19]. Zephyr Bioharness is a multifunctional chest harness able to monitor perspiration, temperature, body activities, and life functions of its user. It is primarily designed for training and exercise. The manufacturer claims the theoretical possibility of the use of this device's special configuration for purposes of military units and it is able to connect to the communication equipment of user [18]. ProeTex is a project running under the 6th EU framework program. This project focuses primarily on the development of "smart textiles" which are designed for the future production of protective wear and accessories for firefighters. Textile sensors developed within this project aim primarily at monitoring basic body functions, physiological parameters, and activities and identifying potential chemical threats (toxic fumes, etc.) and the issues of providing power sources for such devices [19].

Even though there is a considerable overall number of system concepts based on the idea of wearable telemetry systems applicable in IRS, these are in most cases focused on measuring a limited number of specialized parameter. Considering that commercial systems and devices do not allow for recording of the measured data in all cases, which would be useful for offline processing and evaluation of the measured data, the design of the modular telemetry system was also directed towards these kinds of utilization. The aim of this paper was to develop a modular telemetry system [20, 21], which would suit the needs of respective Integrated Rescue System bodies as well as other potential users according to their needs and requirements with the main emphasis on the sensor base, modularity, data transmission security, possibility of visualization of data online using various kinds of devices, battery life, and, last but not least, the user. Within the defined concept, among other issues, it was necessary to research and design a solution of the issue with centralized, or synchronized management of data flow of the designed biotelemetry system of the PAN type. Therefore, besides the overall description of technology, construction, topology, and modular aspects, the article focuses in more detail on the issue of managing data flow from several sensors or the entire sensory systems.

2. Materials and Methods

Over the course of telemetry system design phase, three firefighter units were contacted in order to obtain a portfolio of features desired by the user. The following rank among the major requirements: maximum user comfort (system must

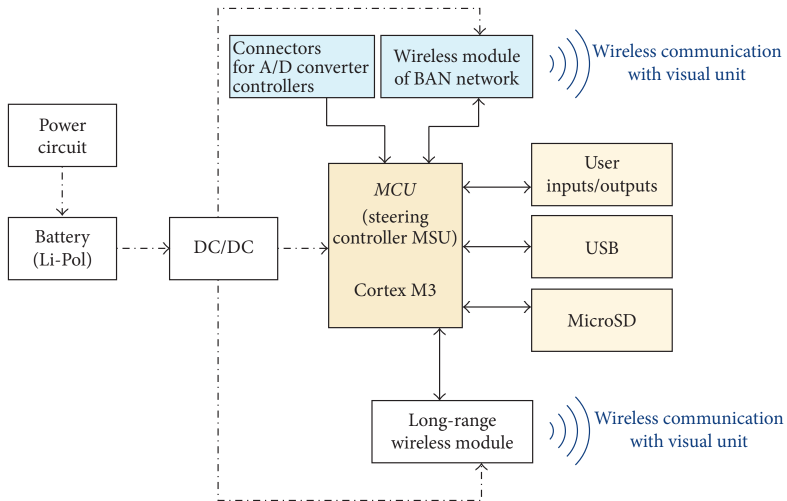

Figure 1: Hardware diagram.

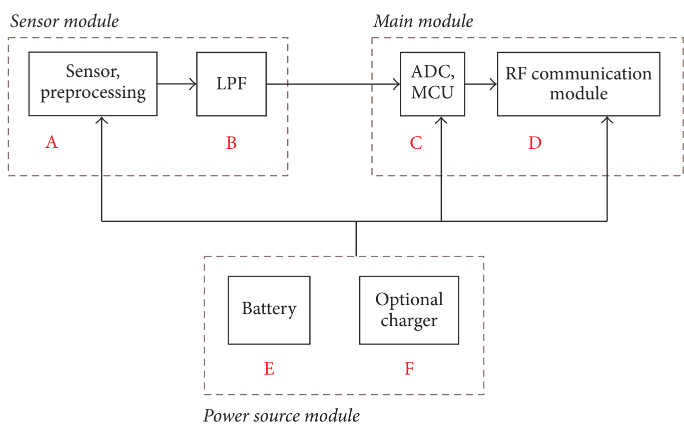

Figure 2: BAN unit designed for FlexiGuard.

not limit the user); minimum maintenance requirements; its use must not prolong the 2-minute time period for deployment and automatic use during intervention.

The results for our research and analyses are then primarily the requirements for high durability (i.e., low energy consumption), appropriate controlling unit (efficiency × consumption ratio), wireless system (consumption × range × data flow), automatic use, simplicity, dimensions, and weight.

The development of the system further involved the design of the software as well as the three main hardware components of the device (sensor network, main module, and visualization unit).

2.1. Hardware Design Specifications. The hardware design was set in order to develop a modular telemetry system providing a simple connection between the sensory base, the receiver (main unit), and visualization unit. Visualization unit may consist of a wide range of devices (laptop, smartphone, or tablet). The major components of the designed system however rely on the solution of sensory network and main unit. Figure 1 presents a chart of the hardware solution.

2.1.1. Sensor Network (WBAN System). Generally, the sensor network consists of several sensory WBAN units and main processing unit. Sensory units work independently; the main unit receives the measured data through simple tasks.

Sensory module comprises a sensor (Figure 2, part A) and supporting circuits such as low pass filter (Figure 2, part B) which processes the signal from sensor and converts analog data to digital if needed (Figure 2, part C). Microcontroller as well provides the data processing and communication with the wireless radio interface (Figure 2, part D). Power source module serves to connect the battery (Figure 2, part E) or optional charger (Figure 2, part F).

In case of using an LiPol accumulator, it is possible to incorporate here the circuit providing the powering process or wireless powering module.

Based on the experience as well as feedback from the participating subjects, optimizations were made to the wireless measuring node. The typology of the system has proven itself useful and stays in use; changes primarily take place in the solutions for encasing this part of the system and further in the circuitry solutions for the measuring node which reflect the course of the current technology development.

The microcontroller type EFM32ZG (manufactured by SiliconLabs, ARM-Cortex0+ core) was used. Solution for the radio communication part of the sensory node represents a dedicated module. This eliminates several issues with the radio signal transmission. Furthermore, this solution is more feasible considering future certification (CE) as the dedicated module has already been certified by the manufacturer. This alternative applies current communication protocols and is therefore compatible both ways.

The result of the circuitry solution optimization process is also the decrease in the number of (passive) components on the printed circuit's board.

Following the experience from testing of the system's versions, space for connecting other peripheries was reduced and we used the universal board printed circuit.

Within the design optimization, respective sensor is placed directly on the main printed circuit of the sensory node; that is, each type of the sensory node (depending on the variable) has a slightly different printed circuit (board); nevertheless as for the modular design they all share a common platform of further evaluation and communication.

Encasing of the module and the powering unit is a major innovation proceeding from the experience from field testing. BAN node consists of a sensory unit smothered in polyurethane hermetical case and a powering unit, also hermetically isolated. Both parts are mounted on each other and held by the outer case. Due to requirements of the device use, emphasis was put on being humidity and sweat resistant, being simple to use, and having mechanical durability. The system of the sensory node consists of an individual measuring unit and the powering subsystem. Joining both of the parts and inserting them into the fixating case activate the device.

Sensitive electronics of the module are hermetically smothered using polyurethane resin. Powering inputs as well as service interface for setting communication parameters and firmware actualization are lined in the form of contact areas on the sides of the module. Depending on the measured variables, an own sensory element is either included (smothered) in the module (e.g., accelerometer module) or feasibly protruded from the module (e.g., contact temperature sensor).

The selected module concept enables the use of both the primary powering units in the case of nodes with low standards of power consumption (e.g., the widespread CR2032 3 V lithium battery type) as well as LiPol accumulators (enhanced with a voltage stabilizer) for nodes with higher consumption.

The module design also includes a mechanical key for securing correct positioning of the powering and system module (contact areas have to face each other); the design calculates the positioning possibilities of the module around its vertical limit.

The wireless sensor network, which should consist of both digital and analog sensors placed on a subject's body, is connected through AD convertor. Each sensor connects to the main unit as soon as it is switched on within the range of the wireless network. Disconnection takes place by their deactivation or outside the reach of the network.

Basic wireless sensor network of proposed system includes thoracic harness used for heart activity detection, humidity sensor, temperature sensor, and accelerometer.

2.1.2. Main Unit. As already mentioned, the main unit receives the measured data and is able to control the sensory unit through simple commands (tasks).

Based on previous practical experience and measurement observations, the unit's hardware was adjusted for intervention monitoring. The adjustment affects both the printed circuit board upon which the main unit is constructed and its encasing. The adjustments reflect primarily the necessity of enhancing its mechanical and chemical resilience following the field testing experience pointing to rare cases of unit's deactivation caused by high amounts of humidity and sweat. Stability of the real time circuitry was enhanced as well, and upgrades also included the powering element of the main unit. Modular sensing unit used by each subject includes data acquisition, data processing, and two-way communication.

Main unit operates in two modes, the measuring and charging mode. Measuring mode activates by a hold switch located on the side of the device unless the device is connected to a PC or a charger through a USB cable. In this mode, the unit is in emergency status ready to connect to sensors. Frequency of saving and transmitting the data follows the device settings and the number of connected sensors.

Connecting the sensors (BAN nodes) is a virtually automatic process. After the sensor turns on within the reach of the wireless network, sensors are automatically connected to the main unit. This connection typically takes up to 30 seconds. Over the course of measuring, it is possible to connect or remove the sensors (BAN nodes) from the provided set. Disconnection of the sensors takes place by their deactivation or reaching outside the wireless range and reconnection then by their reactivation or returning to the area covered by the main unit without any restarts or manipulation with already connected sensors.

USB/charging mode activates once a unit is switched on by the hold switch and voltage is detected at the USB input (indicating the unit is connected to a PC or charger through a mini USB cable). This mode does not allow connection of sensors and proceeds with measuring. When a unit is connected through USB cable to the charger, only recharging takes place. As soon as a unit is connected to a PC, it is fully functional on every operation system as a Mass Storage Device besides being recharged. Before measuring it is necessary to have *data.txt* file created in the root folder as this is where all the received data are stored. In case the file is empty, data is being stored here from the measuring initiation. Should the file already contain any data, new data will be stored at the end of the document to avoid their rewriting.

Main unit is built on a four-layer printed circuit with inner connective layers. Its shape was selected considering the used encasing (OKW box, Minitec series, size L). As a processing microcontroller, the LPC1769 chip by the NXP company is used. Sampling is provided by a crystal with the frequency of 12 MHz; the real time circuit is controlled by a 23.768 kHz crystal. The XB24CZ7UIS-004 module by Digi used for communication with the visualization unit connected to the UART interface as well as a line for controlling sleep mode. An AP281M4IB module provides wireless communication between sensors within the ANT network. It connects to the microcontroller similarly through UART interface together with several lines for controlling sleep mode, consumption, and baud setting. The printed circuit is further equipped with a holder for SD cards which are used as the storage device. Communication with an SD card is provided for by an SPI type interface. Powering branches of wireless modules of a card are supplied by MOS-FETs switched by the microcontroller. This enables total disconnection of powering from respective modules, thus reducing consumption to a minimum level if necessary.

A Li-Pol accumulator with its capacity of 1050 mAh together with a DC\DC LTC3530 convertor (set to 3,3 V) supplies the microcontroller with power. The accumulator is charged using the integrated LTD4054 circuit. As the input voltage, 5 V from the USB connector is used. The unit is furthermore ready for inductive charging of the Qi1 standard. This functionality has not been implemented into the training module but is to be used with the intervention module which represents one of the application requirements from end users. The status of accumulator is monitored by a simple circuit, once again switched by MOS-FET. This eliminates possible random loss of power in cases the unit has not been used for a longer time. An MCP111T module reduces risks of critical accumulator failures which would lead to its destruction. The module switches off the DC\DC convertor if low voltage is detected, therefore protecting the accumulator. Besides the above accumulator, the unit includes CR1216 coin button batteries holder for the purpose of powering the microcontroller's real time circuit during the absence or complete battery discharge. Modular sensing unit is also equipped by four LED indicators, button, USB connector, and a JTAG programming connector. The outer dimensions are 88 × 50 × 21 mm. The main unit weights 57 grams.

2.2. Software Design Specifications. After the initial configuration has completed, the software functions independently without the necessity for operational interventions. The configuration is set in a way ensuring that, in cases of intervention module's and visualization unit's loss of connectivity, all data are stored on the internal memory of the intervention module and subsequently and automatically synchronized with the visualization unit. The system's functioning is therefore outage-free as for the quality of the measured data.

Current version is in accordance with the system concept fully modular and ready for work with multiple platforms of the controlling microprocessor. This solution will enable a low cost and technically simple porting of the entire operating firmware of the intervention module for potentially new or upgraded platforms based on the ARM Cortex A3 architecture. The created platform of embedded drivers remains the shared solution for firmware of the used sensory nodes for the used WBAN network and therefore applicable also to the ARM Cortex A0 platform. This solution offers flexible upgrades of the system as for new peripheries and functionality without the previous high cost and time consuming changes in the design of the whole system.

Firmware of the whole system is designed in the programming language C and optimized for the gnu 11 standard. Firmware has been developed in the Eclipse environment and easy to implement.

The firmware configuration for a particular main unit runs through the configuration file. This is where the number of the main units is set as well as the desired number of up to eight sensors which would be used, time variables and so on. Complete setting possibilities are described in the file.

Once the controller is initialized and running, the main function is called. This initializes and sets up the entire unit, which is followed by the program entering an infinite loop which processes blocking and time consuming operations, especially the process of saving files to the storage device. The main loop is interrupted using operations of interruptions of individual peripheries such as timer, universal asynchronous serial port (UART), and analog-digital convertor.

The firmware uses the principle of double-buffering and saves the received data from sensors to either of the two magazines. As soon as a magazine is full, it switches to the other magazine and the full one is processed. The processing is initialized using the interruption of the timer (clocker) operation and proceeds further in the main loop where the content of the magazine can be converted in any combinations into ASCII code and can be saved on the SD card and sent to the visualization unit. The interruption also provides fully automatic connection process between sensors and the main unit. Data flow and processing diagram are shown in Figure 3.

Subsequently, a transmission system model of a BAN type (body area network [22]) was created based on the game theory (users behaving like game players). Considering, for example, a 3 s measuring cycle, during which all nodes are to send their respective measured data and the measuring is controlled deterministically, each node is assigned an exact time period of 0–3.000 ms during which it broadcasts (broadcast takes approximately 100 ms). An issue arises in case more nodes are connected that a single timeframe can contain, as simultaneous broadcast of two or more sensors causes collisions and data fail to transfer.

2.3. Design of the Transmission Network Model. The main idea of the discussed design was to avoid the issue arising with switching on the sensor unit, when the unit goes through a cold start and starts sending data to the main unit. As each unit switches on at a different time, this results in their

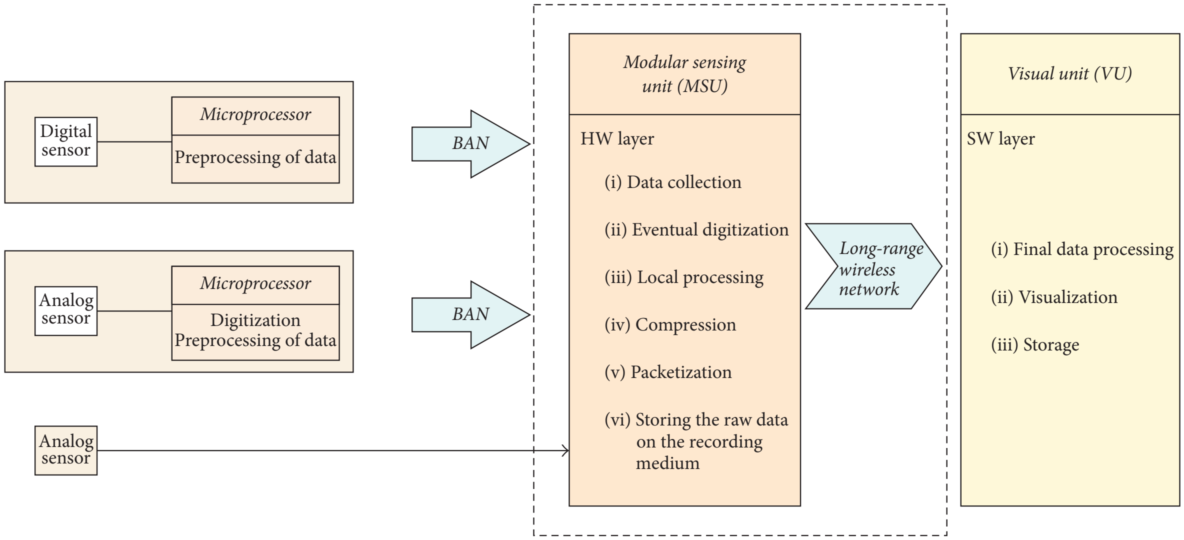

Figure 3: Data flow and processing.

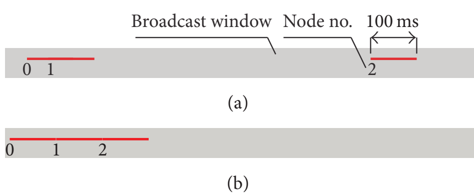

Figure 4: Example of possible units' colliding arrangement (a) and deterministic unit arrangement (b).

random arrangement in the broadband. Each unit broadcasts for a certain time period. As demonstrated on Figure 4(a), with three randomly arranged units, broadcasting times of units 0 and 1 collide and this results in no transmitted data. Unit 2 transmits all data. As per standard approach, the units receive a signal to stop transmitting. Then, each unit is addressed in order to obtain the total number of units. Once this information is obtained, the main unit assigns exact broadcasting times to the units and sends a signal to resume to data transfer. The resulting situation is demonstrated in Figure 4(b).

However, if the signal is not received when addressing the units, after the restart of the system the unit will then broadcast in the initial time and further collisions may occur. The signal is not received if the unit is outside the range or the batteries die. This is why the designed resolution method removes the main unit from control and leaves it to the units. Central unit only sends through the broadcast signal the amount of received data from respective units and successful broadcasting times. The units adjust their broadcasting time based on these data.

Model of the transmission network was realised using Javascript, HTML and CSS technologies. The ECMA 6 specification was used for Javascript and the code was subsequently transpired using the babljs compiler into ECMA 5 specification supported by current browsers. The entire development stack is controlled by Gulp.js, which represents technology for task management which supports previous technologies and individual tasks, such as compilation and minification of Javascript. The node.js technology was used for library management. At the same time, it is used as the environment for the compiler and gulp.js. The complete code runs in a browser on the user's end.

Basic construction of the model includes three elements simulating data transmission and timing, that is, central unit, clocker, and node (see Figure 5(a)). The entire model is based on a star typology in which nodes communicate only with the main unit and vice versa. This variation of typology does not allow nodes to communicate among each other.

Clocker is responsible for the functioning of the whole system (see Figure 5(b)). It works as an internal timer for all component systems. Upon activating the model, it launches under the ServiceWorker browser, which calls individual steps of nodes and the central unit during an infinite loop. ServiceWorker is a service (web thread) which runs in the browser on the background. Clocker has information on the broadcast window time, and depending on a given setting it is sent to broadcast units, once for every set of x broadcast rounds. ServiceWorker allows for switching between real time simulation and accelerated (faster) mode when clocker works at the maximum speed of the hardware.

Main unit is responsible for the count of the data sent successfully by the respective nodes (see Figure 5(c)). The inner implementation of the sent data count is based on the principle of associative array storing each unit that

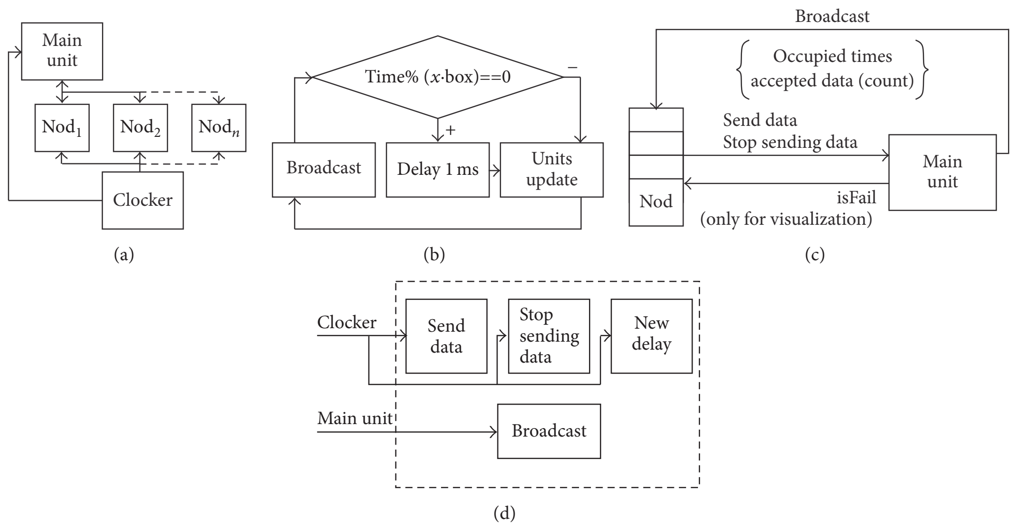

Figure 5: Flow chart of the basic model construction (a), inner implementation of clocker (b), main unit (c), and internal arrangement of a node (d).

starts broadcasting in a given time into the array of units broadcasting in the given time. If there is more than one unit in the array at a moment, the broadcast is considered as unsuccessful and the result is stored. The unit receives a message that it failed to transfer the data (due to visualization); however the unit disregards the message and does not further consider it. This is how the process described in the premises chapter is preserved, when the unit is not aware if it succeeded to transmit the data or not. The central unit also provides for sending the broadcast to all nodes active at the moment. Broadcast includes information on the amount of data sent by each unit and also information of occupied broadcast times.

Node is a single broadcasting unit in the system. Following the creation of a node type system, this node is included in the pole of nodes and using white noise it selects a random place in the broadcasted loop. From this place, it immediately starts to broadcast (transmit) with random latencies, modulated by red noise. Node incorporates the clock method which is called by the Clocker object and it is where the actual time in the window is stored. Once all the times have been generated, node waits until the method is called and, subsequently, depending on the generated times, proceeds with actions assigned to respective times (broadcast start, broadcast stop, and generating times for the next round). Once in x rounds the node receives the broadcast signal with the data on which times had the highest ratio of successful broadcasts and the number of successful broadcasts. It then adjusts its broadcast strategy based on the received information. Each node works as a state automat with two states, one when it broadcasts and the other when it is waiting for the next broadcast. Figure 5(d) demonstrates the internal arrangement of a node.

Each node furthermore includes the strategy module which is used by the unit to store the last six entries on success percentage of broadcast. If the arithmetic mean of the total success percentage drops below the set threshold, the unit performs a so-called jump. It differs from the initial jump primarily in that the new position is selected from the pole of random numbers which are filtered using values generated from the memory heatmap. This heatmap is generated by each node before the jump.

Every broadcast carries information on the times of successful data broadcasts (transmissions) and uses this information to assign "scores" of respective times in its memory heatmap. To reduce the number of possible accidents, considering identical memory heatmaps, partially random forgetting of these heatmap prints takes place. This eliminates the possibility of an identical heatmap for two different units.

Before a jump, a unit assigns scores to times generated by the white noise. Assigning is processed as the unit considers the selected broadcast time from the heatmap and calculates the total score from its closest surroundings. All times with scores above the mean value remove the nod from the random selection.

During broadcast, unit selects a change in strategy if the conditions allow it. If 100% data transmission occurs over six consecutive broadcasts, the unit attempts a move towards zero times. This choice of strategy is desirable due to the fact that the units, considering the random nature of selecting broadcast times, tend to create considerable gaps between themselves which, however, are not big enough for another unit to fit into. This way they take place and a major part of bandwidth remains unused. Unit always attempts a random move by several tens of milliseconds. When its broadcast success decreases, it returns to its initial place before the move and the attempted move is no longer considered.

When the unit performs a big jump, the sensor for small moves is automatically reset to zero. It is possible to a certain

Table 1: Overview of the adjustable settings and standard model setting values.

Parameter	Description	M_{S8} setting value
Box (s)	Broadcast broadband capacity (for one round)	1
Jump threshold (%)	Percentage variable defining the level of threshold under which nodes opt for jump	20
x-broadcast	Variable defining number of rounds after which broadcast message launches	3
Move threshold (%)	Percentage variable defining success level required to attempt small move	100
Start lower threshold	Indicating whether a node decides to jump over or below the threshold	True
Experiment time (s)	Duration of the measuring	300
Start delay (s)	Initial broadcast time of a node	0.1
Rounds stay	Defining the difference between threshold and a unit's success ratio required for a unit to perform a jump	6
Fixed time	Switching to deterministic mode	False
Fast simulation	Switching from real time to fast simulation	True
Intelligence	Dismissing all strategies and switching to the random broadcast mode	True
Memory	Value which will appear in the memory map	3
Min shift (ms)	Minimum move when making a small move	1
Max shift (ms)	Maximum move when making a small move	10
Nodes	Total number of nodes	8

extent that unit stops moving due to fluctuations caused by red noise despite the available space around. Due to this fact, the sensor is reset with 1% probability also with unsuccessful jumps.

For the purposes of the model, a graphic interface was created allowing for adjustments in basic parameters of the entire system as well as monitoring its condition. Also, a visualization unit was created using the oCanvas library providing real time monitoring of the arrangement of units in broadcasting times and the duration of their broadcasts. The interface also includes a switch designed for switching the system from stochastic to deterministic, in which each unit calculates its broadcasting time based on its ID and the duration of the broadcasting window.

$$\text{Time} = \text{ID}_{\text{unit}} \cdot t, \tag{1}$$

where t is the actual time of the broadcast and ID_{unit} represents its position in the pole of units. In the deterministic state, unit does not oscillate around the broadcast time but transmits precisely in the calculated broadcast time. This implies limits of unit broadcasting in the deterministic mode, which, when exceeded, no other units fit into the broadcast bandwidth and thus produce a 100% data loss.

$$\text{limit} = \frac{\text{broadcast time window}}{t}. \tag{2}$$

The most vital adjustable parameters of the model were incorporated into the designed software. Table 1 provides characteristics of the adjustable parameters. The tab also includes settings of the model standard type (M_{S8}), which were compared to other adjustment settings. This type of settings proved the most stable and most successful during the experiments.

For further evaluation of the broadcasting success of the designed broadcasting strategy, strategic setting of the standard type (see Table 1) was compared to the white noise broadcast that simulates cold starts of the units (i.e., the units performs cold start after each broadcast and its broadcasting time changes). Also, the designed broadcasting strategy was compared to the white noise broadcast in the case of full broadcasting range. The effects of memory, broadcast duration, jumps, and moves to the success of broadcasting were also examined. Fragmentation of time for strategic setting of M_{S8} was also examined within the scope of evaluation.

A set of 20 experiments was performed for each setting type of the model, and the duration of each experiments was 300 seconds. Having the broadcast set to once in three rounds, the success was evaluated every 3 seconds, which yields 100 values of success for each unit for one measurement. In the case of experiments with 8 broadcasting units it is 2,000 values of success for each unit, and therefore 16,000 values for the total of the 20 experiments.

3. Results and Discussion

For the purposes of evaluating the suitability of the designed strategy, success percentage of the broadcast was examined using standard setting for 8 nodes (M_{S8}), standard setting for fully occupied bandwidth, that is, for 10 nodes (M_{S10}), broadcasting using white noise (M_{wn8}) for 8 nodes, and broadcasting using white noise with fully occupied bandwidth (M_{wn10}). Success percentage was further measured when changing standard settings, particularly with the setting of so-called aggressive memory, which means that the standard memory was set to 10 and the forgetting parameter was set to 1.

Within the scope of results evaluation, normality of the measured data was considered using Shapiro-Wilk test of normality at the significance level of $p = 0.05$, when the normal distribution hypothesis was rejected for $p < 0.05$. Due to the fact that the normality test fails to confirm normal distribution of all measured data, Wilcoxon nonparametric

Table 2: Results of Wilcoxon test in the form of p values for the measured data distributions.

	M_{S8}	M_{wn8}	$M_{S8\text{-Me-10}}$	M_{wn10}	M_{S10}	$M_{S8\text{-Sh-50}}$	$M_{S8\text{-Mo-20}}$
M_{S8}	—	$<2.2e-16$	0.1928	$<2.2e-16$	$<2.2e-16$	$2.795e-08$	$2.428e-13$
M_{wn8}	—	—	$<2.2e-16$	$1.46e-08$	$<2.2e-16$	$<2.2e-16$	$<2.2e-16$
$M_{S8\text{-Me-10}}$	—	—	—	$<2.2e-16$	$<2.2e-16$	$7.434e-08$	$1.108e-15$
M_{wn10}	—	—	—	—	$<2.2e-16$	$<2.2e-16$	$<2.2e-16$
M_{S10}	—	—	—	—	—	$<2.2e-16$	$8.812e-15$
$M_{S8\text{-Sh-50}}$	—	—	—	—	—	—	0.0003284
$M_{S8\text{-Mo-20}}$	—	—	—	—	—	—	—

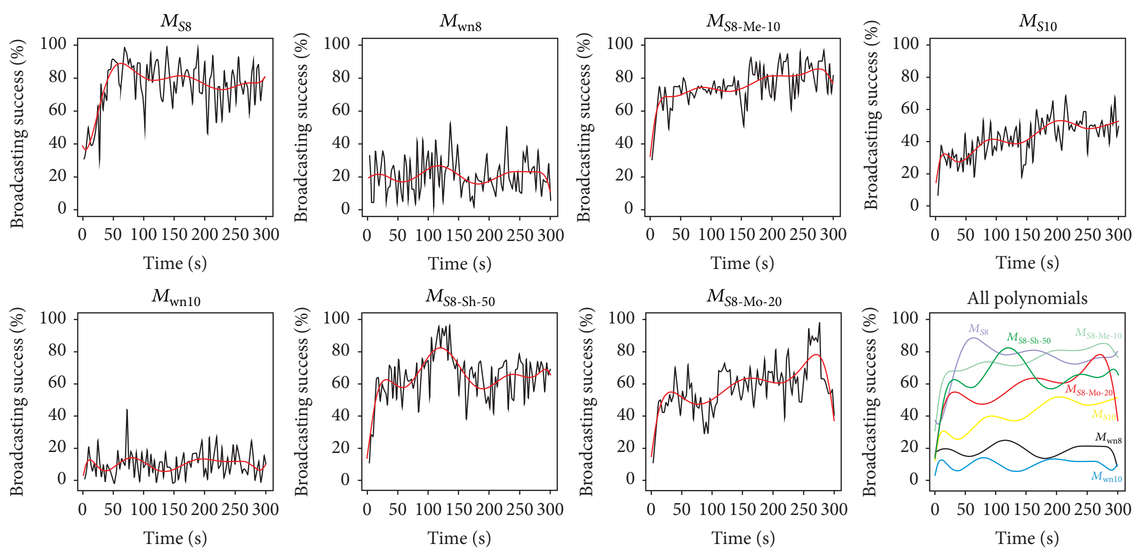

Figure 6: Mean broadcast success ratio depending on the selected broadcasting strategy.

test was used for further evaluation of differences in data distribution, testing the hypothesis that medians of two examined data vectors come from the same distribution. Significance level of $p = 0.05$ was used for the test, while hypothesis about intergroup differences on the level of medians was accepted for $p < 0.05$. The results of the Wilcoxon test show that statistically significant differences were found in all cases except when comparing M_{S8} compared to $M_{S8\text{-Me-10}}$; see Table 2.

Graphic representation of the summarized results of the mean success of units adjusting their behavior based on the prescribed strategy when using white noise and changing the above described parameters is demonstrated by Figure 6. Red curve crosses the data with polynomial of degree three.

When comparing the mean broadcast success ratio using M_{S8} to mean broadcast success ratio using M_{wn8}, it was found that the mean success ratio is 4 times greater with the designed broadcasting strategy (see Figure 6). In this case, comparing the broadcasting time of 1000 ms, the bandwidth is occupied at 70%. In the case of fully occupied bandwidth, the selected strategy M_{S10} succeeds better with every instance compared to broadcasting using white noise M_{wn10}, approximately 4 times (see Figure 6).

When changing the memory setting to aggressive memory, no significant difference was found between $M_{S8\text{-Me-10}}$ and M_{S8}. The aggressive memory setting means that every broadcasting time leaves a greater trace in the memory print, which however had no influence on the success of broadcasting.

At high values of max shift (max shift > 50 ms), decrease in the mean success ratio of units was observed at high probability due to more frequent collisions during moves (see $M_{S8\text{-Sh-50}}$ on Figure 6). The system does not converge into a state which would allow for placing a unit in a freshly created free slot. Small shift describes the effort of a unit to defragment time. In other words, the value of max shift basically characterizes the speed of defragmentation; however increasing max shift values increases the probability of collision. With lower values, the free time defragments at slower speed. Statistically, a situation may take place in some cases when the units occupy broadcasting times inefficiently, and due to slow shift and slower defragmentation of free

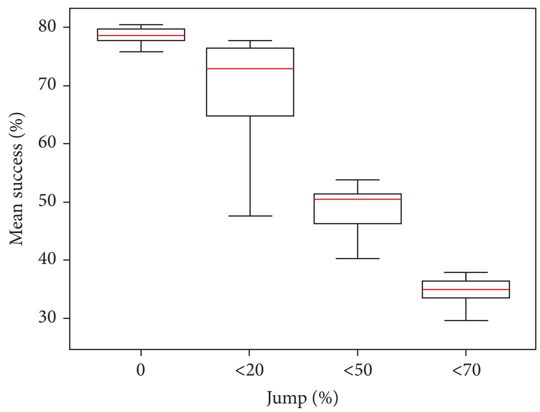

Figure 7: Effect of jump threshold on mean success.

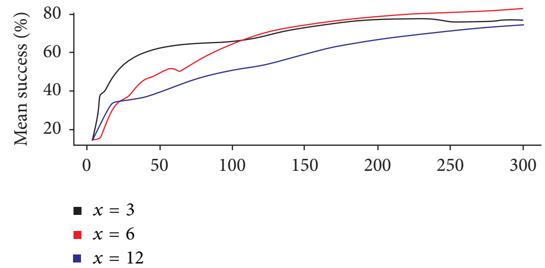

Figure 8: Mean broadcasting success depending on broadcast duration M_{S8}.

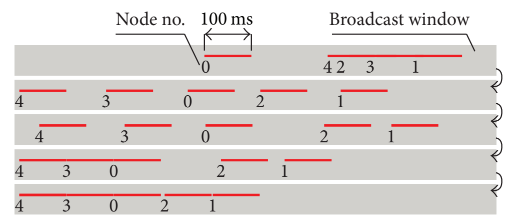

Figure 9: Example of gradual time defragmentation by the designed software.

time, some units would wait longer for a free slot. At lower values, as in the case of M_{S8}, with the max shift ≤ 20 ms, lesser collisions happen owing to the shifts and therefore also better defragmentation. Therefore, shift has no direct effect on the units' distribution; it is nevertheless vital for providing free broadcast range for next possible units.

The move parameter sets the success ratio at which the units attempt to defragment time. By standard setting, the value is set to 100%. In the diagram for $M_{S8\text{-Mo-}20}$, this value is set to 20%; that is, units will attempt time defragmentation at low success ratios. Time defragmentation will therefore start earlier, which however causes more frequent collisions decreasing success, as illustrated.

Besides the above, the article aimed to identify the effect of jump threshold on the mean broadcast success ratio. Figure 7 demonstrates the results in the form of boxplots, with each boxplot describing the distribution of the mean broadcasting success ratios of nodes for respective jump threshold settings for M_{S8}. At the same time, each boxplot illustrates, starting from the bottom vertical line, the distribution minimum, first quartile, median, third quartile, and maximum. Graphic representations suggest that increasing the value of threshold for unit's big jump decreases the success of units. Units perform jump more frequently and come closer to the success of white noise. Performing jumps was experimentally proven to be statistically most accurate when reaching 0% success ratio. The influence of the jump threshold is defined by the jump threshold parameter (see Table 1), and it can be said that increasing the value of this parameter brings the system closer to the setting of the white noise.

Besides the presented results, the behavior of the model M_{S8} when changing x parameter was measured (see Table 1), that is, when changing the duration of the broadcast. Duration of the broadcast affects primarily the steepness of the success ratio curve, as presented in Figure 8. Increasing the broadcast duration slows down the feedback to the system and units therefore broadcast potentially longer in the collision spots. With lower values, the feedback speeds up which results in faster adaptation of the system; this however causes increased energy consumption. Figure 8 demonstrates the decrease in success percentage caused by lower amount of broadcast messages received by units over the same experiment duration, which results in lower adaptation speed of the system.

The entire model and the source code were systematically tested aiming to eliminate implementation errors, enhancing accuracy of generating noise functions and functionality of the idea of decentralized operation. The designed operation system using competitive strategy is functional, as presented by the attached diagrams and confirmed by statistic tests. Figure 9 illustrates how basic arrangement of units into the broadcasting range is followed by applying the strategy of small moves of the units in the broadcast and their convergence to the left of the broadcasting range. The condition for move can be set by the *move threshold* parameter.

In the work of Gorman et al. [23], the following formula is used for fragmentation calculation:

$$\text{fraglevel} = \frac{\text{Total Free Pages} - \sum \left(2^i k_i\right)}{\text{Total Free Pages}} \times 100. \quad (3)$$

However, this formula does not consider possible collisions as it applies to a spot in the memory with no possibility of collisions. To describe time fragmentation by parameters, this formula was adjusted to consider use in an environment allowing for situations with a seemingly free slot. A seemingly free spot in the broadcast time represents a situation when units broadcast in collision, and these collision times appear

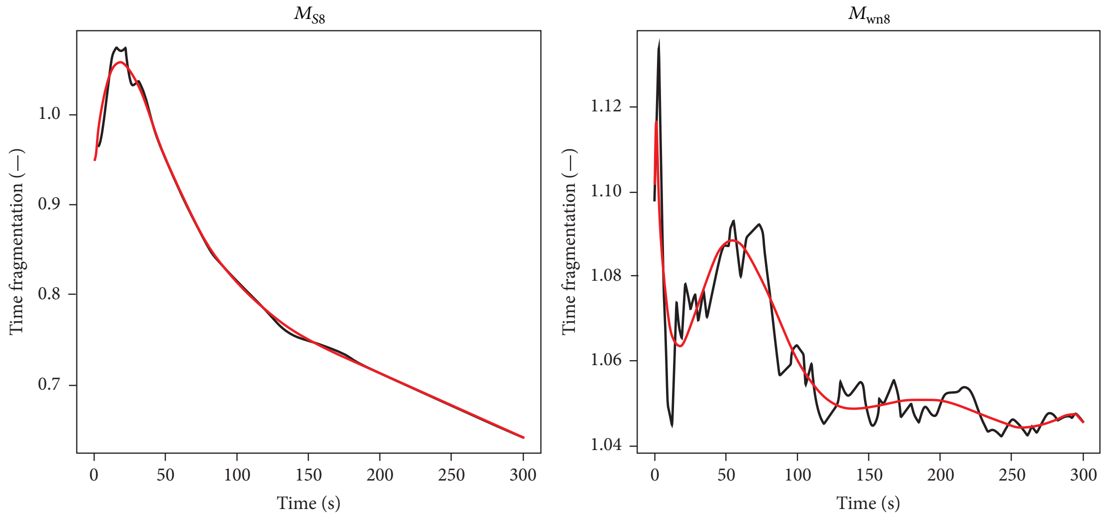

Figure 10: Defragmentation of time in standard and white noise setting.

to increase the free spot. The adjusted formula offers and idea of a free spot depending on collisions f_c.

$$f_c = \frac{\sum t_f - \left(\sum t_{f\max} - \sum t_c\right)}{\sum t_f}, \quad (4)$$

where t_f represents free time, t_c represents collision time, and $t_{f\max}$ is the total sum of the greatest block of free time. If the value of fragmentation exceeds 1, it means that collision time is greater than free time. The following generalized formula is used to determine the maximum value of f_c:

$$f_{c\max} = \frac{(n-1)\,t_v}{t_{\max} - t_v}, \quad (5)$$

where $t_{\max}$ represents the total broadcast duration, t_v is the duration of the broadcast time of a unit, and n represents the number of units.

Figure 10 presents the behavior of f_c parameter in the designed optimum model M_{S8} and M_{wn8} model. The parameter demonstrates the decrease of the value of time fragmentation, which indicates an increasing free spot in the broadcast time in M_{S8}. For comparison, we may observe that the value of the fragmentation parameter in M_{wn8} is always greater than 1; that is, the units experience more collisions than free time.

4. Conclusion and Future Work

FlexiGuard modular telemetry system was developed by the authors for the use by Integrated Rescue System bodies. Individual parts of the system were designed with the focus on minimum demands on the user, automatic use, and maximum modularity. Functionality of the system was verified by a series of practical laboratory tests as well as under real conditions. Based on the performed testing and feedback from end users, the system was fine-tuned. Furthermore, a model of a broadcast network was created based on the theory of games. A new decentralized stochastic model of data flow management in a wireless biosensory network based on competitive strategy relying on the theory of games was also designed and tested. The model is operated by a delayed feedback proceeding from an approach which uses units with separated broadcasting and receiving components and are incapable of an immediate decision on successful or unsuccessful broadcast. If the units are switched on, they go through a cold start when broadcasting in white noise. This noise was modeled and compared to the approach of decentralized operation, in which the units receive delayed feedback on broadcasting times of other units together with the information on their own success. In the simulations, the designed competitive operation strategy, which evaluates each unit based on its success and changes the broadcasting strategy accordingly, has proven several times more efficient than leaving the units in their condition after the cold start. Each unit changes its strategy over the course of broadcast not only on the basis of success percentage. Several of the model parameters are controlled by noise functions; therefore the units do not behave identically. This is furthermore given by the fact that each unit creates its own memory heatmap of broadcast times modulated by a random selection.

The original design used the centralized operation which stops all units and then gradually calls them, which is followed by ascribing deterministic broadcast time to each unit in which they broadcast. This approach loses its effect, if does not fail completely, in situations with the number of sensory units unknown or changing over time, when broadcast times of units overlap and the central unit does not receive the signal. This leads the central unit to assume that the involved units are incapable of broadcast, switched off, or out of the network range, and the deterministic control system fails.

We are currently working on implementing adjustments to the broadcast network in to the FlexiGuard units and testing larger numbers of units in cooperation with the army.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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C Článok 3

Socha, V., Kutilek, P., Stefek, A., Socha, L., Schlenker, J., Hana, K., et al.

"Evaluation of Relationship between the Activity of Upper Limb and the Piloting Precision"

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Evaluation of relationship between the activity of upper limb and the piloting precision

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***Abstract* – Flying an aircraft requires a significant degree of coordination of upper and lower limbs. Such movements tend to be rather uncoordinated in the case of inexperienced pilots which results in inaccurate piloting. The aim of this study is to prove or disprove the dependence of the upper limb activity in relation to the aircraft steering during various actions which are required for precise maneuvering. We also deal with the design of a method to determine the degree of correlation between the movement of the hand and the airplane. The study was conducted on 8 subjects with the same level of experience during 11 hours of flight training on the simulator of type TRD40 and aircraft of type DA40. Subjects performed 14 maneuvers in total. Between takeoff and landing a recurring cycle of four maneuvers has been carried out by the subjects. Repeated maneuvers were in the order from the straight-and-level flight, horizontal turn by 360°, ascend turn by 180°, and descent turn by 180°. Recorded data except for basic flight data (magnetic course, banked and altitude) have been variables depicting the activity of the pilot's upper limb. The activity was measured using triaxial accelerometer located on the dorsal side of the distal end of the forearm. The correlation coefficient proved relationship between the upper limb movement and aircraft steering both at bank and altitude. It testifies that change of bank and altitude of aircraft is directly connected with upper limb movements. Resultant activity standard deviation relation correlation coefficient is 0.7.**

Keywords – uper limb activity; piloting precision; flight maneuver; aviation

I. Introduction

The collection and processing of physiological data from pilots during flight is nowadays a widely discussed topic. Typical feature of flying a modern aircraft is that the demands for mental activity of pilots are constantly rising. This phenomenon gave impulse to the development of a scientific discipline called Aviation psychophysiology, which is a part of aviation medicine. The main objective of aviation psychophysiology is the study of interrelationships between the states of mental functioning, physical performance of pilot during flight and physiological response which can be recorded objectively using sensors [1]. Thanks to acquired knowledge we know how great a stress overload pilots are exposed to during flights and how they are able to resist and cope with it. These factors play a very important role in flight safety. By an early detection of limit fatigue of pilot through scanning of the physiological parameters, we can prevent airplane accidents. The following system: pilot – aircraft – environment is therefore studied.

From the available sources, not a single study was identified which would focus on evaluation of correlation between the piloting precision and the upper limb activity. However many studies have used physiological parameters to evaluate the magnitude and phasing of muscle activity required to fly an aircraft. For example Hewson et al. [1] examined dependence of muscle forces and electromyography activity on aircraft or helicopter piloting. The aim of these types of studies was to examine the muscle activation patterns and steering forces of novice and experienced pilots during simulated flight or measure the force variability and landing performance of pilots during an instrumented landing in a flight simulator [2-5]. The use of physiological parameters for assessment of mental workload of pilots, or, for example truck drivers in transportation is quite common. Data is usually collected both during real flight or driving a car as well as on flight or drive simulators. Differences between studies can be found in the selection of physiological parameters studied (hearth and respiratory rate, skin conductance, temperature, electromyography, etc.), use of sensors in data collection or methods for biological signals processing [6-10]. Until now no publication has dealt with evaluation of the relationship between the upper limb activity and the piloting precision during pilot training. Since it is generally known that movements have direct impact on physiological functions such as respiratory and heart rate, the use of accelerometers in telemetric systems can provide appropriate additional data for a more accurate assessment of physiological functions in the upcoming studies. Thus, the main aim of this study is to prove or disprove the dependence of the upper limb activity in relation to the aircraft steering during various actions which are required for precise maneuvering.

Human movement as a concept cannot be merely seen as physical manifestations but it necessarily includes psychological, mechanical and especially physiological and anatomical aspects [11]. Upper limb tremor is closely related to movement activity. Physiological tremor is somewhat rhythmic, roughly sinusoidal involuntary movement of the upper limb, which is barely visible by eye. It is typical for activities requiring an extreme precision [11]. For this reason we also had to take this physiological factor which affects precision of piloting into account in assessing movement of the upper limbs.

This study may be a contribution for the field of human-machine interface as well as in the design of other systems for monitoring of training of pilots and air traffic management personnel. Improving and streamlining of training process may ultimately support aviation safety.

II. Materials and Methods

A. Participants and Measuring Procedure

Twenty subjects (17 men and 3 women) were selected for this study from among 100 applicants, both Faculty of Aeronautics TUKE students and professional pilots. Selection consisted of medical examination and passing an aviation theory and psychological test. Selected subjects can be divided into three groups: one being a group consisting of Faculty of Aeronautics students with no previous piloting experience, both in piloting an actual plane, or a flight simulator. Their professional experience was ranked as 0. This group consisted of 12 subjects. The second group as well consisted of students, pilots in training, who have experience with piloting a plane or a flight simulator, but are not yet holders of a pilot license. Their professional experience was ranked as 1, and the group consisted of 5 subjects. The final, third group contained professional pilots as subjects, who are holders of Personal Pilot License (PPL). Their professional experience was ranked as 3, and there were 3 subjects in the group.

This work will further focus on evaluation of the group of participants, who have piloting experience. The observed sample was a result of a merger of group 2 and 3, totaling 8 subjects (22±5 years). The reason for this was that during the ongoing study, instructor intervened with piloting of subjects classified as group 1. This resulted in a situation when the activity of the right arm in this sample was measured having the left arm constantly in contact with lever. Participants were informed about this fact beforehand, and other actions connected to piloting (rotation speed increase, adjusting the display etc.) were done using the right hand.

Training schedule is demonstrated in Fig. 1. Each subject completed one flight lesson every training day. Measurement was carried out during pilot training only under two flights on simulators of Type TRD40 which are located at the Faculty of Aeronautics, Technical University of Košice. Flight Simulator TRD40 is hardware and software designed for simulation of flying CESSNA 172 type of aircraft. Classical analogue way of displaying flight and navigation data was chosen. Following flights were realized using Diamond DA40 aircraft.

During a single flight, a pilot´s task was to perform 14 maneuvers altogether. Besides taking off and landing, these were straight-and-level flight (HPL), horizontal turn by 360° (360), ascend turn by 180° (S180), and descent turn by 180° (K180). These four maneuvers were repeated three times as a set. Landing took place as the last maneuver. Respective maneuvers were divided by so called Markers, which were marks inserted at the beginning and at the end of every maneuver using a custom designed software, which was a part of the measurement. Beginnings and ends of the respective maneuvers took place according to instructor´s instructions.

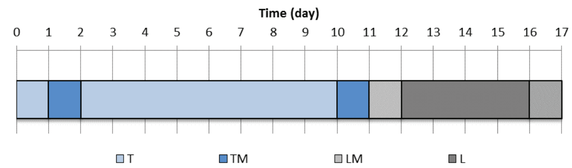

Figure 1. Training schedule demonstrating flying lessons without measurement on a simulator (T), with measurement on a simulator (TM), with measurement on aircraft (LM) and without measurement on aircraft (L)

B. Measuring Equipment

For recording movement activity of the upper limb a measurement system which included a three-axis capacitive digital MEMS (micro-electro mechanical system) accelerometer of Type MMA8452 was used. During the measurement of movement activity of the pilots´ upper limb, a range of acceleration of ±2g, sample frequency of 50 Hz was used. The output of the accelerometer was a 12 bit value.

For measuring the upper limb activity during flight, placement of sensor on the distal end of the dorsal part of left forearm was chosen, a place where a watch is normally worn. Sensor was mounted to the anatomical segment using a nylon band with Velcro fastener. Fig. 2A demonstrates the position of the accelerometer. Primary reason for this placement choice was that forearm copies manual piloting movements. Furthermore, this placement is convenient due to the fact that it does not limit the pilot in any way.

In the case of measurement during a real aircraft flight, a reference accelerometer was used in order to measure only the acceleration of a human body segment, not the entire aircraft acceleration. This reference accelerometer, output value of which in given time was always subtracted from the value indicated at the same time by the limb-mounted accelerometer, was mounted on the subject´s thorax. An advantage of this placement was also that it resulted in a certain elimination of the subject´s body.

Fig. 2B demonstrates the orientation of the accelerometer in relation to handling the lever. The used accelerometer was placed in a way that the measured activity in respective axes complied with handling the lever. The main assumption is that the activity in the x axis will describe the movements of the lever in the sagittal plane from the point of view of the pilot, and therefore its relation to the altitude change. Y and z axes activity resultant will be analogically connected to the bank.

C. Data Recording and Processing

Information on flight data during respective maneuvers of a single real aircraft flight were acquired only via the instructor. In the case of simulator flight it was one of the two possibilities of the flight data acquisition. The instructor´s task, besides instructing a pilot, was to record altitude and magnetic cursor deviations, and plane´s bank, as maximum and minimum deviations.

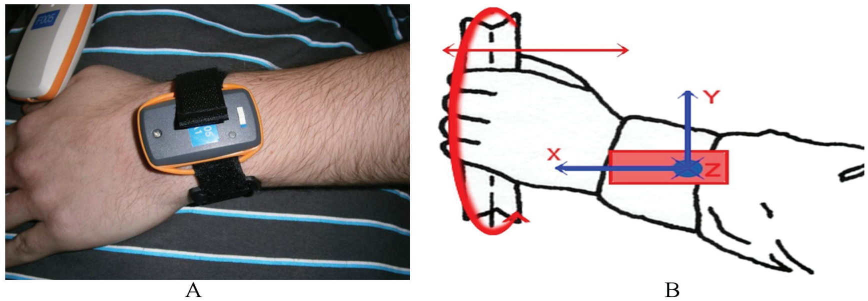

Figure 2. Placement of the accelerometer to measure the upper limb movement (A) and accelerometer orientation in relation to the arm and lever (B)

Flight data during the measurement of the upper limb activity on a flight simulator were recorded with the sampling frequency of 2.5 Hz. Between the maneuvers that had to be made during a single flight according to prescribed rules, there were periods of time which didn't belong to maneuver and were used only for leveling off the aircraft and preparing the pilot for the next maneuver. All such periods have been marked by marks and removed from the subsequent data processing. However the marks don't always label precise sections of maneuver appropriate for evaluation. To avoid errors in evaluating deviations, it was necessary to split the measured section into the next smaller phase. This splitting created pre-initiation phase, phase of maneuver and post-maneuver phase (see Fig.3). Deviations of phase maneuver were time synchronized with the data of the upper limb activities. Movement corresponding to the bank was evaluated as resultant activity of the upper limb in the y-z plane. Motion in the x-axis responded to changes in flight altitude.

HPL maneuver was evaluated according to altitude and magnetic course. It was assumed, that these parameters are constant during the entire, precisely made maneuver. Thus, we assume that the measurement of these variables, real value of which is x_s, only statistical errors (of random nature) occur. Difference between the ith measured value and the real value of the variable is "ith measurement error" [12].

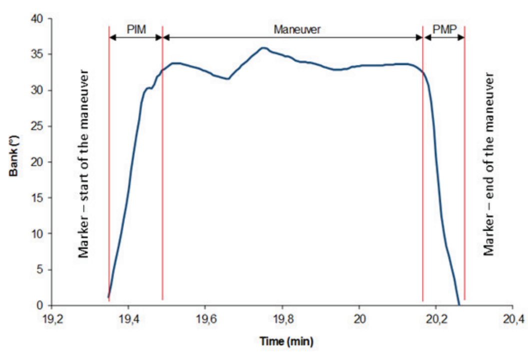

Figure 3. Splinted horizontal sweep of 360° maneuver on the next smaller phase. PIP – pre-initiation phase, PMP – post-maneuver phase

We cannot determine this error, for example in the case of magnetic course, since we do not have the "real" value of the magnetic course, which the subject was told to follow. Thanks to multiple measurement (in our case, sufficiently long measurement), we are however able to determine the presumable reference value. A number of *n* values of the measured variables (magnetic course, altitude and bank) were obtained. Using statistical method, it can be scientifically proven, that arithmetical division of an observed set of values stands for the most likely value of the measured variable (reference).

When reaching a sufficient number of measurements (values in one measurement), therefore if $n \rightarrow \infty$, the arithmetical division value is convergent with the real value of the performed maneuver. For quantitative evaluation of measurement accuracy, standard deviation is used [12]. Therefore, for the further resolving of the issues, calculation of error based on standard deviation will be used for processing flight data collected by flight simulator. Since in all cases, a set of the processed data is a selection from the realized measurement, sample standard deviation will be used, assuming a result in the form of more accurate values. On the other hand, due to large number of measured values, the difference between standard deviation and sample standard deviation disappears [12].

D. *Evaluation of relationship between the activity of upper limb and the piloting precision*

As designed recherche showed, that the issue of evaluating the development of piloting precision by observing the activity of the upper limb, or issue of similar nature, has not been described yet. Therefore this chapter will focus on designing new methodology for the analysis of the upper limb influence on piloting.

Basic hypothesis states, that upper limb movements affecting the lever, will indicate the change in the aircraft´s bank, altitude and magnetic course. This change of flight parameters ought to be in a direct relationship with the observed activity. An observation analysis implies, that an observed activity in a sequence with relatively low variability causes continual course of maneuver performance in the given sequence. Vice versa, high variability of the activity will cause a set of changes in the maneuver. On the other hand, relatively high levels of activities compared to other measured values cause actual change of the observed parameter, as opposed to low level of activities. The above mentioned implies, that even by a relatively high mean value of the activity level, piloting can be precise , as long as the activity deviation from the mean value is low. It is however also possible, that during a maneuver which requires constant rate climb or bank, in terms of precision the spread of the activity will be low compared to its mean value. When observing the upper limb activity and its influence on the maneuver performance, the main assumption is that spread (standard deviation) in the measured sequence will have a significant influence of the piloting precision. This hypothesis arises from a logical deduction relying on the fact that even if high levels of activities occur during the whole flight, piloting will not change significantly. The reason for this is, that rapid lever manipulation does not reflect in the same rapid reaction of the aircraft. In case of a one-off high level activity, flight parameter will change, which will reflect in the increase in the deviation from its mean value.

In case of evaluation, which is an objective of this work, it will be assumed that performing a constant rate maneuver by small error will indicate low deviation in the activity. To compare level of errors during performing particular flight task with activity, comparative statistical methods were used. Basic issue arising from the said methodology and hypotheses is that in case of measurements carried out using Diamond DA40 aircraft, no data on the course of the flight are available (as opposed to measurements realized on a flight simulator). It is therefore necessary to use data recorded by the instructor, which may describe necessary characteristics of piloting errors during further evaluation. For the relevance of the use of data recorded by the instructor and their subsequent use for the evaluation of flights realized using DA40 type aircraft, it was necessary to verify the relevance of these data. This issue was resolved by comparing the available data recorded by the instructor with the data obtained using a software tool, which is a part of TRD40 flight simulator. Particularly, the comparison between maximum and minimum deviations during performing maneuver directly correlate with the recorded data. All values (for all evaluated measurements) of nuances between maximums and minimums for particular flight parameters (altitude, bank, magnetic course) were taken into account for the calculation of correlations.

III. RESULTS

A. *Rusults of evauation of data recorded by the instructor*

Mean data error of data recorded by the instructor compared to measured data was also calculated. The calculated correlation for bank deviations is C_n=0.96 and mean error in the instructor´s records is Ch_n=±0.51°. Fig 4 represents a graph of correlation of maximum and minimum bank deviations nuances.

Correlation for the relationship between the instructor´s and flight simulator´s data is $C_H=0.96$ and error in instructor´s determination of maximum and minimum deviation nuance is CH_H =±13.33 *(ft)*. This error shows as statistically insignificant. Fig.5 represents a graph of correlation of maximum and minimum altitude nuances.

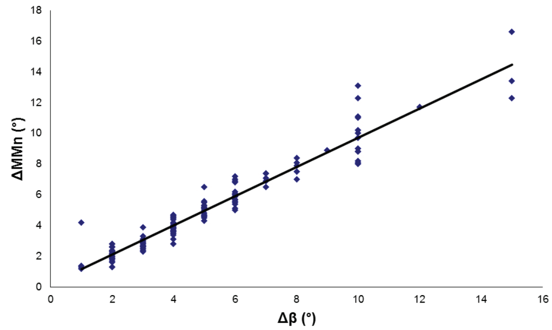

Figure 4. Relationship between maximum and minimum deviation nuance in bank based on the instructor´s data (Δβ) and flight simulator (ΔMMn)

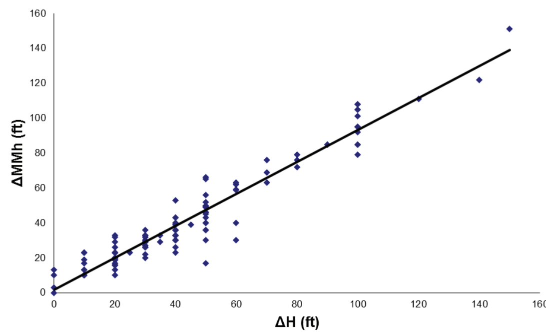

Figure 5. Relationship between maximum and minimum deviation nuance in altitude based on the instructor´s data (ΔH) and flight simulator (ΔMMh)

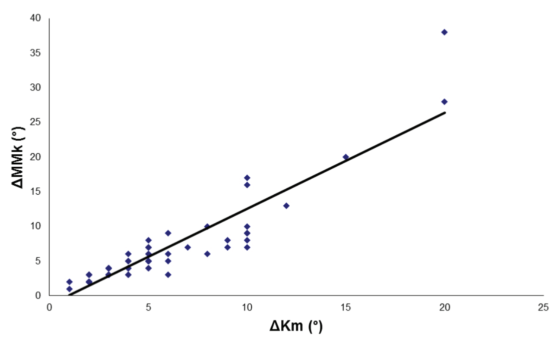

Figure 6. Relationship between maximum and minimum deviation nuance in magnetic course based on the instructor´s data (ΔKm) and flight simulator (ΔMMk)

In the case of evaluation of the relationship between maximum and minimum magnetic course values nuances for the two types of recorded data, correlation coefficient is $C_{km}=9.16$, and instructor´s mean error in deviations record is CH_{Km}=±1.36 (°). Fig.6 represents a graph of correlation of maximum and minimum magnetic course nuances.

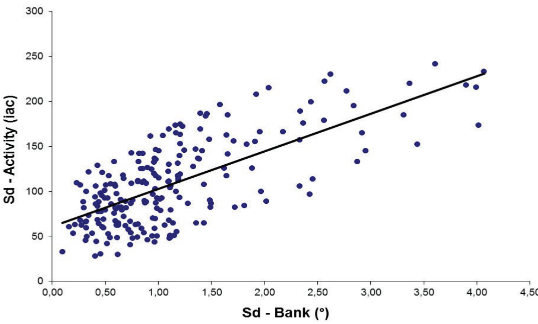

Figure 7. Relationship between activity standard deviation and bank standard deviations

Besides the interpreted findings, it was also found that the standard deviation of the observed bank parameters is also related to the instructor´s records, in this case the correlation coefficient is C_{nsd}=0.84. A relation was also found between other parameters. Table I demonstrates results of significant correlation coefficients which are significantly different from 0 based on spearman´s coefficient and statistic.

The table shows correlation coefficients results for mutual relationship between nuances recorded by the instructor (Δβ, ΔKm, ΔH), maximum and minimum nuance (dMM) and standard deviation. Correlation coefficients were calculated for the observed maneuver for all subjects including all measurements with given parameter.

Based on the above results, it can be said that values recorded by the instructor are relevant for the evaluation of errors in piloting, and therefore can be used in further evaluation.

B. Comparation of upper limb activity and flight parameters

Resultant activity standard deviation relation correlation coefficient on the *z* and *y* axes is C_{yz-n}=0.7. Fig.7 demonstrates graphic representation of the result of this relationship.

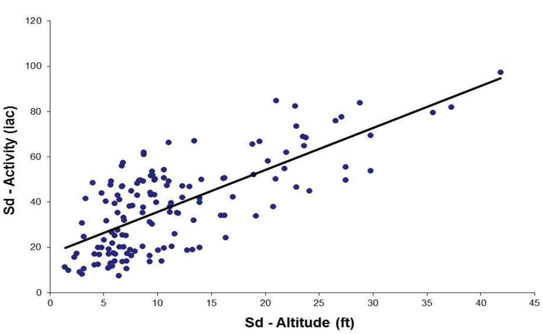

Figure 8. Relationship between activity standard deviation and altitude standard deviations

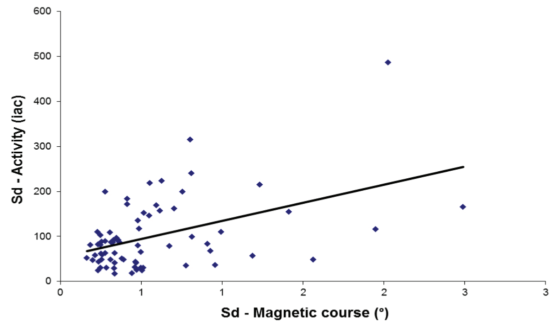

Figure 9. Relationship between activity standard deviation and magnetic course standard deviation

The relation between the altitude mean value and the upper limb activity was observed similarly to the case of bank. Movement of the upper limb in the x axis (sagittal) was observed. The resulting correlation, just as in the previous case, is statistically different from 0 and its value is C_{yz-h}=0.72. Fig.8 demonstrates the relationship between these two variables.

In the case of observing activity and its influence on magnetic course, we proceeded from the observation of the upper limb movement resultant in *z* and *y* axes. Correlation coefficient is C_{yz-Km}=0.46 and is not statistically different from 0. Fig.9 represents the graph of the observed relationship.

IV. DISCUSSION

The objective was to determine the extent of correlation of these two variables. Data recorded from every subject and for every maneuver was used for this analysis, just as in the previous chapter. The results show, that the stated hypothesis can be proven. The correlation coefficient proved relationship between the upper limb movement and aircraft steering both at bank and altitude. It testifies that change of bank and altitude of aircraft is directly connected with upper limb movements. Based on the stated hypothesis it is assumed, that standard deviation of an activity will be in a direct relationship with flight parameter standard deviation.

Rebuttal of hypothesis in the case of monitoring of upper limb activity in the y and z axes and its effect on the magnetic course is most probably attributable to the fact that magnetic course does not depend solely on the bank but also on the speed and impact of the wind and also on bank angle in the longitudinal and transverse axes of the aircraft [13].

Due to the fact that no publication has dealt with the relationship between the activity of upper limb and the piloting precision yet, we are not able to comprehensively conclude on this issue. Additional comparative study would be appropriate in order to answer questions that have been yielded by this work.

TABLE I. CORRELATION RELATIONSHIP BETWEEN VALUES RECORDED BY THE INSTRUCTOR AND VALUES OBTAINED BY FLIGHT SIMULATOR

Correlation coefficients for bank parameters

	dMMn	sd	Δβ
dMMn	-	0,820977	0,965844
sd	0,820977	-	0,839123
Δβ	0,965844	0,839123	-

Correlation coefficients for magnetic course parameters

	dMMk	sd	ΔKm
dMMk	-	0,946638	0,916068
sd	0,946638	-	0,936923
ΔKm	0,916068	0,936923	-

Correlation coefficients for altitude parameters

	dMMh	sd	ΔH
dMMh	-	0,906191	0,962594
sd	0,906191	-	0,931938
ΔH	0,962594	0,931938	-

V. CONCLUSION

This study was a pilot study in the field of evaluation of relationship, i.e. correlation, between the upper limb activity and precision of piloting during training process. As shown, no one before us determine the correlation of trained pilots by using newly designed method based on accelerometers. Practical use of new telemetry systems with automatic software evaluation may provide a contribution to evaluation of human – machine interface. Acquired knowledge may be applied during the process of training of pilots directly in the aircraft. Flight simulator can easily determine piloting inaccuracies using integrated software, however when flying on an aircraft, direct access to the data is not possible. Therefore, another application of the knowledge in the future may be possible in the process of programming of applications capable of immediate evaluation of piloting accuracy during flights in the aircraft.

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D Článok 4

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Basic Piloting Technique Error Rate as an Indicator of Flight Simulators Usability for Pilot Training

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Abstract – *Flight simulator utilization for basic types of pilot training is restricted by regulations. Flight simulators could contribute to improvements of training quality, especially for initial training to obtain pilot license and, last but not least, to increase flight safety. The goal of this study was to evaluate flight simulator usability for basic piloting technique training. For this purpose, piloting error rate for 35 subjects was evaluated. Within prescribed, continuous flight simulator training consisting of 11 flight hours, progress in piloting precision was monitored during four different manoeuvers. The paper further evaluates influence of the transition between simulated and real flights with regard to progress or regress of executed manoeuvers precision. The results indicate, that during basic pilot techniques training on flight simulator, continuous and statistically significant decrease of error rate during standard manoeuvers execution is achieved. For acquisition of the habits related to mastering basic piloting techniques, the current possibility to use 5 training hours on flight simulator is insufficient. Habits acquisition is noticeable first during 11th flight simulator hour. The study also indicates that the acquired flight simulator habits related to piloting precision applying basic piloting techniques are not observable during the transition to real flights.*

***Keywords**: Flight Simulator, Piloting Error, Piloting Technique, Pilot Training, Safety*

Nomenclature

BITD	Basic instrument training device
CPL	Commercial pilot license
DA40	four-seat, single engine, light aircraft Diamond DA40 Diamond Star developed by Diamond Aircraft Industries
FNTP	Flight navigation and procedures trainer device
IFR	Instrument flight rules
PPL	Personal pilot license
TRD40	Product name of simulator used in study
ULL	Ultralight pilot license
S2M	Measurement performed during simulated flight in 2nd training hour
S6M	Measurement performed during simulated flight in 6th training hour
S11M	Measurement performed during simulated flight in 11th training hour
A12M	Measurement performed during real flight in 12th training hour
A17M	Measurement performed during real flight in 17th training hour
SLF	Steady level flight or straight and level flight
H360	Horizontal 360° turn with bank angle of 30°
C180	180° climb turn with the prescribed vertical speed of 500 ft/min and bank angle of 15°
D180	180° descend turn with the prescribed vertical speed of 500 ft/min and bank angle of 15°
B	Bank angle
H	Height
MC	Magnetic course
VS	Vertical speed

I. Introduction

Air traffic development puts an emphasis on continuous improvements in the domain of safety. Introducing new technologies implies increased demands on theoretical and practical aircraft operation skills including the demands on a crew itself. Studies dealing with aviation accidents claim human factor as one of the most frequently contributing factors [1]. Human factor occurs when piloting skills of a crew are insufficient or when a pilot is surprised by adverse situation to which he or she reacted inadequately [2]. Even though the results are different, it is unambiguous that human factor contributes to 70 up to 85% of aviation accidents [3], [4].

The most frequent human errors are related to human skills (up to 80 % of human errors). Half of these errors contribute to chain of events leading to an incident [5].

The main role in reducing the human factor regarding pilots plays the pilot training, education, skills and emergency training of situations which may occur during a flight[6]-[8]. The training itself and preparation for unexpected events in the operations may considerably increase the amount of successfully handled non-standard occurrences in the aviation.

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To date, flight simulators became one of the important elements of pilot training. Owing to their rapid development, pilots can be partly trained and examined on these devices. Also, international standards and regulations reflect this development and so they specify requirements for their operational utilization [9]. Pertaining modular courses, it is possible to fly 5 hours without instrument flight rules (IFR) with Basic Instrument Training Devices (BITD) or Flight Navigation and Procedures Trainer devices (FNPT) during a personal pilot license (PPL) or commercial pilot license (CPL) pilot training. During an IFR (single engine) training it is possible to fly 20 hours with FNPT I or up to 35 hours with FNPT II. In case of a multi-engine IFR training, it is possible to conduct 25 hours with FNPT I and 40 hours with FNPT II.

Certified flight simulators can be utilized during pilot training for specific flight tasks but also for pilot examination (see [10]). Incorporating flight simulators into pilot training undoubtedly contributed to reducing risks and improving the quality of training which leads to increased flight safety [11], [12] and partial reduction of training and aircraft operational costs [11].

Pilots on visual flight rules (VFR) course, i.e. trainees for PPL and ultralight pilot license (ULL) qualification, are trained mostly in real operations. In majority of flight schools, training syllabus does not include flight simulator lessons or it is very limited. During this type of course, trainee's capabilities, experience, skills and habits are assessed. Training isconsidered as finished if the minimum requirements are satisfied and the trainee is ready to prove his ability to fly as a pilot-in-command, perform procedures and manoeuvers corresponding to the requirements of PPL license and also prove the capability of flying an aircraft with respect to its limits, perform all manoeuvers smoothly and precisely, demonstrate good judgment and developed sense for flight, apply theoretical knowledge in practice and control an aircraft so that there are no serious doubts about how manoeuvers or procedures are executed.

Following the requirements, it is necessary to objectively monitor and evaluate training progress during this type of course. Generally, PPL (or ULL) training is based on successfully passing theoretical preparation comprised of flight rules, aircraft technical knowledge, flight planning and execution, meteorology, navigation, operational procedures, flight basics etc.

The most important, however, is mastering of basic piloting techniques. For the purpose of a training oriented to mastering the techniques correctly, flight simulators could contribute to improved training quality and eventually also to flight safety. Therefore, it is important to focus on specific options for implementing flight simulators into PPL or ULL training and determine, whether the need to extend such training could be justified with regard to the existing regulations and standards. However, there are no studies regarding optimal utilization of flight simulators for this purpose.

Most of the existing studies are focused on military aviation in this domain [13]-[15].

In these cases, unfortunately, overall training process evaluation, where flight simulators are utilized, is missing. Moreover, available studies are mostly concerned with simulator assessment, based on skills evaluation of pilots which are or were holders or a valid pilot license (see [16]-[19]).

With regard to the above-mentioned issues, this article deals with evaluation of pilot training with utilization of flight simulator where the main emphasis is put on basic piloting techniques. The goal of this study is to evaluate usability of flight simulator for a training of basic piloting techniques by the means of evaluating error rate during an execution of basic prescribed manoeuvers by trainees beginning the course. Another goal is to evaluate the influence of the transition between simulated and real flights with regard to progress or regress in the precision of executed manoeuvers. This way, usability of flight simulators during initial training can be assessed.

II. Materials and Methods

II.1. Participants

For the purposes of this study, a selection of students from the Faculty of Aeronautics, Technical University of Košice, Slovakia, was conducted.

The goal was to select representative sample of subjects, consisting of beginners with the highest uniformity possible. The selection was conditioned by some criteria consisting by successfully passing psychological and intelligence tests. Intelligence tests were aimed at aviation regulations and flight basics.

Apart from that, participants had to meet the requirements for medical fitness in line with Commission Regulation (EU) No 1178/2011- Annex IV [10] and could not be holders of a pilot license (ULL, PPL or higher). This way, 35 subjects were selected (27 men and 8 women with an average age of 23±4 years), which met the mentioned requirements.

II.2. Training Schedule

All participants underwent common theoretical preparation in the extent of 2 hours, which was focused on acquainting the subjects with pilot cabin ergonomics, control elements arrangement, their purpose and use during flight. Practical training was conducted according to the methodology depicted on Fig. 1. The schedule consisted of 14 simulated flights on TRD40 flight simulator and 3 real flights on Diamond DA40 aircraft.

The group of subjects went through flight simulator training (11 hours) which was followed by first real flight (1 flight hour) and then again 3 flight simulator hours.

The training was finished by 2 hours of real flying.

The interval between individual training hours did not exceed 2 days. During all flights, analogous projection of flight, navigation and engine readings was used in the aircraft (simulator) flight deck.

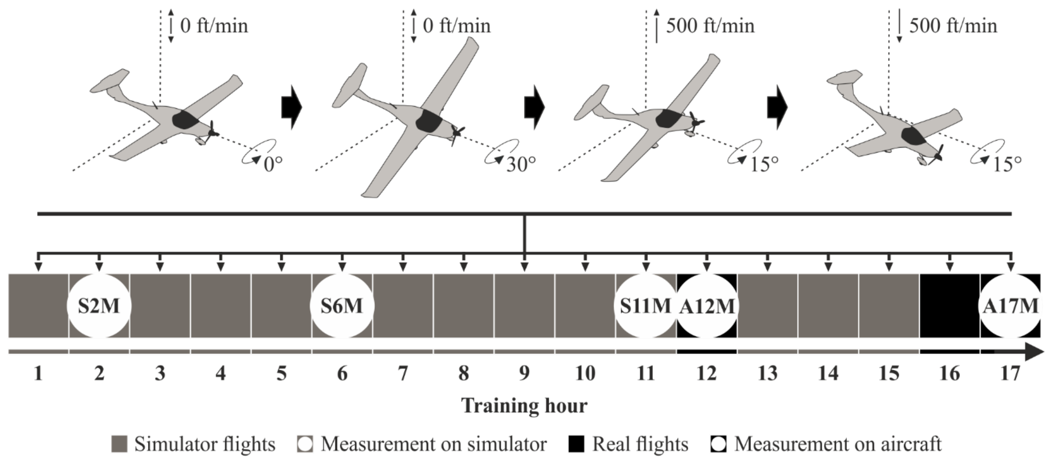

Fig. 1. Concept of the training process showing intervals of piloting precision measurements

All flights were performed under uniform meteorological conditions with few or no clouds and visibility of ground. Both real and simulated flights were performed in the terminal manoeuvring area of Košice International Airport (ICAO code: LZKZ).

During all flights, the subjects had to execute precisely defined flight actions to maintain required flight parameters during steady level flight (SLF), horizontal 360° (H360) turn with bank angle of 30°, climb or descend 180° (C/D180) turn with bank angle of 15° and vertical speed of 500 ft/min.

The sequence of manoeuvers was strictly followed and individual manoeuver series were repeated three times a flight. Apart from take-off and landing, three series of manoeuvers were executed, namely in the sequence SLF, H360, C180 and D180 (Fig. 1) what assured the uniformity of training and measurements.

II.3. Measurements and Data Analysis

For the purpose of this study, the main emphasis was put on evaluation of piloting precision during prescribed flight tasks. Each manoeuver was prescribed in terms of flight parameters or rules, about which the subjects were informed during theoretical preparation. Concerning the SLF manoeuver, the most important was to maintain constant altitude whilst the altitude itself (its value) was not important. Further, it was important to maintain constant magnetic heading where the heading itself was also not important. In case of the H360 manoeuver, pilots had to perform horizontal turn whilst the bank angle had to be constant at the level of 30° and simultaneously constant altitude had to be maintained.

During C180 or D180 manoeuvers, the subjects performed climb or descend turn of prescribed vertical speed 500 ft/min and bank angle of 15°. With respect to the nature of the training, two data sets were available for processing of piloting precision, namely instructor records of error rate during individual executed manoeuvers and flight records acquired from simulator flight recorder. Pertaining real flights, it was not possible to obtain data from flight recorder. Due to this, it was necessary to compare the evaluation of piloting precision by the means of processing data obtained from instructor and subsequently to evaluate the relevance and accuracy of executed manoeuver error prediction by the instructor with comparative methods.

If the hypothesis of sufficient correlation between two piloting precision errors (instructor - flight simulator) can be confirmed, it is possible to evaluate piloting error rate based on notes from instructor. This concept of assessing evaluation relevance concerning piloting error rate was performed in the previous study (see [20]).

The evaluation methodology in this study was based on the assumption that in case of achieving sufficient amount of records (with the simulator data recorder) of given flight parameter ($n \rightarrow \infty$), the arithmetic average of the monitored flight parameter will be approaching actual prescribed value. It is then possible to quantify error rate by calculating standard deviation. In the mentioned study, deviations recorded by instructor were additionally used in form of maximum deviation from prescribed flight parameters (altitude, bank angle, vertical speed etc.), which the subject was supposed to maintain.

Instructor noted the errors to checksheets in form of maximum deviations from prescribed flight parameters during execution of individual monitored manoeuvers.

It was possible to interpret individual notes as X^{+PE}_{-ME}, where X is prescribed flight parameter value (altitude, bank angle, vertical speed and magnetic heading), $PE$is the maximum plus error and ME the minimum minus error. The total error Δ for particular parameter would then follow the formula:

$$\Delta = PE - ME \quad (1)$$

From the equation it is apparent that it describes an error which specifies variance of values between maximum and minimum deviation.

The nature of recording the error rate did not allow other forms of piloting precision evaluation. In the above-mentioned study, piloting precision evaluation was compared with calculated deviations.

The authors used the same data as in this study. The results of analysis pointed that error rates calculated and evaluated by instructor are mutually correlated and so it is possible to use only instructor's notes for further evaluation. For details of the results see [20].

The evaluated piloting technique error rate was based on Eq. (1). Data characterised by Δ were divided into datasets, which described piloting error rate for all subjects during SLF execution (error rate of maintaining magnetic heading and constant altitude), H360 (error rate of maintaining prescribed bank angle of 30° and constant altitude) and C180 and/or D180 (error rate of maintaining prescribed bank angle of 15° and prescribed vertical speed of 500 ft/min).

With regard to the fact that manoeuver series were executed three times, mentioned datasets contain data describing error from all executed manoeuvers.

The datasets were subsequently separated and put into corresponding phase of conducted training (or more precisely assigned to corresponding measurement).

It means that all data from observed error rate of specific flight parameter for given manoeuver were assigned to S2M, S6M, S11M, A12M and A17M. Data distributed in this way were subjected to statistical analysis.

II.4. Statistical Analysis

For statistical evaluation of mutual differences between individual measurements, non-parametric Mann-Whitney U test was used [21]. The selection of non-parametric testing was conditioned by testing of normal distribution. For this purpose, Jarque-Bera test was used [22], which tested the hypothesis that data from observed vector (in this case S2M, S6M, etc.) originate from normal distribution. The testing was done with 5% level of significance and it was possible to conclude the hypothesis that the data do not originate from normal distribution with $p < 0.05$. Normal distribution was not proved for all monitored datasets what led to the utilization of non-parametric testing for inter-group differences. By the means of Mann-Whitney U test, it was tested whether two monitored populations originate from distribution with equal mean to identify inter-group differences.

The testing was done with level of significance $p = 0.05$ whilst the hypothesis of significant inter-group differences concerning means was concluded with $p < 0.05$. The testing was conducted for mutual comparison of all performed measurements regarding error rate of characteristic flight parameter during specific manoeuever. Data interpretation was done with the help of box plots where each box plot specifies error rate distribution during particular flight parameter execution and during specific training phase.

Each box plot contains in essence all values of calculated errors for all subjects where its horizontal lines represent (from the bottom) minimum, first quartile, mean, second quartile and maximum of monitored dataset. In individual box plots, values considered as outliers were market as extremes which were clearly separated from the rest of the data. Values marked as outliers met the following condition:

$$Q1 - 1.5\,IQR > X_{out} > Q3 - 1.5\,IQR \tag{2}$$

where $Q1$ is first quartile, $Q3$ is third quartile, IQR is inter-quartile span calculated as $Q3 - Q1$ and X_{out} is the value being clearly out of the monitored dataset [23].

For statistical analysis and the above-described calculations, Matlab environment (MATLAB R2013a, MathWorks, Inc., Natick, MA, USA) was used.

III. Results

The results are presented in the form of graph and sheet pairs which represent statistical evaluation and error rate distribution of monitored flight parameter.

P-values in presented sheets constitute Wilcoxon signed-rank test results where $p < 0.05$ points out statistically significant difference among two groups of measurements. Statistical evaluation of piloting precision regarding maintaining of magnetic heading during steady level flight revealed significant differences among all measurements except between S2M and A17M measurements (see Table I). During first measured flight hour, error rate median for given flight parameter was on the level of 5°.

During second measurement, error rate median considerably decreased to the level of 1.75°. During 11th flight hour on the flight simulator (S11M), median of monitored flight parameter error rate decreased ones more to the level of 1° of the deviation from prescribed magnetic heading.

TABLE I

THE RESULTS OF MANN–WHITNEY U TEST FOR PILOTING PRECISION EVALUATION CONCERNING MAINTAINING PRESCRIBED VALUES OF MAGNETIC HEADING AND ALTITUDE DURING HORIZONTAL STEADY LEVEL FLIGHT

	Magnetic course					Height				
	S2M	S6M	S11M	A12M	A17M	S2M	S6M	S11M	A12M	A17M
S2M	-	$1.65\ 10^{-07}$	$3.34\ 10^{-18}$	$1.86\ 10^{-09}$	0.08	-	$1.60\ 10^{-04}$	$1.92\ 10^{-13}$	$3.32\ 10^{-04}$	0.92
S6M	$1.65\ 10^{-07}$	-	0.05	$4.48\ 10^{-13}$	$2.38\ 10^{-05}$	$1.60\ 10^{-04}$	-	0.03	$7.31\ 10^{-01}$	$8.71\ 10^{-04}$
S11M	$3.34\ 10^{-18}$	0.05	-	$3.17\ 10^{-23}$	$5.47\ 10^{-12}$	$1.92\ 10^{-13}$	0.03	-	$2.23\ 10^{-23}$	$2.03\ 10^{-10}$
A12M	$1.86\ 10^{-09}$	$4.48\ 10^{-13}$	$3.17\ 10^{-23}$	-	$8.92\ 10^{-12}$	$3.32\ 10^{-04}$	$7.31\ 10^{-01}$	$2.23\ 10^{-23}$	-	$4.48\ 10^{-03}$
A17M	0.08	$2.38\ 10^{-05}$	$5.47\ 10^{-12}$	$8.92\ 10^{-12}$	-	0.92	$8.71\ 10^{-04}$	$2.03\ 10^{-10}$	$4.48\ 10^{-03}$	-

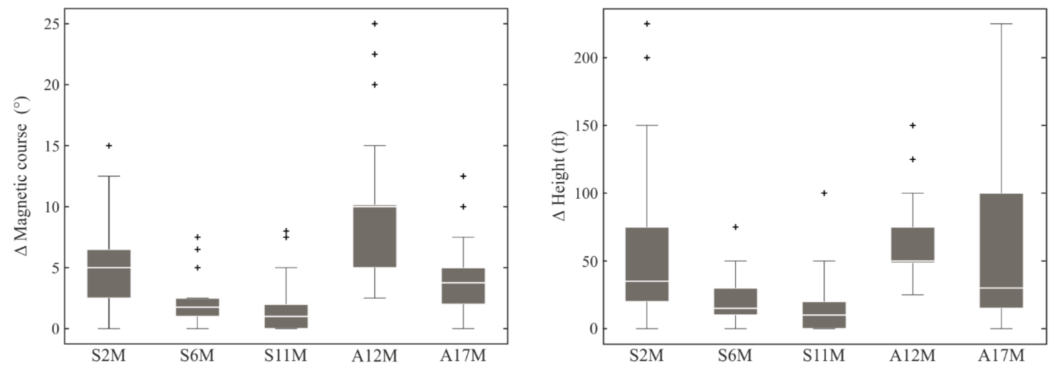

Fig. 2. Graphical depiction of recorded error rate distribution concerning the deviation from prescribed magnetic heading and altitude for horizontal steady level flight

TABLE II
THE RESULTS OF MANN–WHITNEY U TEST FOR PILOTING PRECISION EVALUATION CONCERNING MAINTAINING PRESCRIBED VALUES OF BANK ANGLE AND ALTITUDE DURING HORIZONTAL 360° TURN

	Magnetic course					Height				
	S2M	S6M	S11M	A12M	A17M	S2M	S6M	S11M	A12M	A17M
S2M	-	$1.54\ 10^{-10}$	$9.10\ 10^{-18}$	0.09	0.13	-	$1.13\ 10^{-07}$	$1.88\ 10^{-16}$	0.90	0.41
S6M	$1.54\ 10^{-10}$	-	0.39	$2.29\ 10^{-10}$	$1.69\ 10^{-09}$	$1.13\ 10^{-07}$	-	0.17	$1.36\ 10^{-10}$	$3.07\ 10^{-05}$
S11M	$9.10\ 10^{-18}$	0.39	-	$2.70\ 10^{-15}$	$9.92\ 10^{-15}$	$1.88\ 10^{-16}$	0.17	-	$4.31\ 10^{-18}$	$3.91\ 10^{-11}$
A12M	0.09	$2.29\ 10^{-10}$	$2.70\ 10^{-15}$	-	0.96	0.90	$1.36\ 10^{-10}$	$4.31\ 10^{-18}$	-	0.21
A17M	0.13	$1.69\ 10^{-09}$	$9.92\ 10^{-15}$	0.96	-	0.41	$3.07\ 10^{-05}$	$3.91\ 10^{-11}$	0.21	-

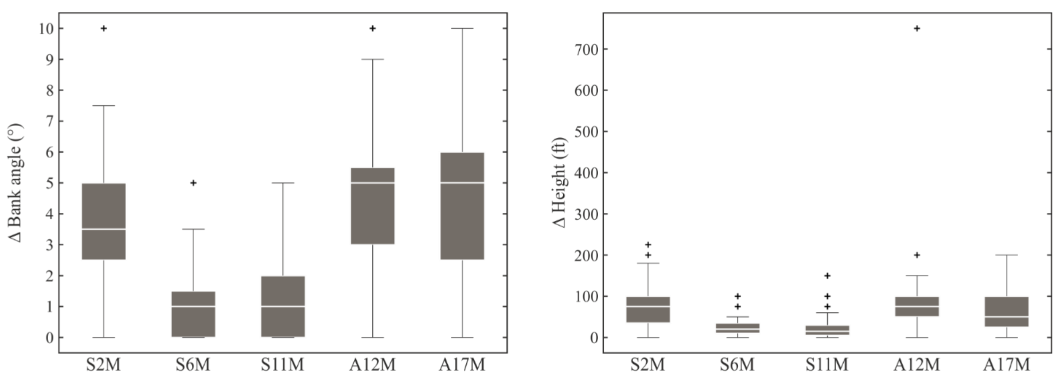

Fig. 3. Graphical depiction of recorded error rate distribution concerning prescribed bank angle and altitude for horizontal 360 turn

The decrease is statistically significant in comparison with previous measurements (S2M and S11M).

Monitoring of piloting precision during first real flight (A12M) revealed significant increase in the error rate where its median concerning deviation from prescribed magnetic heading increased up to 10°. A12M measurement indicates statistically significant difference when compared with the rest of the measurements.

During the last measurement (A17M), statistically significant decrease of median in comparison with A12M was achieved up to the level of 3.75°. It can be noted that between second real flight (A17M) and first flight simulator flight there is no statistically significant difference in the error rate and so has the error rate stabilized on the level of S2M measurement. Graphical presentation of the results and the progress of recorded error rate development is depicted on Fig. 2.

Statistical evaluation of piloting precision concerning maintaining of required altitude during steady level flight revealed significant differences among all measurements except between S2M and A17M measurements (see Table I). Error rate median for maintaining constant altitude during S2M reached the value of 35ft. The error rate then considerably decreased to the level of 15ft during S6M. During S11M, error rate median of 10ft was recorded where this difference is statistically significant compared to previous measurements.

During the first real flight execution (A12M), considerable increase of error rate median pertaining monitored flight parameter (med=50ft) was achieved compared to all the previous measurements.

During A17M, statistically significant decrease in error rate median (med=30ft) was achieved in comparison to A12M.

The difference in error rate recorded during S2M and A17M is not statistically significant and so it is possible to conclude that the error rate during A17M was stabilized on the level of S2M. Graphical presentation of the results and the progress of recorded error rate development is depicted on Fig. 2.

Statistical evaluation of piloting precision concerning maintaining 30° bank angle did not reveal any statistically significant differences between S2M and A12M, S6M and S11M, A12M and A17M measurements (Table II). P-values from Wilcoxon signed-rank test results are in these cases greater than selected level of significance $p = 0.05$. It means that the error rate decreased during S2M and S6M measurements (from 3.5° to 1°) and then it stabilized so that the error rate recorded during S11M measurement is similar to the S6M measurement. Median of error rate for bank angle remains for S6M and S11M the same, i.e. 1°. It can be noted that the error rate exhibited by subjects during S11M measurement is still considerably lower than for the first measurement. Median of error rate increased to the level of 5° during A12M but no significant difference between this and S2M measurement was identified.

Therefore, it is possible to come to a conclusion that the error rate during the first real flight achieved the level from first contact with the flight simulator (S2M).

The error rate did not change even after the next real flight execution (A17M) and so it remained the same as for A12M (med=5°). Graphical presentation of the results and the progress of recorded error rate development is depicted on Fig. 3.

Statistical evaluation of piloting precision with regard to maintaining prescribed altitude during horizontal turn revealed no statistically significant differences among S2M and A12M, S2M and A17M, S6M and S11M, A12M and A17M measurements (Table II). The progress can be interpreted in the same way as in the previous example. Initial median of error rate for S2M measurement was on the level of 75ft which indicates statistically significant difference from S6M (med=20ft).

Between S2M and S6M measurements, statistically significant decrease in error rate was recorded. Subsequently, S11M measurement indicated another decrease in error rate compared to previous measurements, namely to the value of 11ft.

The decrease during S11M compared to S6M is, however, not statistically significant. During the first real flight, error rate increased to 75ft, i.e. to the level of S2M. Subsequently, A17M measurement indicated decrease in error rate to 50ft but this decrease is not statistically significant compared to A12M. Significant difference was also not confirmed in case of A17M comparison with S2M. Graphical presentation of the results and the progress of recorded error rate development is depicted on Fig. 3.

Statistical evaluation of piloting precision concerning 15° bank angle during 180° climbing turn revealed significant differences between all measurements, except between S2M and A17M, S6M and S11M measurements (see Table III). Graphical presentation of the results and the progress of recorded error development is depicted on Fig. 4. Error rate decreased between S2M and S6M measurements from 3° to 2.5°. Median value decreased between S6M and S11M (from 2.5° to 1.75°), however, this decrease was not statistically significant with regard to the data distribution in these groups, so it can be concluded that the error rate remained the same for S6M and S11M measurements.

TABLE III
THE RESULTS OF MANN–WHITNEY U TEST FOR PILOTING PRECISION EVALUATION CONCERNING MAINTAINING PRESCRIBED VALUES OF BANK ANGLE AND VERTICAL SPEED DURING 180° CLIMB TURN

	Magnetic course					Height				
	S2M	S6M	S11M	A12M	A17M	S2M	S6M	S11M	A12M	A17M
S2M	-	$3.09\ 10^{-07}$	$1.04\ 10^{-14}$	$1.87\ 10^{-03}$	0.93	-	$7.92\ 10^{-04}$	$4.26\ 10^{-13}$	$1.72\ 10^{-03}$	0.02
S6M	$3.09\ 10^{-07}$	-	0.41	$2.21\ 10^{-09}$	$6.47\ 10^{-06}$	$7.92\ 10^{-04}$	-	$3.38\ 10^{-04}$	$3.98\ 10^{-09}$	0.16
S11M	$1.04\ 10^{-14}$	0.41	-	$5.97\ 10^{-17}$	$1.20\ 10^{-11}$	$4.26\ 10^{-13}$	$3.38\ 10^{-04}$	-	$2.49\ 10^{-20}$	$5.52\ 10^{-06}$
A12M	$1.87\ 10^{-03}$	$2.21\ 10^{-09}$	$5.97\ 10^{-17}$	-	$4.08\ 10^{-03}$	$1.72\ 10^{-03}$	$3.98\ 10^{-09}$	$2.49\ 10^{-20}$	-	$8.24\ 10^{-07}$
A17M	0.93	$6.47\ 10^{-06}$	$1.20\ 10^{-11}$	$4.08\ 10^{-03}$	-	0.02	0.16	$5.52\ 10^{-06}$	$8.24\ 10^{-07}$	-

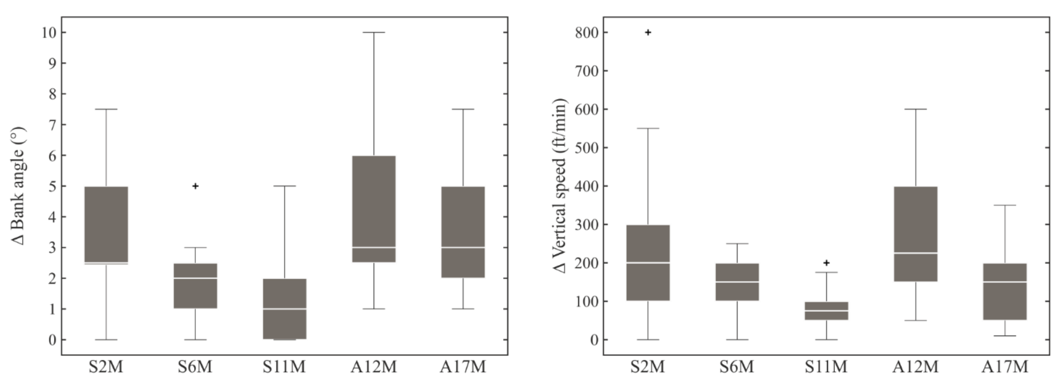

Fig. 4. Graphical depiction of recorded error rate distribution concerning prescribed bank angle and vertical speed for 180° climb turn

Error rates increased considerably during first real flight A12M (med=4.75°) compared to previous measurements. During the last measured flight (A17M), significant decrease in median of error rate compared to A12M was recorded and the achieved level was 3°.

Furthermore, it is possible to notice that between A17M and S2M there is no statistically significant difference and so it is possible to conclude that the error rate during the last executed real flight decreased to the level of first simulated flight. Statistical evaluation of piloting precision with regard to maintaining prescribed vertical speed at the level of 500 ft/min during a climbing turn identified significant differences between all measurements except between S6M and A17M (see Table III). Graphical presentation of the results and progress of recorded error development is depicted on Fig. 4. The error rate decreased between S2M and S6M so that median value decreased from 160 ft/min to 100 ft/min. Another decrease in the error rate median value from 100 ft/min to 70 ft/min was identified between S6M and S11M. Significant increase in the error rate was observed during first real flight A12M (med=240 ft/min) followed by a decrease during second real flight A17M (med=110 ft/min) to the level achieved during S6M.

Statistical evaluation of piloting precision concerning 15° bank angle during 180° descend turn indicated significant differences among all measurements except between A12M and A17M, S2M and A17M measurements (see Table IV). Calculated p-values from Wilcoxon signed-rank test were greater than the selected level of significance $p = 0.05$. Error rate progressively decreased during the training process on the flight simulator. The error rate median decreased from 2.5° to 2° compared to S2M and S6M measurements and it continued to decrease further up to the level of 1° achieved during S11M.

First real flight measurement on the DA40 aircraft indicated significant increase in error rate compared to earlier measurements (med=3°), achieving the results of S2M measurement. For the following real flight (A17M), the error rate preserved the level of 3°, i.e. no significant difference was identified between A17M and A12M measurements. Fig. 5 shows the results and the progress of recorded error rate development. Statistical evaluation of the piloting precision regarding maintaining vertical speed at the level of 500 ft/min during a descending turn, significant differences were identified between all measurements except between S6M and A17M (see Table IV). Graphical representation of the results and the progress of recorded error rate indicated development similar to previous cases as depicted on Fig. 5.

In this case, median of vertical speed error rate decreases significantly when compared to S2M (med=200 ft/min) and S6M (med=150 ft/min) measurements. Decrease in error rate was identified also between S6M and S11M (from 150 ft/min to 80 ft/min) measurements. During first real flight A12M, significant increase in error rate median value was achieved, namely 220 ft/min.

During the final stage of the training, the median decreased to 170 ft/min which is statistically similar to S6M, while $p \approx 1$. For overview of the error rate progress during given training, all above-mentioned courses were normalized. Normalized courses were achieved based on the development of median values of error rates for given manoeuver and were calculated to a single scale with regard to the maximum value from given dataset

TABLE IV
THE RESULTS OF MANN–WHITNEY U TEST FOR PILOTING PRECISION EVALUATION CONCERNING MAINTAINING PRESCRIBED VALUES OF BANK ANGLE AND VERTICAL SPEED DURING 180° DESCEND TURN

	Magnetic course					Height				
	S2M	S6M	S11M	A12M	A17M	S2M	S6M	S11M	A12M	A17M
S2M	-	$4.47\ 10^{-08}$	$4.63\ 10^{-18}$	0.02	0.35	-	0.03	$2.13\ 10^{-11}$	$9.65\ 10^{-03}$	$9.01\ 10^{-03}$
S6M	$4.47\ 10^{-08}$	-	0.04	$9.17\ 10^{-08}$	$3.36\ 10^{-08}$	0.03	-	$1.78\ 10^{-06}$	$7.47\ 10^{-05}$	1.00
S11M	$4.63\ 10^{-18}$	0.04	-	$2.09\ 10^{-17}$	$1.85\ 10^{-15}$	$2.13\ 10^{-11}$	$1.78\ 10^{-06}$	-	$7.21\ 10^{-19}$	$1.16\ 10^{-04}$
A12M	0.02	$9.17\ 10^{-08}$	$2.09\ 10^{-17}$	-	0.21	$9.65\ 10^{-03}$	$7.47\ 10^{-05}$	$7.21\ 10^{-19}$	-	$3.06\ 10^{-06}$
A17M	0.35	$3.36\ 10^{-08}$	$1.85\ 10^{-15}$	0.21	-	$9.01\ 10^{-03}$	1.00	$1.16\ 10^{-04}$	$3.06\ 10^{-06}$	-

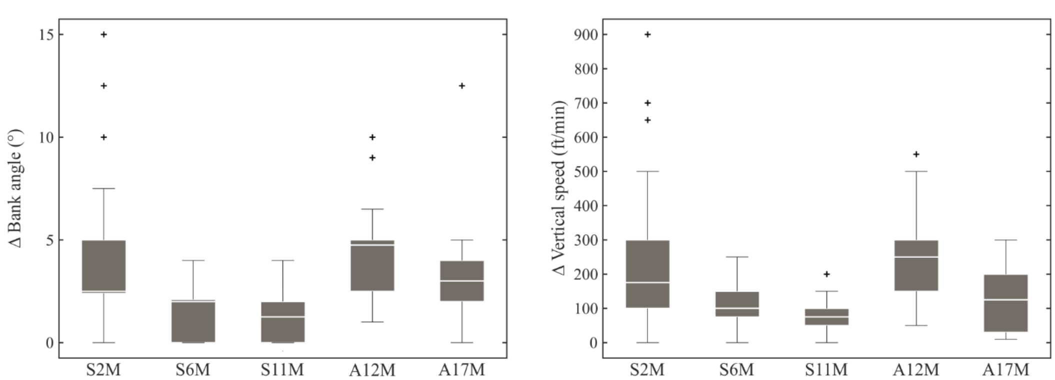

Fig. 5. Graphical depiction of recorded error rate distribution concerning prescribed bank angle and vertical speed for 180° descend turn

Normalization was based on the equation:

$$N_i = \frac{med_i}{n_{max}} \tag{3}$$

where N_i is i-th normalized value, med_i is i-th median from given dataset (where $i = 1, \dots, 5$, for each individual case of performed measurement) and n_{max} is maximum of medians regarding monitored error rate of flight parameter during given manoeuver.

The graph summarizing normalized courses of error rate for specific manoeuvers and monitored flight parameters is depicted on Fig. 6.

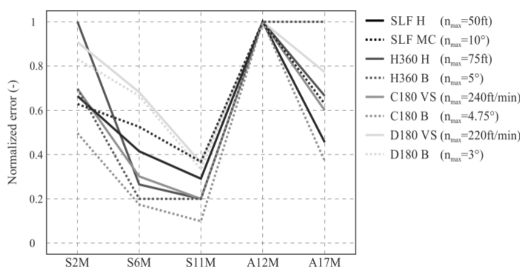

Fig. 6. Depiction of normalized error rate courses for monitored flight parameters during executed flight manoeuvers (SLF – steady level flight;H360 – horizontal 360° turn; C180 – 180° climb turn; D180 – 180° descend turn; H – height; MC – magnetic course; B – bank angle; VS – vertical speed; n_{max} – normalization coefficient representing the maximum in given dataset)

IV. Discussion

The results indicate that regarding horizontal steady level flight, error rate continuously decreases during flight simulator training. At the same time, increase in piloting precision is observable in both monitored cases, i.e. both concerning magnetic course and altitude.

The error regarding constant magnetic course and its maintaining decreased from 5° to 1° after 11 lessons on the flight simulator. Concerning altitude, decrease in median of error from 35 ft to 10 ft was recorded during the same time period as in the previous case. In this case it is possible to conclude, that the utilization of flight simulator contributes to perfection of basic piloting technique but it is not possible to conclude, that flight simulator utilization in the extent of 5 hours is sufficient (as permitted by current regulations).

During the transition from flight simulator to real operational environment, error rate significantly increased in both cases compared to S2M. Furthermore, in both cases it is possible to observe significant decrease in error rate during last executed (real) flight to the level achieved during S2M. It is possible to conclude, that usability of flight simulator has no influence on maintaining altitude and magnetic heading during horizontal steady level flight execution.

With regard to the piloting error rate during horizontal 360° turn, significant decrease in bank angle and altitude error rate can be recognized within 6 hours on the flight simulator. During next flight simulator training, statistically significant change cannot be observed, i.e. between S6M and S11M there is no significant difference. It is possible to conclude that in the discussed case, flight simulator contributes to basic piloting technique perfection. It is also possible to conclude that it is not necessary to utilize the flight simulator for training in the extent of 11 flight hours. During the transition to real flights (A12M), error rate in both monitored flight parameters increased to the level of S2M and it persisted there during second real flight execution. Compared to horizontal steady level flight, the pilot precision results from horizontal turn execution are more satisfying.

However, it is not possible to conclude that flight simulator training has positive influence on error rate during real flight manoeuver execution.

Concerning climb and descend turn, piloting precision was evaluated regarding maintaining prescribed bank angle and vertical speed of climb or descend.

The results indicate that piloting error rate tends to decrease with improved pilot experience or more precisely with accumulated flight hours. This was confirmed by the monitoring of piloting precision progress during flight simulator training.

According to the evaluation of bank angle during climb or descend 180° turn, the errors performed by the subjects during flight simulator training were not striking. In this case, error median was between 1° to 3° for prescribed bank angle of 15°. Pertaining both monitored cases (C180 and D180), significant error decrease can be noted during flight simulator training.

With a closer look on the transition between simulated and real flights, it can be observed that error rate in bank angle increased many times and in both cases (C180 and D180) it either stabilized on the level of S2M or it was higher. So it is possible to conclude, that initial training on the flight simulator (in this case 11 hours) has marginal or no effect on the capability to maintain prescribed bank angle. It is obviously possible that monitoring of other type of manoeuver would produce different results. In any case, taking into account the fact that for prescribed training, which consisted in total of 17 flight hours, and repetitive series of manoeuvers, the results are unsatisfactory.

In case of evaluating error rate regarding vertical speed, similar progress as concerning bank angle evaluation can be observed in both cases (C180 and D180). The evaluated error was relatively high in early phase, i.e. 160 ft/min for C180 and 200 ft/min for D180 during S2M. This error, however, considerably decreased during flight simulator training up to the median of 70 ft/min or 80 ft/min respectively. Nevertheless, better change can be observed in this case during the transition from flight simulator to real aircraft.

Even though significant increase of error rate is visible during the first real flight compared to simulated flights, during the training in both cases (C180 and D180) the error rate decreased during A17M to the level of S6M. In this case it can be concluded that although the transition from flight simulator to real aircraft had no effect on maintaining prescribed vertical speed of climb/descend, it was possible to monitor acquired pilots' habits, which were reflected during real flights. This stems from the fact that during real flights (or more precisely during 3 hours of real aircraft training) the error rate considerably decreased to the level of S6M (i.e. 6 flight simulator hours).

By the look on the overall evaluation comprising all monitored error rates (see Fig. 6) and based on the above-mentioned notions, it is possible to say that, in general, during basic piloting technique training on a flight simulator, continuous decrease in error rate during standard manoeuvers execution occurs. To adopt the habits related to precise handling of basic piloting techniques, 5 flight simulator hours are insufficient.

The habits for precise execution of selected manoeuvers are in most cases noticeable first after 11th hour of continuous flight simulator training. During the transition from simulated to real flights, basic piloting technique error rate, in general, increases substantially.

In this case, acquired habits from flight simulator are not observable. The habits acquisition is observable in some cases during second real flight but this does not support the idea that flight simulator training influences precise manoeuver execution and maintaining prescribed flight parameters.

V. Conclusion

The presented paper evaluates usability of flight simulators during training of beginner pilots for the purpose of improving habits related to precise piloting. Piloting errors can negatively influence flight safety.

In this work, piloting technique error rate was evaluated during horizontal steady level flight, horizontal turn, climb and descend turn. Generally, such errors can contribute to decreased flight safety pertaining less experienced pilots, especially during approach phase, dense flight traffic, etc.

For example, error rate in maintaining bank angle negatively affects radius and time of a turn, potentially affecting expected flight trajectory. Another example is deviation from vertical speed, which can lead to erroneous climb to assigned altitude [24]. Therefore, the primary goal of this study was to identify possibilities for basic piloting technique training by the means of flight simulators with the main focus on beginner pilots. It is clear that flight simulator is used not only for fluent and precise manoeuver execution training but at the same time it serves as the means for establishing and reinforcing correct habits for pilots, whilst abiding prescribed procedures, especially during non-standard situations which they may face during real operations and whose realistic simulation can be an issue from the standpoint of obeying safety regulations.

However, the results indicate that for basic piloting technique training and with regard to real flights execution, a flight simulator is insufficient.

Within piloting precision monitoring it was further revealed that 5 hours of flight simulator training are insufficient (as stipulated by current law). The limitation lies with the fact, that only one specific type of flight simulator was used. Nevertheless, in the future it would be possible to compare the presented results with training on other types of flight simulators.

Another limitation is low amount of executed real flights. It is not possible to evaluate and compare continuous progress/regress regarding piloting precision during real flights. On the other hand, the presented paper is oriented primarily to flight simulator.

Next studies could be more oriented to the above-mentioned issues. Also, it would be possible to optimize the effectiveness of flight simulator utilization for flight training with the employment of piloting precision evaluation [25]. Next research in this domain could be related to the evaluation of physiological parameters (see [26], [27]) which would determine the level of pilot's psycho-physiological state capable of influencing flight execution. In addition, the concept of piloting precision evaluation or dynamic evaluation of error rate related to flight characteristics could be used as complementary information to prevent conflicts, e.g. as part of free flight systems [28] or with regard to pilot situational awareness [29]. From this study it is apparent, that flight simulators nowadays have and in the future will have their irreplaceable position within pilots training.

Their importance lies with correct habits acquisition, errors elimination, prescribed procedures training, emergency situation handling etc.

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E Článok 5

Socha, V., Szabo, S., Socha, L., Kutilek, P. & V. Nemec

"Evaluation of the variability of respiratory rate as a marker of stress changes"

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Evaluation of the variability of respiratory rate as a marker of stress changes

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Abstract
Psychic discomfort or pilot´s stress can negatively influence the course of flight. Therefore it appears reasonable to monitor those parameters, which directly reflect the psychic and physical state of the pilot. This work focuses on the analysis of respiratory rate of pilots as a marker of stress changes. The measured sample consisted of 17 pilots – beginners in carrying out flight tasks with a variable degree of difficulty. Interquartile range as a marker of variability was primarily used for the evaluation of respiratory rate. The results show, that by this type of evaluation, the respiratory rate is a suitable marker of stress change.
KEY WORDS: respiratory rate variability, stressful situation, piloting, human factor

1. Introduction

With an ongoing development of aviation, more attention is focused on the issues of safety during performing flight tasks. Among the factors influencing the flight safety, there are, among others, the pilot´s psychic stress. Due to this situation, studies are undertaken focus on psycho-physiological parameters in pilots as markers of stress during flight [1]. The elevation of stress level leads to limiting of perception abilities and consequently to difficulties in situation assessment [2]. The influence of these facts leads to the decrease in pilot´s performance.

When elevating the stress level, or in stress situations, a change in physiological functions takes place, such as the change in heart rate, respiratory rate, blood pressure etc. [3]. This is the reason why measuring physiological parameters can serve as directs markers of psychic stress [4]. In most of receding studies focusing on stress assessment, heart rate was primarily evaluated, and respiratory rate was measured only as a side variable. For the collection of data reflecting physiologic functions, indirect non-invasive methods of measurement are used. The main reason for the choice of these methods is the comfort of the measured subject during the measurement, which restrict the occurrence of measurement artefacts directly caused by the subject. These circumstances justify the use of non-invasive sensors during the measurement of respiratory rate, using primarily the changes in the thoracic wall based on the changes of respiratory volumes in inspirium and expirium [5,6].

2. Materials and methods

Participants and measuring equipment

The measured sample consisted of 17 students of the Faculty of Aeronautics TU Košice aged 22±5 years without any previous flight experience. The group consisted of 2 women and 15 men. The main requirement of the subjects was a valid public health certificate according to the valid requirements for the health fitness of aviation staff JAR-FCL 3.105. The measurements were carried out using TRD-40 flight simulator and Diamond DA-40 aircraft. The actual flights took place at the Košice International Airport (LZKZ). For the elimination of the influence of the visualization of the aviation, navigation, and engine data on the stereotype of the piloting of subjects, both in the case of simulator and real flights, analogue aviation data were used. The subjects completed a theoretical preparation before the actual measurements.

A piezoelectric sensor was used for a non-invasive measurement of the respiratory rate, as a part of a telemetric FlexiGuard [7] system, developed at the Joint Department of Biomedical Engineering CTU and CU in Prague. The piezoelectric unit for the measurement of respiratory rate was located at the middle line under the processus xiphoideus (approx. 7 cm) in the area of epigastrium with a belt encircling the body at this level (Fig.1). The location of the unit was chosen due to a more significant volume change caused by respiration and due to the minimization of movement artefacts, resulting in more precise identification of inspiration. [5]. Respiratory rate was calculated using the period between the identified inspirations. Data representing the number of breaths per minute (bpm) were sent to the modular sensing unit (MSU) with the frequency of 5Hz using RF interface. The designed software provided for an insertion of time markers, used to for the determination of the beginning and the end of the realized maneuver enabling us to identify the time span of the realized flight task. Fig 2.demonstrates an example of a measured signal with marked maneuvers.

Fig.1Measuring system with modular sensing unit (A) and a respiratory rate sensor (B).

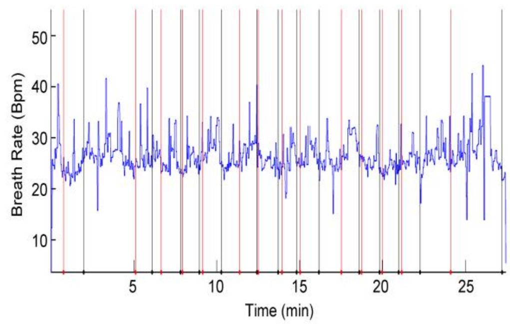

Fig.2 Example of the measured respiratory rate with markers of the beginning (red) and end (black) of a maneuver.

Measuring procedure

The course of the flight on a TRD-40 flight simulator consisted of six maneuvers, absolved by the participants. The first maneuver was a takeoff (TO). This was followed by a straight flight (S), horizontal 360° turn (H360) by a 30° bank angle, climbing 180° turn (C180) and descending 180° turn (D180) at the climbing/descending vertical speed of 500 ft/min and a 15° bank angle. This series of the four maneuvers was repeated three times during the flight. The maneuvers ware sequenced according to their difficulty in an increasing fashion. The least difficult maneuver was a straight flight, and the most difficult were C180 and D180 [8]. At the end of the measuring, subjects performed a landing maneuver (L).

The coursed of the flight on Diamond DA-40 took place identically to the one at a flight simulator for this type of aircraft. In order to compare the measurements, flights had to be realized at the same atmospheric conditions. The actual flights thus took place during standard flight conditions with a visible ground surface (VFR). Individual measurements of respiratory rate were collected using the above-mentioned measurement device. At the instructor´s command, the beginning and the end of each realized manoeuver were marked by a time marker. For further evaluation, only respiratory rate data in their respective sequences were used.

Statistical analysis

For the evaluation of the stress reaction, a mean value is often used [3,9,10]. However, when comparing several subjects, it is necessary to consider physiologic values of each individual´s respiratory rate. This fact is not always taken into account. Therefore, in many studies, standard deviation is often used to evaluate physiologic parameters, of other characteristics of variability mostly as an addition to the mean value [8,11]. Standard deviation counts on the mean value, however its value does not define the value of data, but how widely are the values distributed in the given set [12]. This is why the standard deviation is independent from the physiologic value of respiration and serves as a marker of variability.

For the testing of the normal distribution of the dataset in individual measurement phases of flights, Kolmogorov–Smirnov test was used. The assumption about the normal distribution of the examined data was proven only in five measurements. In the case of the rest of the datasets, the normal distribution of the data hypothesis was rejected at a significance level of $p = 0.05$. For this reason, as a marker of the variability of the respiratory rate, interquartile range of the first and the third quartile was used. For the comparison of the coincidence between individual measured maneuvers for all subjects, Wilcoxon two sample test was used. The testing took place at the significance level of $p = 0.05$. For this evaluation, within the scope of this paper, for the exception of the takeoff and landing, all data for the first series of maneuvers were used (S, H360, C180 a D180) due to the elimination of the influence of the training on the results.

3. Results

From the calculated mean values of the respiratory rate for a given maneuver in all subjects, boxplots (Fig 3, Fig 4) were processed for the flights on TRD-40 and Diamond D-40. It is obvious from the graphs representing the mean values distribution, that with this type of evaluation, differences in mean values of respiratory rates are not significant for respective maneuvers. Based on Wilcoxon test, no statistically significant difference was proven at the significance level of $p = 0.05$. This is probably due to the fact, that the mean value of the respiratory rate is specific for each individual, and at the same time may be influenced by various inner and outside environment factors, which can affect the values of the respiratory rate [13].

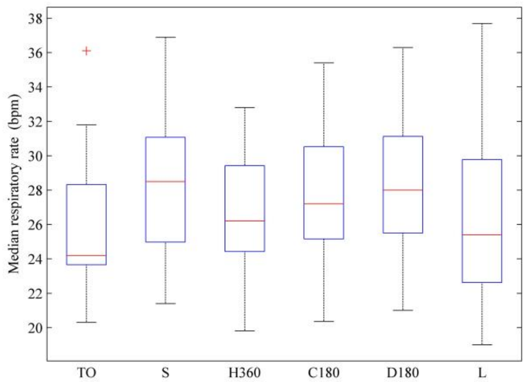

Fig.3 Graphic representation of the distribution of medians of the respiratory rate for the TRD-40 flight simulator measurements

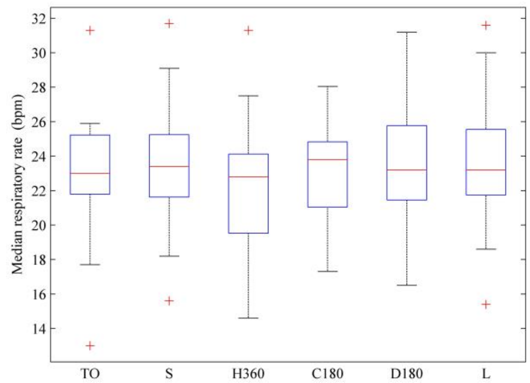

Fig.4 Graphic representation of the distribution of medians of the respiratory rate for Diamond DA-40.

In the assessment of interquartile ranges (ΔQ) of the respiratory rate, as a marker of variability, the results point out to a significant difference in individual maneuvers (Tab.1, Tab.2). Boxplots of the ΔQ parameter for individual maneuvers are represented by Fig. 5 and Fig. 6. It is obvious from the graphs, that the mean value of the variability in the takeoff maneuver acquires the greatest values for the simulator (4.2 bpm) as well as for the aircraft (5.9 bpm), while in both cases, no statistically significant difference was found when compared to a landing maneuver.

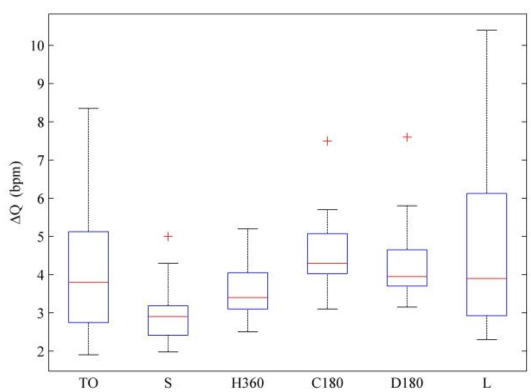

Fig.5 Graphic representation of the distribution of interquartile ranges for the TRD-40 flight simulator measurements

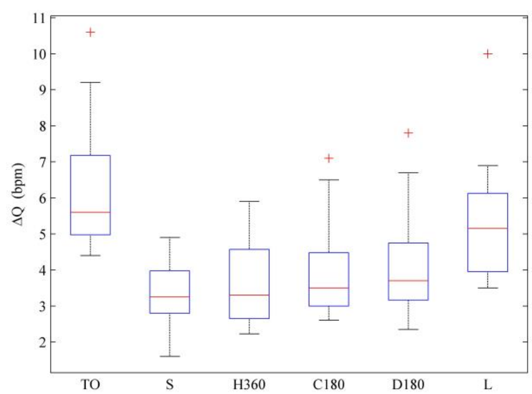

Fig. 6 Graphic representation of the distribution of distribution of interquartile ranges for Diamond DA-40.

Table 1.
Wilcoxon test results for measurements performed on TRD-40 flight simulator.

Maneuver	**TO**	**S**	**H360**	**C180**	**D180**	**L**
TO		0,06	0,40	0,52	0,71	0,76
S	0,06		0,02	0,00	0,00	0,01
H360	0,40	0,02		0,01	0,08	0,36
C180	0,52	0,00	0,01		0,22	0,50
D180	0,71	0,00	0,08	0,22		0,69
L	0,76	0,01	0,36	0,50	0,69	

Table 2.
Wilcoxon test results for measurements performed on DA-40 aircraft type.

Maneuver	**TO**	**S**	**H360**	**C180**	**D180**	**L**
TO		0,00	0,00	0,00	0,00	0,17
S	0,00		0,78	0,36	0,14	0,00
H360	0,00	0,78		0,26	0,09	0,00
C180	0,00	0,36	0,26		0,53	0,00
D180	0,00	0,14	0,09	0,53		0,02
L	0,17	0,00	0,00	0,00	0,02	

For the rest of the maneuvers realized at the simulator, the lowest mean value of variability S is (2.9 bpm), and it is significantly different from the other. Mean value ΔQ in H360 is 3.6 bpm, and a significant difference was only proven with S and C180. Between C180 and D180 maneuvers, no statistically significant difference of the mean values ΔQ (4.1 bpm a 3.9 bpm) was found. In this case this was an expected situation, since the maneuvers differed only in the climbing or descending. In the case of measurements realized with the aircraft, only the ΔQ markers in the takeoff and landing are statistically significant compared to other maneuvers.

4. Conclusions

Based on the evaluation of respiratory rate (RR) of pilots during carrying out maneuvers with a different degree of difficulty, it was found that RR evaluation using mean values is not suitable for the assessment of the stress changes. The above mentioned apparently follow from the fact that the mean value of the respiratory rate is dependent on the physiologic value of breathing in individual subjects [13]. Therefore it is only possible to compare subjects on a mass scale only under the condition that the referential mean value is the same for all subjects. On the other hand, during the evaluation using the ΔQ variability it was proved, that in measurements realized at the simulator, maneuvers S, H360 a C180 are distinguishable. It is therefore observable, that with the increase of the maneuver difficulty, RR variability increases. The calculated values of ΔQ in C180 and D180 do not show significant difference. In this case it is a presupposed situation, since the flight tasks differ only in the climbing or descending .

During the measurement on Diamond DA-40, the mean value has an increasing character with S, H360, C180 and D180, these values are however not statistically significantly different. This is probably due to the experience gained on the simulator, non-uniform weather conditions, the influence of overload on the monitored results, or continuous stress. On the other hand, during the takeoff and landing maneuver, which the subjects have absolved for the first time, there is a significant increase in ΔQ.

This work pointed out to a fact, that a change in physiologic parameter, as RR variability, can reflect the reaction to a stress situation, which can have a significant effect on the examination of the human factor. In the future studies, it would be suitable to focus on an evaluation of a larger subject sample, from which a limitation of this work also follows.

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F Článok 6

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Study of heart rate as the main stress indicator in aircraft pilots

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Abstract – **Heart rate is a parameter describing activity of human heart and its psycho-physiological character based on sympathovagal balance of autonomic nervous system, which could be instrumental for indicating stress in aircraft pilots. The assessment focuses on transition from the airplane´s analog presentation of flight data to digital visualization (glass cockpit). The main objective was to examine heart rate of pilots according to the change of flight data imaging during proposed training program, using flight simulator (TRD40 type) and aircraft (DA40 type). Another aim is to interpret stress during different flight tasks and define its influence on pilots' performance. A group of ten healthy pilots with the same level of experience participated in a seven week training program. A custom designed system consisting of non-complex units was used for measuring procedures during every recorded flight. Heart rate was recorded using a commercial chest belt made by Garmin®. Spectral analysis of the measured signal has provided the status of sympathovagal balance based on Lomb normalized periodogram. Variation of mental stress according to the values of low to high frequency ratio LF/HF was proven according to the course of training. Results show that the transit from analog to digital visual presentation of avionic data induces stress among pilots and heart rate could be an appropriate parameter defining the actual stress condition.**

Keywords – stress; piloting; heart rate; flight data presentation; flight task

I. INTRODUCTION

Generally, stress represents a state of mental or physiological strain following on adverse stimuli or inappropriate condition. The effect of stress causes the autonomic nervous system (ANS) to activate, resulting in its sympathetic and parasympathetic component influencing the activity of the heart. In the extensive field of stress indicators there are several psychophysiological parameters describing the state of increased mental strain. The most commonly used value which directly or indirectly reflects ANS is heart rate. Also parameters like electro-oculography or electro-encephalography were measured in the evaluation of psychological pressure in aviation and land transport, but the heart rate has been always considered as a major indicator. Previous studies also confirmed that pilots' psycho-physiological parameters provide information about psychical and physical condition [1]-[6]. Psychic condition of aircraft pilots during various flight tasks represents the main factor affecting comfort, accuracy and safety of the flight [7]. It has been proven that the training degree of pilot has an impact on his mental condition [2]. Despite significantly advanced technologies, it is necessary to determine factors representing potential causes of accidents. It has been confirmed that 60 – 80% of aircraft accidents was caused by human errors, and 50% of them directly by pilots [8], [9]. According to the aforementioned, it is obvious that measurement of parameters describing pilots' status whether mental or physical may lead to safety improvement in aviation.

Thus, the drop and increase of heart rate is also influenced by other factors that have to be taken into consideration in evaluation. In addition to neural modulation, although it seems to be the best way to describe heart activity there is humoral mechanism that affects heart rate as well. It involves factors such as thyroxin or genetically coded adrenalin and noradrenalin ratio, which depend on the given situations. Thyroxin is hormone produced by thyroid that affects the heart´s sensitivity to catecholamine. Besides humoral regulation, a number of other factors influence heart rate, temperature, altitude, volume of potassium and calcium in blood flow [10]-[14].

Proceeding from the facts above, neural modulation seems to best describe heart activity according to stress evaluation. Focusing on heart rate evaluation there is a necessity to use suitable parameters drawing sympathovagal balance. It has been proven that the frequency domain analysis of heart rate using LF/HF ratio (sympaticus/parasympaticus ratio) is appropriate to describe ANS activity as well as heart activity and mental stress [15]-[17].

This paper´s main aim is to describe mental demands of pilots in training through heart rate measurement during proposed training program, using flight simulator and real aircraft. The evaluation focuses on the shift from aircraft using analog presentation of flight data to aircraft providing digital visualization (glass cockpit). The initial assumption is that heart rate as the main psycho-physiologic indicator of stress will vary according to the change of flight data visual presentation. Therefore, the assumption is that heart rate will rise in the switch from using analog flight instruments to glass cockpit. Although the assessment of psycho-physiological features is an already familiar technique [1], [16] it has never been used to assess the impact of flight data visualization.

II. Materials and Methods

A. Participants and measuring procedure

Ten healthy beginner pilots (8 males and 2 females) with no previous flight experience participated in this study. Their height ranged from 158 to 199 (Mean = 181.6 cm; SD = 10.8 cm) and weight ranged from 50 to 90 (Mean = 72.2 kg; SD = 10.7 kg). The main condition for the subjects to be included in the study was meeting medical requirements according to valid flight crew medical licensing JAR-FCL 3.105.

Measurement was realized using a TRD40 type flight simulator, hardware and software equipment of which simulates CESSNA 172 and Diamond DA40 aircraft flight. Real flights took place at Košice international airport. (ICAO code: LZKZ). In both cases, the analog visualization of flight and navigation data was classic, with so-called "Basic-T" arrangement. (Fig.1A). In the case of digital visualization (glass cockpit), the dashboard was equipped with an integrated flight instrument system Garmin G1000 (Fig.1B). This system was used in both TRD40 and DA40.

Each pilot completed an eleven hour long training course consisting of simulator flights with analog data visualization associated with theoretical lessons. For these flights, the heart rate measurement was done using the 2nd (T2M) and the 11th (T11M). The first simulator flight was more or less informatory, and served as a session for pilot to get acquainted with the devices, simulated flight characteristics etc. Other measured flights were realized in order to improve piloting skills. After T11M measurement, the training was followed by moving directly into the Diamond DA40, still with analog flight instruments (L12M). Furthermore, a set of three training (not measured) flights in simulator and one real measured flight took place (L17M). Until this phase of the training, all flights were realized with analog data presentation. Afterwards, the change to glass cockpit occurred and two measurements were realized during two consecutive flights. The first on the simulator (T18M) and the second in the aircraft (L19M).

In order to compare the measurements, flights had to be realized in the same atmospheric conditions. The real flights thus took place during standard flight conditions with visible ground surface (VFR). Another important aspect was to design a uniform flight plan for each realized task. Thus, besides the takeoff and landing, three series of maneuvers were exercised, including straight on-level flight, horizontal 360° turn by a 30° bank angle, climbing 180° turn and descending 180° turn at the climbing/descending vertical speed of 500 ft/min and a 15° bank angle. The congruence of all training lessons was reached by a precise designation of the course of flight based on the aforementioned maneuvers. All tasks were supervised by an instructor, who instructed the pilot to follow the set schedule. The average flight length from the takeoff to landing was 38.2 min (SD ± 4.4 min), while take off was characterized by the aircraft leaving the ground and landing by returning to the ground.

A

B.

Figure 1. Analog visualization of flight and navigation data arranged as "Basic-T" (A) including airspeed indicator (1), attitude indicator (2), altimeter (3)| and heading indicator (4) and glass cockpit (B) with integrated flight instrument system Garmin G1000 (5).

B. Measuring equipment

Flexiguard system (FG) [17] was used for measuring procedures during every recorded flight. This system provides for real-time monitoring of user parameters and parameters of environment in which the user is currently located. The system is composed of three subunits. The first is an actual sensor unit which records desired values and communicates via wireless system, or sends acquired parameters to the second subunit, which is the central unit. Its function is to collect data from sensors, process, partially evaluate, store and finally send them to the third subunit connected to PC. The part of FG intended for heart rate measurement is a commercial Garmin® chest belt communicating with central unit through wireless connection using *ANT+* protocol as well. The belt was located in the middle line of the processus xiphoideus in the area of epigastrium, with a belt encircling the body at this level (Fig.2).

Data representing heart rate (bpm) were sent to modular sensing unit (MSU) with sampling frequency of 5Hz using radio frequency (RF) interface. Data sent to MSU were subsequently directed to the visualization unit using another RF interface. Visualization unit in our case comprised of a laptop with a custom designed software to observe the course of the measured heart rate. The custom designed software enabled for the insertion of time markers, serving to mark the beginning and end of a realized maneuver, which provided for identification and time span of the realized flight task. Fig.3 shows an example of a recorded signal with marked maneuvers the recorded data were saved directly to a μSD card, which is a part of MCU, as well as on the visualization´s unit hard drive.

C. Data evaluation methodology

Data regarding information of heart rate collected during the whole flight were unevenly sampled. This was probably caused by communication artifacts, which occurred between the chest belt and MSU. In any case, the only verified and utilized techniques for the determination mental stress determining sympatho-vagal balance. For the determination of cardiac autonomic regulation, power spectral analysis is widely used in beat-to-beat variations of heart rate. Unevenly sampled data however did not provide for the intended analysis type using FFT in order to determine power spectral density (PSD) [18], [19]. Therefore, Lomb-Scargle periodogram was used for the calculation of power spectrum [19], [20]. This method is based on evaluating data only in t_i, times, which correspond to the actual recorded values. Assuming that there are N data points $h \equiv (t_i)$, i=,…,N, the average and the spread of data are calculated first. [47]. Lomb-Scargle periodogram, or spectral power as function of angular frequency is defined as:

$$P_N(\omega) \equiv \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_j (h_i - \bar{h})\cos\omega(t_j - \tau)\right]^2}{\sum_j \cos^2 \omega(t_j - \tau)} + \frac{\left[\sum_j (h_i - \bar{h})\sin\omega(t_j - \tau)\right]^2}{\sum_j \sin^2 \omega(t_j - \tau)}\right\} \quad (1)$$

In which τ is defined by:

$$\tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j} \quad (2)$$

Parameter τ is a kind of offset, which causes $P_N(\omega)$ to be completely independent of any t_i shifts by any constant. The advantage of this method is the fact, that weighing of data is not realized using time interval, but using a point [21]. Calculations were carried out in a custom designed Matlab® program, part of which is also *"lomb"* implemented function.

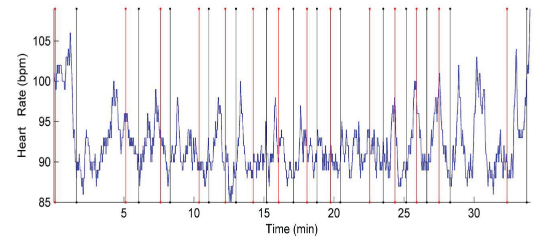

Figure 3. Example of the measured heart rate during T2M for Subject with markers of the beginning (red) and end (black) of a maneuver.

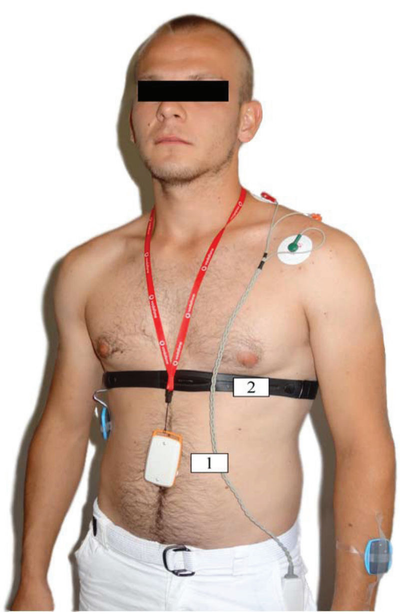

Figure 2. Measuring system with modular sensing unit (1) and a heart rate sensor (2)

Spectral analysis subsequently determined power spectral densities for low frequency band (LF) in-between 0,04 – 0,15 Hz and high frequency band (HF) in-between 0,15 – 0,40 Hz. Spectral densities were calculated as the area under the curve of the given frequency range. These bands reflect sympathicus and parasympathicus activity of ANS [22], [23]. LF reflects both sympathetic and parasympathetic activity, but generally is a strong indicator of sympathetic activity. On the other hand, HF reflects the activity of parasympathicus [22]-[24]. It has been proven in several studies, that an increase in mental stress is connected to an increase in the activity of sympathicus, and that activation of sympathicus is responsible for the increase of LF/HF ratio [15], [25]. For this reason, the focus of the statistical evaluation was indeed LF/HF ratio, which describes sympatovagal balance.

D. Statistical analysis

From the calculated LF/HF ratio values, six statistic samples were created relating to the measuring. To verify the normality of the sample distribution, Kolmogorov-Smirnov test was used. The assumption of normal distribution of the samples was not proven in any of the cases. Hypothesis on normal distribution was rejected on significance level $p=0.05$. Nonparametric testing was thus selected for further evaluation. To compare match between measurements, Wilcoxon two sample test was used. Testing´s significance level was $p=0.05$ and results with s $p<0.05$ were considered as statistically significantly different. Results for each evaluated parameter were graphically interpreted using box-plots representing median, the first and the third quartile, maximum, minimum, and extreme values of the obtained statistic samples.

III. RESULTS

Tab 1. presents results in significant difference between measurements together with medians. No norms for evaluating mental stress using LF/HF ratio have been designed yet. It is therefore impossible to determine, whether the value of this ratio points out to a high or low level of stress. Therefore, it appears redundant to describe increments and or decreases of median between measurements. Significant difference between measurements will thus be an important indicator.

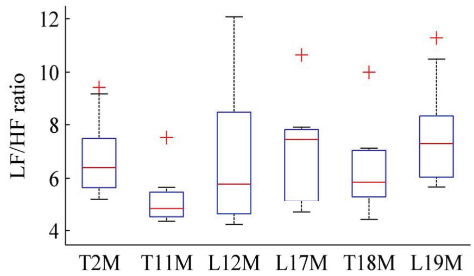

Figure 4. Graphic representation of the distribution of LF/HF ratio for all performed measurements.

The results show that the median of LF/HF ratio obtained during the second measurement is significantly lower than other measurements, except for T11M. Significant difference was also found between T18M and T19M.

Considering subsequent course of the training, the LF/HF median during the first measurement is significantly higher than T11M, also on flight simulator with analog visualization of flight data *(p=0,02)*. During the subsequent measurement on Diamond DA40 (L12M), the mean value rose compared to T11M, however, statistically insignificantly (p=0.146). Fig.4 demonstrates, that in the case of this measurement, high variability of calculated values is observable, causing L12M not to differ significantly from any of the measurements. During another aircraft measurement (L17M), median increased compared to the previous one, how very this difference is not statistically significant. After the shift back to the flight simulator, this time with digital visualization, the mean value of LF/HF ratio increased significantly compared to T11M (p=0.001), and it is at the same time significantly lower than in the case of aircraft measurement with digital visualization of flight data (p=0.031).

IV. Discussion

Mental stress influence heart rate due to the ANS influence. In such case, heart rhythm is controlled via nerves. We differentiate afferent nerves, carrying impulses from the heart to the central nervous system, and efferent nerves, which further divide into sympathetic and parasympathetic. Due to sympathicus´ influence, changes such as increased heart rate, speed of carrying impulses and contraction power. Activity of sympathicus is increased when working, or influenced by emotions and stress. Parasympathicus, on the other hand, has the opposite effect on the heart – drops heartbeat, slows down the carrying of the impulse in AV node and lowers the contractility of the atria. Proceeding from the fact, that LF/HF ratio is an indicator of sympato-vagal balance, which informs about stress, or mental stress, it was obvious that increasing this ratio will mean to increase mental stress.

As it was mention, there is currently no norm, which would state the extent of mental stress based on LF/HF ratio value. On the other hand, evaluation using this parameter is possible, based on findings of previous studies [15], [25].

TABLE I. Wilcoxon test results for performed measurements with medians (Mdn) of LF/HF ratio.

Meas.	T2M	T11M	L12M	L17M	T18M	L19M	Mdn
T2M		0,002	0,604	0,888	0,489	0,297	6,23
T11M	0,002		0,146	0,021	0,036	0,001	4,74
L12M	0,604	0,146		0,762	0,968	0,278	5,77
L17M	0,888	0,021	0,762		0,370	0,673	7,04
T18M	0,489	0,036	0,968	0,370		0,031	5,70
L19M	0,297	0,001	0,278	0,673	0,031		7,26
Mdn	6,23	4,74	5,77	7,04	5,70	7,26	

In the scope of our work, the results show, that mental stress was relatively high during the first simulator measurement with analog visualization of flight data, compared to measurement which took place after eight practice simulator flights. In this case, the result was expected, since repeating the identical flight plan, subjects gained enough skills and experience. Another expected result was the fact, that upon switching to aircraft, the level of stress in participants increases.

The results suggest, that the first measurement of mental stress using flight simulator (T2M) was not significantly different from real flights. Assumptions were not proven between two measured flights (L12M and L17M), where significant decrease in stress in L17M compared to L12M was expected. Conditions are however different between simulated and real flights. Several factors beyond our competence could possibly influence measurements, such as turbulence or wind during taking off and landing. These matters caused non-uniformity of flight conditions which with most probability caused high variability in the recorded data during L12M. When changing to the other way of visualizing flight and navigation data (glass cockpit), it is possible to observe that during flight simulator measurement (T18M), the LF/HF ratio is significantly larger than in T11M. Considering the fact that participants gained experience during real flights, the switch back to the simulator should cause no trouble.

The only change in this measurement was the change in data visualization, which made the participants return to the level of T2M measurement, if we evaluate their sympatovagal balance. Another assumption was proven when switching back to aircraft (L19M), where the LF/HF increment, and thus the stress level increment, was significantly different. In case of comparing this flight with the previous with analog visualization, no significant decrease or increase in stress was found.

The above findings show, that a change in the visualization of flight and navigation data from analog to digital influences mental stress in pilots.

V. Conclusions

The work aimed to describe the influence of visualization of flight data on mental stress of the pilot. Based on verified, and nowadays available means for this kind of evaluation, it was possible to verify the influence of the change of visualization on psycho-physiological parameters of pilots. This area is relatively new and has not been an object of study yet, therefore more studies in this field are necessary. The main limitation of this work is a small number of participants. It would also by suitable to examine the efficiency of pilots based on measuring the precision of piloting in both types of visualization and use other parameters, such as breath rate, myopotentials etc.

Further development in this topic could reach the design of such telemetric systems, which could serve for e.g. dynamic evaluation of pilots´ state and provide feedback to the instructor, of traffic control staff. Aforementioned findings and proposals can positively influence the improvement of aviation safety.

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G Článok 7

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Effect of the Change of Flight, Navigation and Motor Data Visualization on Psychophysiological State of Pilots

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Abstract — **Psychological discomfort and stress may negatively affect various work activities especially in professions that are directly responsible for the lives and health of human beings. We can find these kinds of professions mainly in civil aviation, specifically the profession of a pilot. Analysis showed, that the legislative requirements for the qualifications of a pilot, require only the competence for a particular aircraft but they don't take in account the ergonomics of the cabin and the visualization of the basic flight data (analog, glass-cockpit). That's the reason why this paper assesses the influence of flight, navigation and engine data visualization on psychophysiological state of the pilot. In this paper we used the measuring of the heart rate as the main indicator of stress. Spectral analysis was used for the assessment of stress levels with main focus on the activity of the autonomic nervous system. The evaluation was based on twenty subjects in flight training, which were divided into two groups. Each group had different methods of training based on flight data visualization. The results show that the group with the more extensive glass-cockpit training exhibit lower values of psychophysiological stress. These findings may contribute to the increase of aviation safety and the description of human-machine interface in aviation.**

Keywords: avionics; stress; human factor; human-machine interface; piloting

I. Introduction

In terms of training and preparation of pilots, methods are applied (or rather not applied) connected to switching of the visualization of basic flight, navigation and motor data on the instrument panel of the aircraft´s cockpit. Recent state, which is a reflection of the legal requirements for pilot preparation for such switch is objectionable. A pilot´s competence is conditioned by the plane type, however attributes such as cockpit ergonomics as for the data visualization are not taking into the account. Hence the issue of the visualization of the flight, navigation and motor data is not yet resolved for particular types of planes. This situation forces a pilot, who only has experience with flights using analog visualization on a particular type of plane, to fly using digital (glass cockpit) visualization on the same type of plane without any retraining. These situation occur mainly in general aviation and they may play a key role in the human failure.

Recent development in the field of the basic flight, navigation and motor data visualization on the plane´s cockpit instrument board steers towards the replacement of the classic analog indicators (airspeed indicator, attitude indicator, altitude meter, compass, variometer, clinometer) with digital visualization using primary flight display in combination with navigation display (e.g. GARMIN 1000), which in some cases substantially change the visualization of the mentioned information which are vital for piloting and navigation of a plane.

A typical feature of flying a modern aircraft is the constantly increasing demands especially on the mental activity of pilots [1], [2], which points out to the necessity of monitoring psychophysiological parameters. These parameters can influence the pilot´s performance as for piloting technique, which results in digressions of the actual position of the plane and the plane´s trajectory from the required flight and navigation parameters.

The field of collecting and processing physiological data of pilots during the flight is a widely discussed subject. It has been proven, that the measured physiological quantities are influenced by the change in the difficulty level of flight tasks both in real and simulated flights, [3], [4]. It has been also found, that the level of pilots´ mental stress depends on the level of his training [5]. Mental discomfort of the pilot, high level of stress, or lack of experience can influence the course of flight negatively. Exactly for this reason, measurement and evaluation of psychophysiological state of a pilot in relation to the cockpit ergonomics can lead to optimalization of the human-machine interaction in aviation.

There are various physiological parameters among the observed values in the evaluation of mental pressure. The

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most frequently observed value is the heart rate, then there come other bodily functions, which directly or indirectly reflex the activity of the autonomic nervous system. [6] - [12]. Generally, in stressful situations, the autonomic nervous system activates its sympathetic sub-system, increasing the heart and respiratory rate and blood pressure, as well as blood flow in skeletal muscles, and decreasing the blood flow in smooth muscles. This also elevates sensory perception (dilated pupils), activates energy reserve, etc. On the other hand, parasympathetic nervous system is active outside stressful situations, and its effects are basically the opposite of those of sympathetic nervous system. It slows down the heart and respiratory rate, increases the blood flow in smooth muscles, etc. [13]. Thus, using indicators such as heart rate, it is possible to evaluate whether or not the observed subject is under stress.

The main objective of this article is therefore the evaluation of the changes in psychophysiological state when changing the presentation of flight, navigation and motor data by means of measuring the heart rate. This objective is presented mainly due to the fact that human-machine interaction plays a key role in aviation and can affect its safety. Although the evaluation of psychophysiological parameters is not a new method, [14], [15] it has never been used in the evaluation of the influence of avionic data presentation.

II. Materials and Methods

A. *Participants*

Twenty students of the Faculty of Aeronautics of Technical University of Kosice, who have been chosen from among 100 applicants took part in this study. The choice of the participants consisted in completing theory and psychological tests and medical examination. Every selected participant complied with the medical fitness criteria according to JAR-FCL 3.105. The participants did not have any previous experience with piloting a plane.

Students were split into two groups (Group A, Group B), while the first group members undertook a course using recent training methods focusing on the switch between the analog and glass-cockpit visualization during the training. The other group went through theoretical and practical training for digital visualization of flight data. Group A consisted of 8 men and 2 women at the average age of 22±5 years, and Group B complied of 9 men and 1 women aged 23±3 years.

B. *Measuring Procedure and training schedule*

Flight simulator TRD40, equipped with hardware and software to simulate flight on CESSNA 172 and Diamond DA40 was used for the measurements, Real flights took place at the international airport in Kosice (ICAO code: LZKZ). In both cases, the analog visualization was common using so called “Basic-T” set (Fig.1A). As for the measurements with the digital visualization alternative, the dashboard was equipped with an integrated Garmin G1000 flight instrument system (Fig.1B). This system was used in both TRD40 and DA40.

A.

B.

Figure 1. Basic flight, navigation and motor indicators presented by analog (a) and digital (b) data visualization.

Before measurements and simulated flights took place, all subjects completed basic theory training focused on coping with piloting followed by instructing the pilots with simple flight simulator piloting technique using analog visualization (with duration of one flight hour). After finishing the first training on a flight simulator, the first measurement (M1) of heart rate (HR) of each subject took place. This was followed by basic piloting technique training on flight simulator with analog visualization of flight data (with duration of 8 flight hours) focused on acquisition of basic piloting skills aiming to follow given flight parameters including straight and level flight, horizontal turn to a given course, climb and descent turn at given vertical speed with turning to the given course. Except for the take-off and landing, the sequence of the flight tasks was strictly prescribed in order to maintain the uniformity of measurement procedure. After completing the introductory program for flight simulator with analog visualization, another measurement (M2) of HR on flight simulator with analog visualization (with the duration of 1 fight hour) was performed.

Prior to the real flight training, all subjects completed theory preparation followed by the third measurement (M3) of HR on a Diamond DA40 plane with analog visualization (lasting 1 flight hour). Following three lessons took place on flight simulator with analog visualization, after which subjects again performed real flight which was one flight hour long. This stage of piloting with analog visualization was followed by the fourth measurement (M4) of HR on an aircraft with analog visualization (with a duration of one flight hour). The described training and measurement methodology was applied to both groups A and B. In the following stages of the training process, the methodology was different for both groups.

Group A undertook theoretical preparation for the acquaintance with glass cockpit visualization according to the procedures applied by this kind of visualization change. Added to that, the following numbers of flight hours usually exceed the number of hours undertaken in practice, in which also flight simulator is usually not used at all. This means that the subjects from group A completed brief theoretical preparation (with duration of 1 hour) followed by the fifth measurement (M5-A) of HR on flight simulator with glass cockpit visualization (lasting one hour), and the sixth measurement (M6-A) of HR on an aircraft with glass cockpit visualization (with duration of one hour).

Group B undertook detailed theoretical preparation for the acquaintance with glass cockpit visualization which lasted three hours, plus basic training of piloting technique on flight simulator with glass cockpit visualization which lasted four flight hours. After the completion of this training, the fifth measurement (M5-B) of HR on flight simulator with glass cockpit visualization was performed, lasting one flight hour.

In order to compare the measurements, flights had to be realized at the same atmospheric conditions. The real flights thus took place during standard flight conditions with a visible ground surface (VFR).

C. Measuring equipment and data analysis

During flights (including simulated flights), physiological parameters of pilots were recorded using FlexiGuard, a highly modular system for telemetric measurement of physiological state [16]. FlexiGuard system allows for continuous monitoring of physiological parameters of the user and environment parameters in real time. It uses commercial Garmin chest band to monitor heart rate, and connection device using ANT+ for the communication with central unit. Beats per minute (bpm) and R-R interval data is send to modular sensing unit (MSU) with frequency of 5 Hz using radio frequency interface. These data are then send using another RF interface to the visualization unit. Visualization unit consisted of a laptop with custom designed software for measurement of heart rate.

To measure the sympathovagal activity, spectral analysis of the signal of the R-R intervals was used. To obtain power spectral density, the authors used a custom designed software created in Matlab®. The principle of the processing of such signal consisted in removing linear trend and following calculation of power spectral density (PSD) using the Welch method [17], by which the signal is split to overlapping segments, which are then averaged. Hanning function was finally used to remove spectral leakage.

Three basic frequency bands describing autonomic nervous system are recognized by this type of analysis. These are very low frequency ban (VLF) ranging between 0.0033 Hz-0.04 Hz, which indicates altogether activity of various slow mechanisms of sympathetic nervous system, then there is low frequency (LF) band (0.04Hz-0.15 Hz), which reflects the activities of both sympathetic and parasympathetic nervous systems, but is generally regarded as a strong indicator of sympathetic activity, and high frequency (HF) band ranges between 0.15 Hz-0.40 Hz is on the other hand influenced exclusively by vagal activity (parasympathetic nervous system) [18], [19]. Powers in the respective bands were measured by the integration of given sections. Parameters used in the further measurement were therefore powers in LF, HF and LF/HF ratio, which reflects the balance between sympathetic and parasympathetic nervous system.

According to studies [18], [20] stress is often connected with higher sympathetic activity, lowering parasympathetic control, or both. With relation to this, increase in power in the band of low frequencies occurs

TABLE I. STATISTICAL SIGNIFICANCE LEVELS FOR HF PARAMETER

	Group A						Group B					
Meas.	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
1	-	0.0854	0.6433	0.7623	0.0195*	0.8242	-	0.7674	0.0116	0.5905	0.9395	0.2219
2	0.0854	-	0.2124	0.1632	0.9047	0.1040	0.7674	-	0.0069*	0.4582	0.5370	0.1865
3	0.6433	0.2124	-	0.7902	0.0547	0.7023	0.0116	0.0069*	-	0.0592	0.0045*	0.3614
4	0.7623	0.1632	0.7902	-	0.0606	0.9697	0.5905	0.4582	0.0592	-	0.3069	0.4438
5	0.0195*	0.9047	0.0547	0.0606	-	0.0227*	0.9395	0.5370	0.0045*	0.3069	-	0.0799
6	0.8242	0.1040	0.7023	0.9697	0.0227*	-	0.2219	0.1865	0.3614	0.4438	0.0799	-

* Significant values with $p < 0.05$

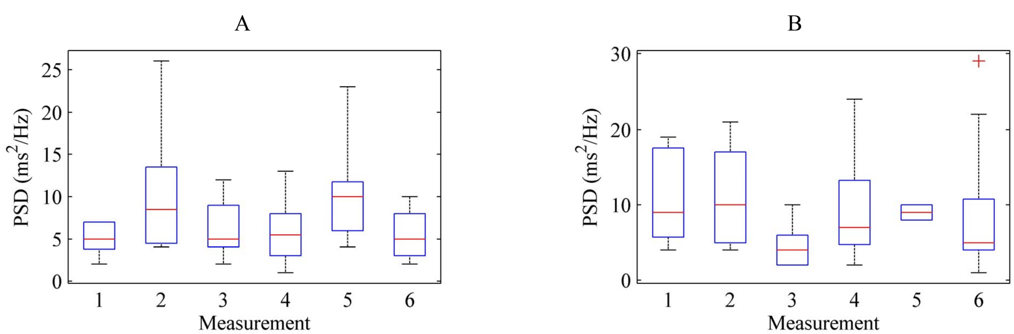

Figure 2. Graphic representation of the HF values distribution for group A (A) and group B (B)

in the evaluation of the heart rate variability, which represent especially sympathetic segment, and to a lesser extent, parasympathetic counterpart. At the same time, power values in higher frequencies (HF) go down in stress situations, which represent the parasympathetic activity and/or increase in LF/HF ratio.

Kubios® [19] software was used to test the calculation accuracy of the software designed for the spectral analysis.

D. Statistical analysis

Datasets were created from the observed parameters individually for each measurement. Kolmogorov-Smirnov test was used to test the normality of the data, set at the significance level p=0.05. The assumed normal distribution was not proven in any dataset. Hence for further statistical testing, nonparametric methods were used. To determine significant differences between measurements in particular parameters of spectral analysis, two tailed Wilcoxon test was used. Testing was realized at the level of significance p=0.05, and significant difference was defined for p<0.05.

Results of spectral analysis were statistically evaluated in Matlab®.

III. RESULTS

Wilcoxon test found significant differences in group A between M1 and M5-A measurements of HR. Compared to M5-A, HF band shows lower power in M1, which represents higher stress load. This result was assumable, since before M1, subjects completed only one flight hour on the simulator when compared to M5-A, by which they had already had 11 training hours on the simulator and completed real flight training. Another significant finding in group A occurred between M5-A and M6-A measurements, when subjects undertook training using digital visualization, while a decrease in HF band occurred in M6-A, in contrast to M5-A. This result represents higher stress load during the change to digital visualization of flight data in a plane even though at this stage, subjects had finished 17 hours of training. As for group B, significant difference was found between M2-M3, and M3-M5-B, while the value of HF band in M3 was lower compared to M2 and M5-B. These results indicate higher stress level in M3. Stress load was higher by the change from the simulator with analog visualization of flight data to the plane with the same equipment, by the change to flight simulator with digital visualization, stress level was lower. When compared to group A, there was no significant difference between M5-B and M6-B. This finding was expected due to the fact that group B completed four hours of training on the simulator with digital visualization before M5-B. As it was also assumed, extra training hours had positive effect on relieving stress levels. Above mentioned results are shown in Tab. 1 and graphically presented in Fig 2.

Insignificant result of LF parameters in group A is interpreted by considerable individual differences in the way of reacting to stress, some subjects show high activity of sympatheticus and some especially vagus [18]. In group B, significant differences were found between M3 and all the other measurements. In M3, there were lower LF values compared to other measurements, which would mean lower stress load, however, since LF parameter represents both sympatheticus and

TABLE II. STATISTICAL SIGNIFICANCE LEVELS FOR LF PARAMETER

	Group A						Group B					
Meas.	1	2	3	4	5	6	1	2	3	4	5	6
1	-	0.1951	0.6499	0.7910	0.9839	1.0000	-	1.0000	0.0104*	1.0000	0.9852	1.0000
2	0.1951	-	0.3720	0.1799	0.2349	0.2743	1.0000	-	0.0004*	0.4065	0.7049	0.4322
3	0.6499	0.3720	-	0.5703	0.6449	0.6774	0.0104*	0.0004*	-	0.0005*	0.0021*	0.0376*
4	0.7910	0.1799	0.5703	-	0.7048	0.5706	1.0000	0.4065	0.0005*	-	0.5520	0.7392
5	0.9839	0.2349	0.6449	0.7048	-	0.8881	0.9852	0.7049	0.0021*	0.5520	-	0.8417
6	1.0000	0.2743	0.6774	0.5706	0.8881	-	1.0000	0.4322	0.0376*	0.7392	0.8417	-

* Significant values with p < 0.05

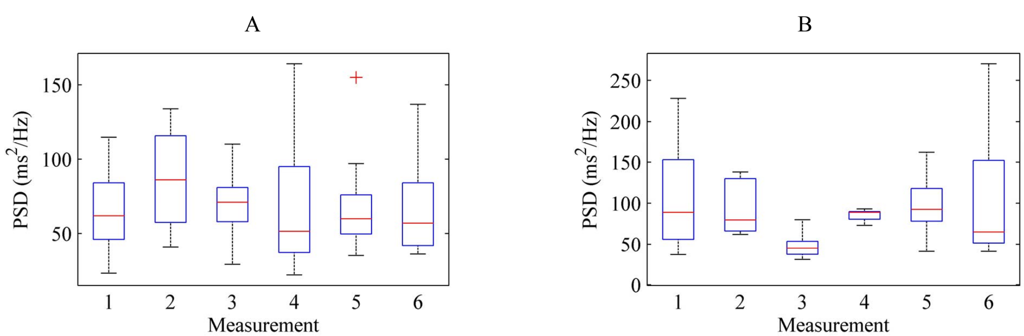

Figure 3. Graphic representation of the LF values distribution for group A (A) and group B (B)

TABLE III. STATISTICAL SIGNIFICANCE LEVELS FOR LF/HF PARAMETER

	Group A						Group B					
Meas.	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
1	-	0.3447	0.5708	0.4274	0.0163*	0.6776	-	0.6038	0.0220*	0.2110	0.4894	0.1672
2	0.3447	-	0.3847	0.1405	0.0755	0.1405	0.6038	-	0.0452*	0.3847	0.9682	0.2031
3	0.5708	0.3847	-	0.8501	0.0073*	0.8501	0.0220*	0.0452*	-	0.5205	0.0350*	0.2031
4	0.4274	0.1405	0.8501	-	0.0054*	0.8501	0.2110	0.3847	0.5205	-	0.3562	0.8968
5	0.0163*	0.0755	0.0073*	0.0054*	-	0.0054*	0.4894	0.9682	0.0350*	0.3562	-	0.2766
6	0.6776	0.1405	0.8501	0.8501	0.0054*	-	0.1672	0.2031	0.2031	0.8968	0.2766	-

* Significant values with $p < 0.05$

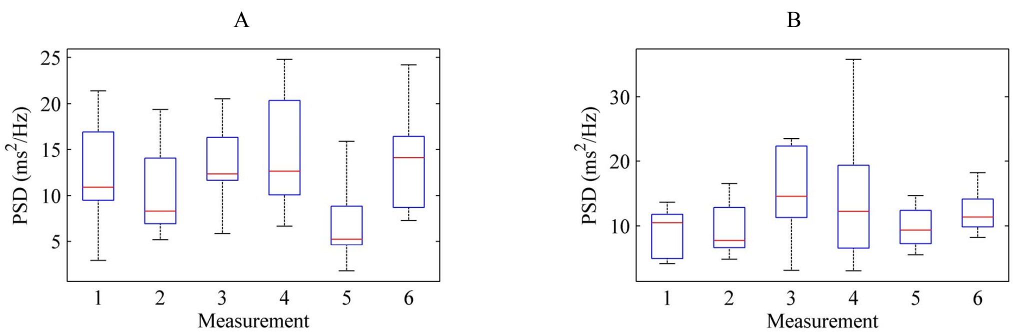

Figure 4. Graphic representation of the LF/HF values distribution for group A (A) and group B (B)

parasympatheticus, we cannot state precisely which part is dominant in this situation. Due to the mentioned individuality and the influence of both ANS parts, we do not consider this parameter crucial in stress level evaluation. Levels of statistical significance between measurements for LF are shown in Tab. 2 and graphically presented in Fig 3.

As for group A, significant difference was found between M1 and M5-A, with lower LF/HF values in M5-A. The results correspond to the HF findings in the same group. Furthermore, significant difference was found in both measurements in the plane (M3, M4) compared to M5-A on the simulator with digital visualization. This situation indicates higher stress load during flight. Similarly to HF parameters, significant difference was found between M5-A and M6-A, when higher stress level occurred after the switch from the simulator with digital visualization to the aircraft with the same equipment.

In the case of Group B, significant differences were found between measurements M1-M3, M2-M3 a M3-M5-B. These results reinforce HF parameters findings in the group B, which means that increased stress level is caused primarily by external factors. Between M5-B and M6-B, no significant difference was found, which complies with HR parameters for this group. Described results are shown in Tab. 3 and Fig. 4.

IV. DISCUSSION

Based on the visualization switch from analog to digital, we assumed higher levels of stress load in group A subjects during the transition from flight simulator (M-5A) to the aircraft (M6-A). At the same time, we expected lower stress load during the change from flight simulator (M-5B) to the aircraft (M6-B) in the case of group B pilots. This assumption was based on the difference between the second phase of the training, in which group B subjects undertook a four hour training on the flight simulator with digital visualization before M5. This assumption was proven on the basis of significant increase in LF/HF parameters and significant decrease in HF values during the switch from flight simulator with digital visualization to real flight with digital visualization in group A. At the same time, as expected, changes in HF and LF/HF parameters were not significant in group B.

The assumption about the increase, or decrease of stress level during training process was not proven only in M3 in group B. Significant stress load in this measurement was with most probability caused by external factors (wind, turbulence, etc.). Although measurements protocol proceeded from identical conditions for flight performance (VFR, METAR), some external factors could not have been changed, mainly due to the fact that the flight plan was set in advance.

V. CONCLUSIONS

Nowadays, spectral analysis of the heart rate variability is standardly used for the assessment of psychological and physical stress. This method has its negatives like the sensitivity of evaluated signals and/or the impossibility of the usage of an uneven sampling rate of the signal. Another main problem can be the insensitivity of the measured signal. This negatives can be eliminated by using various of the nonlinear methods. Every ANS is a nonlinear deterministic system [21] and it offers usage of the above mentioned methods. One of the most interesting methods is the recurrence analysis which is used more and more frequently for the assessment of heart rate variability [22], [23].

In general, monitoring of psychophysiological parameters can contribute to recognize the pilot fatigue borderlines, decrease in concentration, or current physical state of the pilot [18].

Some limitations of this work might be measuring "only" the heart rate, or rather small size of the sample. In any case, this work points out to the necessity of the further research of the pilots' stress levels. In future studies, it would be interesting to observe and evaluate more parameters, such as myopotentials, movement activity, respiratory rate, etc. In any case, the article shows that the change of the cockpit ergonomics including the change of the flight, navigation and motor data presentation causes changes in psychophysiological state of the pilot and the aforementioned findings and proposals can positively influence the improvement of aviation safety.

Furthermore, similar types of measurements may provide contribution in evaluation of human – machine interface.

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H Článok 8

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Recurrence plot of heart rate variability signal in patients with vasovagal syncopes

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ABSTRACT

Currently, heart rate variability (HRV) is commonly evaluated using time and frequency domain analysis in the clinical practice. Due to the fact that cardiovascular system is regulated by the autonomic nervous system (ANS) that also influences HRV, however exhibits rather nonlinear behaviour, it appears more appropriate to apply nonlinear methods to evaluate functioning of ANS. This study presents recurrence analysis as a tool to test the presence of ANS dysfunction that is responsible i.e. for orthostatic (vasovagal) syncope by which abnormal HRV has been demonstrated in the past.

Study included 18 patients that experienced vasovagal syncope (mean age 23.7 ± 5.2 years) and 18 healthy subjects (mean age 24.5 ± 3.2, $p = 0.85$). In all tested subjects, ECG recording was performed during active orthostatic test that comprised two phases (5 min of resting in a supine position and 5 min of active standing). Sequence of R-R intervals (time intervals between two consecutive heart beats derived from ECG) was analysed using standard time (mean *RR*, mean *HR*, *SDNN*, *SDHR*, *RMSSD*, *NN*50 and *pNN*50) and frequency domain (*LF*, *HF* and *LF*/*HF* ratio) analysis. Moreover, recurrence analysis was performed (*RATIO*, *DIV*, *AVDL*, *MAXV*, *DET*, *ENTR*, *LMAX*, *TT* and *LAM*).

Frequency domain analysis did not demonstrate significant difference between the two groups in any of the parameters during both phases of the test. On the contrary, both time domain analysis and recurrence analysis showed comparable findings in both groups during resting phase of the orthostatic test with a significant change of most tested parameters after stand-up.

As the use of time domain HRV may be perceived as problematic regarding their interpretation in short ECG recordings, recurrence analysis appears to be a sensitive tool for detecting ANS dysfunction in patients with vasovagal syncope.

1. Introduction

Currently, the field of medicine is experiencing a rising tendency towards the use of nonlinear methods derived from chaos theory [1–3] that describe the dynamics of a system [4]. What makes nonlinear methods so widely used nowadays is their ability to describe certain ongoing processes in the organism more precisely than a range of other methods [5] that are currently used in medicine.

Every living organism shows signs of chaotic behaviour ranging from sub-cellular level to vital regulations, such as heart rate and blood pressure [4]. Since dysregulation of the latter may prove pathological and yields significant clinical consequences, measurement and evaluation of heart rate and blood pressure behaviour are particularly instrumental and important in clinical practice. Their dysregulation may be caused by abnormal autonomic

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nervous system (ANS) regulation, as in the case of vasovagal syncopes [6]. Dysregulated oscillation activity of ANS in vasovagal syncopes is related to hemodynamic changes that lead to sudden occurrence of bradycardia and hypotension resulting in loss of consciousness and collapse of a patient although there is no structural heart disease present. The most frequent provoking factor resulting in syncopes is orthostasis that leads to blood concentration in lower limb vessels in sensitive individuals. This blood redistribution in the vascular space causes lower blood filling of the heart with resulting activation of baroreceptors in the aortic arch and carotic sinus. Consequently, sympathetic division of ANS is activated, which results in increased heart rate and diastolic pressure [7]. However, in patients with vasovagal syncopes, no increase of sympathetic division activity occurs. Thus blood pressure decreases as a result of diminished ventricular filling and excessive activity of parasympathicus (the other part of ANS) causes bradycardia through mechanoreceptors in pulmonary artery, atrial walls and left ventricle [8]. In fact, vasovagal syncope is not a rare disease and falls among the most common causes of fainting, black-outs, sudden falls and short term loss of consciousness.

Autonomic nervous system, perceived as a fine example of nonlinear deterministic system [4,9,10], influences heart rate and blood pressure in order to secure proper functioning of all organs based on the state of the body. A constant and balanced tone between sympathicus and parasympathicus is responsible for adequate blood pressure and heart rate that reflects an actual hemodynamic need. Thus, ANS functioning can be partly studied using heart rate variability (HRV), an analysis of heart rate changes over time, which reflects the heart's ability to react to the changes of ANS tone [11].

Clinical assumption on vasovagal aetiology of syncope is verified in a defined test that aims to de-mask presence of ANS dysfunction under the heading of so-called orthostatic test. There are two different methods of orthostatic testing, first is active standing and second is head-up tilt test (HUTT) [12,13].

ANS system dysfunction is believed to be present when blood pressure and/or heart rate suddenly decreases during stand-up phase of the test which is usually associated with manifestation of typical clinical symptoms/syncope. However, HRV analysis has proven to better identify and measure autonomic dysregulation responsible for heart rate and blood pressure changes before they manifest themselves in the form of a syncope. Actually, HRV has been known to be an effective tool for the prediction of cardiovascular morbidity and mortality [14–16]. For HRV evaluation, there are commonly used linear methods of analysis (based on time and frequency domain analysis) as well as nonlinear methods [14,17,3,18]. However, linear methods that are based on fast Fourier transform and autoregressive model proved to have a number of disadvantages [10]. Frequency domain also yields disadvantages such as long sessions of obtaining data, non-stationarity, lower sensitivity as well as high sensitivity to noise. On the other hand, recurrence analysis as a new and promising approach to HRV assessment seems to be able to tackle these obstacles relying on the observation that a healthy subject's ANS immediately responds to impulses of the organism resulting in lower occurrence of the same or similar states. In contrast, since autonomic dysfunction causes a significant simplification of bodily functions control (including heart rate variability), similar states recur more frequently. Recurrence analysis seemed to be promising in pilot studies as an effective nonlinear technique capable of presenting discrete abnormalities in heart rate regulation in earlier stages of the autonomic dysfunction [9,19–23].

This work primarily aims to verify relevance of recurrence analysis in the detection of ANS regulation disorders that result in vasovagal syncopes.

Table 1
Study groups characteristics.

	Control group	Syncope group	The significance level
Mean age (years)	24.5 ± 3.2	23.7 ± 5.2	0.8493
Maximal age (years)	33	33	–
Minimal age (years)	20	15	–
Sex (male/female)	9/9	2/16	0.0477

2. Methods

2.1. Participants and measuring procedure

Two groups were formed with the total of 36 subjects. Eighteen patients, 16 women and 2 men, aged 15–33 years (mean age 23.7 ± 5.2 years), suffering from vasovagal syncope comprised the Syncope group. The second, Control group comprised of 18 healthy subjects. 9 women and 9 men, aged 20–33 years (mean age 24.5 ± 3.2 years), see Table 1. None of the subjects had history of cardiovascular disease or other disorders. All subjects participating in this study gave their informed consent with the examination.

Active standing test (including resting supine position phase lasting 5 min and standing position phase of the same duration) was used for this study. Subjects were instructed to avoid alcohol, caffeine and nicotine consumption for at least 12 h prior to examination. In our autonomic laboratory, heart rate variability recordings were assessed under standard conditions. We assessed short-term recordings between 10 a.m. and 12 a.m., and patients remained in supine rest 15 min before recording. Then the 5 min supine rest phase was recorded. For the standing phase, patients were instructed to stand up. To prevent artifacts from muscular contraction, the stand-up phase measurement was initiated after the patient was fully adapted to standing position (usually 10–15 s after standing up) and then the 5 min standing phase was recorded. We did not use paced breathing as it was considered less physiological than normal breathing, however, patients were instructed to breath comfortably a without changing breathing frequency after changing the position of their body. According to literature [24,25], we absolutely agree that short term heart indices are subject to high variation and their reliability is still discussed in literature. We are trying to achieve similar conditions (i.e. time of examination, room temperature, humidity, absence of unwanted noise, etc.) to minimize those variations. During the entire test, ECG and blood pressure were recorded in both phases and sequence of R-R intervals (intervals between two consecutive heart beats) was subsequently derived from ECG recording. This series of R-R intervals was then analysed using Schwarzer FAN Study (FAN®, Schwarzer, Germany) system and HRV analysis was performed in accordance with standard measurement techniques and algorithms [26–28].

2.2. Data analysis

Specifically, sequence of R-R intervals has been analysed using standard time and frequency domain analysis. In addition, recurrence analysis was subsequently performed. In case of the former, following parameters were calculated: mean R-R, mean heart rate (*HR*), standard deviation for R-R intervals (*SDNN*), standard deviation for heart rate (*SDHR*), root mean square of the successive differences for R-R intervals (*RMSSD*), the sum of all R-R intervals occurring more than 50 ms from each other (*NN*50), percentual representation of *NN*50 occurrence in the total sum of R-R intervals (*pNN*50). Parameters derived from geometric methods (Triangular interpolation of N-N intervals and HRV triangular index) were not evaluated, as they are not suitable for short-term 5-min records [14,29].

For direct evaluation of sympathovagal activity, spectral analysis of measured R-R intervals was selected. Kubios® software was used with this regard [30]. This type of analysis distinguishes between three basic bands, which describe the behaviour of the autonomic nervous system. There is the very low frequency (*VLF*) band (0.0033—0.04 Hz) indicating the overall activity of various slow sympathicus functional mechanisms, the low frequency (*LF*) band (0.04–0.15 Hz) reflecting both the activity of sympathicus and that of parasympathicus (but generally being a major indicator of sympathicus activity), and the high frequency (*HF*) band (0.15–0.40Hz) which on the other hand reflects vagal activity (i.e. parasympathicus) [14,31–33]. Power values in individual bands were calculated by integrating respective sequences. Parameters used for further evaluation include power values in *LF*, *HF* and *LF*/*HF* ratio which indicates balance between sympathicus and parasympathicus. These parameters were used in previous studies focused on vasovagal syncope evaluation [34,29,35].

The same sequence of R-R interval was then analysed using recurrent analysis, methodology of which is described in detail below.

2.2.1. Phase space reconstruction

Recurrence analysis starts with phase space reconstruction, for which the length of R-R intervals was used as an input signal. Every given point in the space phase represents a certain state of the system. The most commonly used method for phase space reconstruction is time delay embedding based on Takens' theorem [2,36,37].

State variables can be used to describe the state of a system. They form vectors which represent a trajectory in phase space, which is *N*-dimensional for *N* state variables. On one hand, it is often impossible to observe more than one state variable of a system [2], since they are either unknown or difficult to measure. Using the Takens' theorem [2], however enables us to reconstruct a phase space trajectory from a single observation:

$$x_i = (y_i, y_{i+\tau}, \ldots, y_{i+(m-1)\tau})^T, \tag{1}$$

in which m is the embedding dimension, τ is the time delay and y_i is a single observation, T is period.

Literature offers a range of various approaches when choosing time delay and dimension [36]. To describe system dynamics fully using phase space reconstruction, an accurate set of these parameters is required [36].

The distance between neighboring elements is given by the time delay. Small state difference is determined by a small time delay, and vice versa, large time delays represent states which can be evaluated as independent. Autocorrelation function is one of the older methods for choosing time delay [38,36], however the possibility of nonlinear processes is not taken into account by this method. The accurate criterion for choosing time delay, as latest studies suggest, is mutual information function [36,38,39], which enables to measure mutual dependence of two random variables. The most suitable way for choosing time delay for space portraits is the first minimum of mutual information [39]. Using entropy, the mutual information of two variables can be defined as follows [39]:

$$I(A, B) = H(A) + H(B) - H(A, B), \tag{2}$$

in which $H(A)$ and $H(B)$ are the entropies and $H(A, B)$ is the joint entropy of A and B.

An optimal embedding dimension is required right after the selection of an optimal time delay. It reflects number of the reconstructed shape space dimensions [36]. False nearest neighbor method represents one of the methods used to set optimal embedding dimension, and it proceeds from an observation that the selection of low embedding dimension results in crossing of phase space trajectory [36], representing a situation when points which are distant from each other in original phase space become closer in reconstructed phase space [40]. Modified false nearest neighbour method was introduced by Cao [40,36,41].

A custom designed MATLAB script (MATLAB R2013a, MathWorks, Inc., Natick, MA, USA) was used in this study. Cao's modified method of false nearest neighbour [40], and method of first minimum of mutual information function [39] (to obtain optimal time delay) were used in this work as well.

2.2.2. Recurrence analysis

The objective of recurrence analysis is the comparison of all possible states in the phase space trajectory. It primarily uses recurrence plot (RP), which is able to represent recurrences in a dynamic system graphically (see Fig. 1). RPs are used both to identify interrelations between different systems and to find transitions between different states [2]. This can be described by the following formula:

$$R_{i,j} = \Theta\left(\epsilon - \|x_i - X_j\|\right), \quad \text{for} \quad i, j = 1, 2, \ldots, N, \tag{3}$$

in which N is the number of states x_i, ϵ is a threshold distance, $||\cdot||$ a norm and $\Theta(\cdot)$ the Heaviside function.

The most important parameter in recurrence analysis is the threshold distance. It points out that we can assume an occurrence of the recurrence point in case when the trajectory between two states is smaller than the threshold. A number of studies [42,9,21] focused on the choice of threshold distance ϵ_i, which can be set to e.g. 10% of mean space diameter, 25% of standard deviation, 5–6% of maximal space diameter or to fixed percentage or recurrence points (basically ranged from 1.5% to 15% [43]). The above-mentioned settings are standardly used and we selected the method of fixed percentage of recurrence points *%RR* = 2.5% for this study, being one of the most frequently used method (see also [9,19]).

Graphic representation of multidimensional phase space in 2D graph (see Fig. 1), immunity to noise and nonstationarity, and recording chaotic properties without extensive data collection represent the greatest advantage of RP. Another feature of RP are recurrence points, diagonal lines as well as vertical and horizontal lines. Sequences of recurrent states are represented by diagonal lines, whereas the duration of a non-changing, or slowly changing states are reflected by vertical and horizontal lines. Rare states are represented by single isolated recurrence points [38].

Finally, structures formed by points and lines yielded by RPs comprise a basis for recurrence quantification analysis (RQA), introduced by Zbilut and Webber [44], which allow quantitative evaluation of RPs.

The following measures are standardly derived from RP: Percentage of recurrence points (*RR*) which form RP. This measure corresponds to the probability that concrete state will recur [38]. Higher recurrence means lower system variability. However we use such a threshold distance which ensures 2.5% of recurrence points.

$$RR = \frac{1}{N^2}\sum_{i,j=1}^{N} R_{i,j}. \tag{4}$$

Determinism (*DET*) is the percentage of recurrence points that form diagonal lines [38]. This parameter corresponds to system predictability [38]:

$$DET = \frac{\sum_{l=l_{\min}}^{N} lP(l)}{\sum_{i,j}^{N} R_{i,j}}, \tag{5}$$

in which $P(l)$ is the histogram of the lengths of the diagonal lines (l).

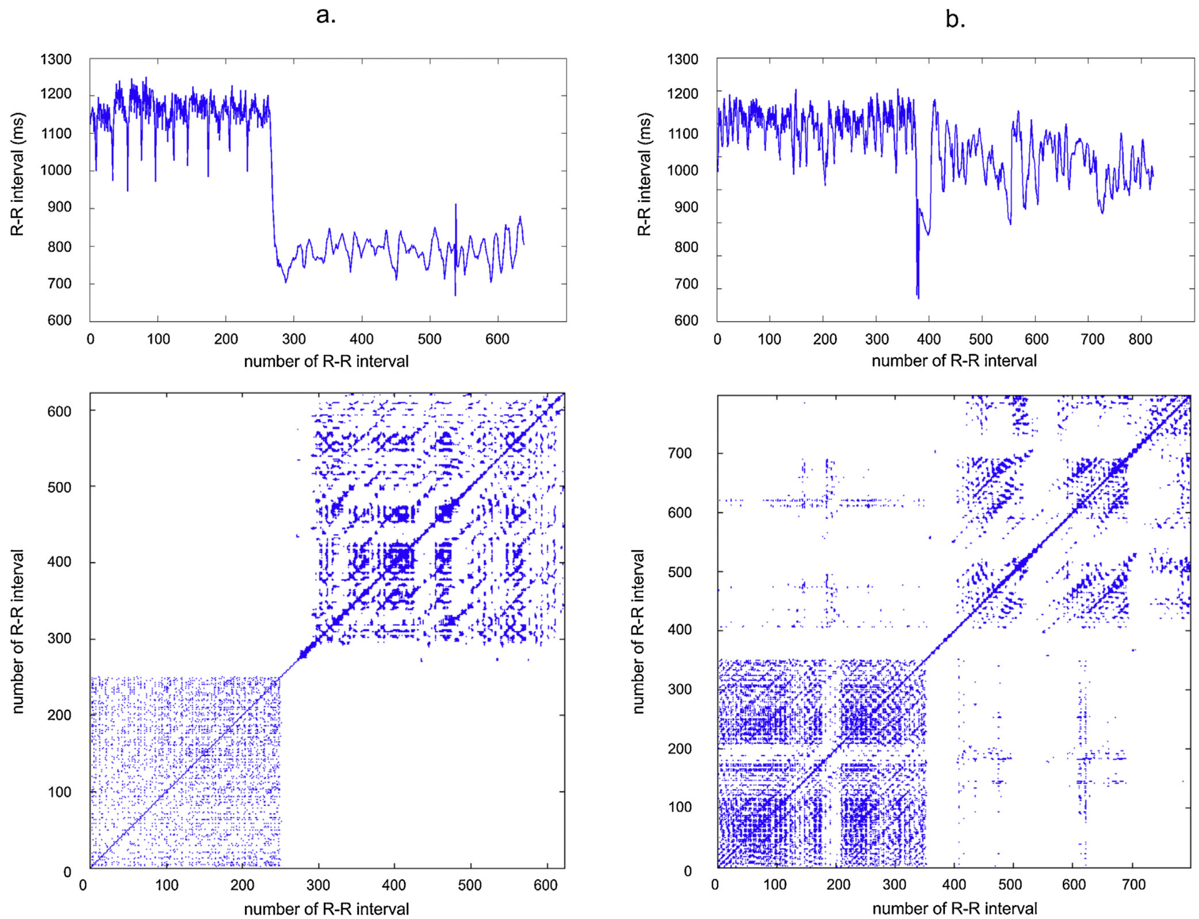

Fig. 1. Example of orthostatic test results in a young healthy man (a) and a young patient with syncope (b) during the orthostatic test. Upper parts of (a) and (b) depict variation of R-R intervals during the two phases of orthostatic test (first (left) part – resting in supine position, second (right) part – standing position; duration of R-R intervals on axis *y* and time represented in form of a sequence of R-R intervals on axis *x*). The lower graphs demonstrate corresponding recurrence plot in both phases of the test in each patient.

Divergence (*DIV*) is related with the Kolmogorov–Sinai entropy of the system [38]:

$$DIV = \frac{1}{L_{\max}} \tag{6}$$

Laminarity (*LAM*), percentage of points which forms vertical lines. This parameter helps to detect laminar states (states that do not change at all or that change very slowly) [38]:

$$LAM = \frac{\sum_{v=v_{\min}}^{N} vP(v)}{\sum_{v=1}^{N} vP(v)}. \tag{7}$$

in which $P(v)$ is the histogram of the lengths of the vertical lines (v).

Ratio between *DET* and *RR* (*RATIO*), can be used to discover transitions [38]:

$$RATIO = N^2 \frac{\sum_{l=l_{\min}}^{N} P(l)}{\left(\sum_{l=1}^{N} lP(l)\right)^2}. \tag{8}$$

The *DET* and *RR* ratio (*RATIO*) are used to identify hidden transitions [38].

Trapping time (*TT*), the average length of vertical lines. This parameter informs us for how long is the system trapped in a specific state [38]. It represents frequency and length of laminar states. Low values of *LAM* and *TT* indicate high complexity of a system [9].

$$TT = \frac{\sum_{v=v_{\min}}^{N} vP(v)}{\sum_{v=v_{\min}}^{N} P(v)}. \tag{9}$$

Longest diagonal line (*LMAX*) [38]:

$$L_{\max} = \max(\{l_i; i = 1, \ldots, N_l\}). \tag{10}$$

Maximum length of a diagonal line *LMAX* and its reciprocal value *DIV* might be related to the largest positive Lyapunov exponent [38].

Longest vertical line (*MAXV*) [38]:

$$MAXV = \max(\{v_i; i = 1 \ldots N_v\}). \tag{11}$$

Average length of diagonal line (*AVDL*) reflects average time when there are two segments of the trajectory in phase space close to each other [38]:

$$AVDL = \frac{\sum_{l=l_{\min}}^{N} lP(l)}{\sum_{l=l_{\min}}^{N} P(l)}. \tag{12}$$

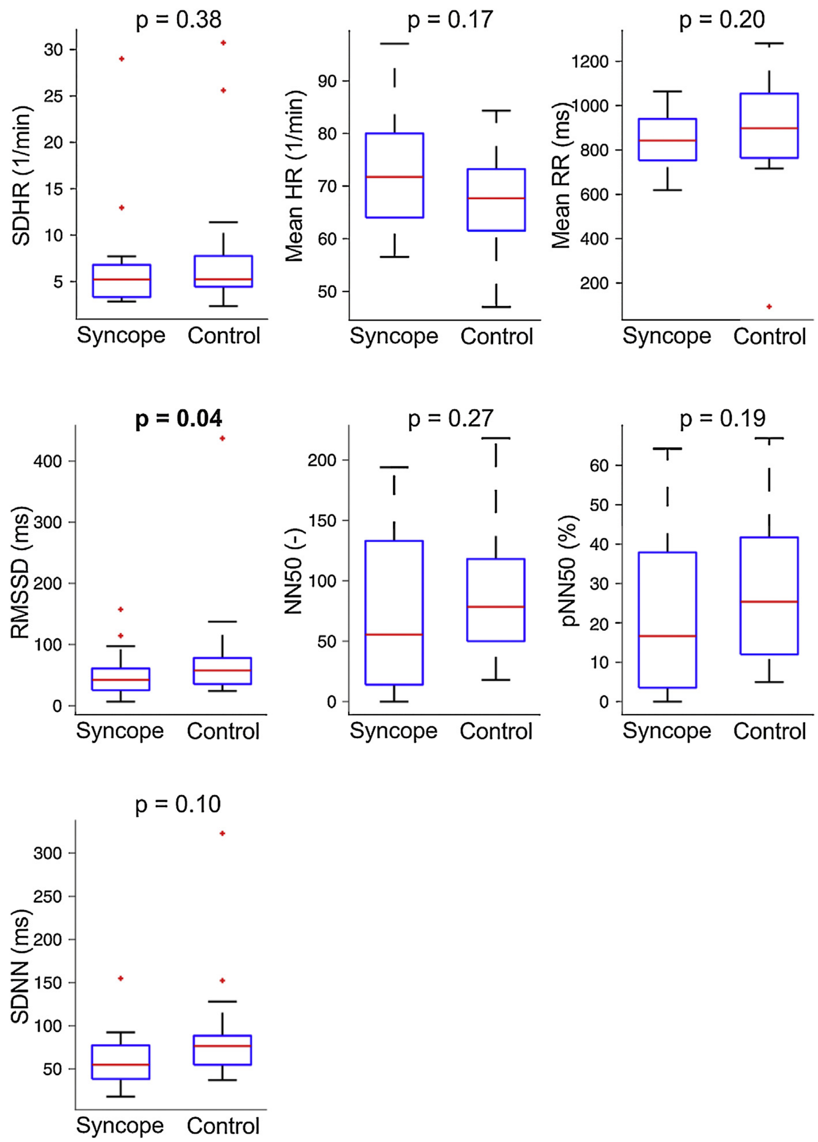

Fig. 2. Box-plots illustrating the comparison of time domain parameters between patients with syncope and control group during laying phase of the active standing test.

Shannon entropy (*ENTR*) reflects the complexity of system dynamics [38]:

$$ENTR = -\sum_{l=l_{\min}}^{N} p(l) \ln p(l). \tag{13}$$

For more details with regard to RQA measures, see also [38].

2.3. Statistical analysis

Parameters of time and frequency domain analysis and RQA measures were calculated for each subject and each phase of measurement. Kolmogorov–Smirnov test was used to verify the normality of parameters in each group. The assumption of normal data distribution in the observed participant samples was not proven in any of the cases and the normal data distribution hypothesis was rejected at significance level $p = 0.05$.

Therefore, non-parametric Wilcoxon test was used to compare statistical significance in the two observed groups. Testing was realized using significance level $p = 0.05$, and results $p < 0.05$ were considered significant. The results and observed differences in the measured parameters between the two groups were visualized as box-plots representing median, the first and third quartile, maximum, minimum and extreme values of the obtained statistic samples. The statistical analysis was performed in MATLAB environment (MATLAB R2013a, MathWorks, Inc., Natick, MA, USA).

3. Results

According to an earlier study by Pietrucha et al. [45], syncopes were induced in similar proportion of women and men. Also, there was no significant relation between gender and orthostatic test results [45].

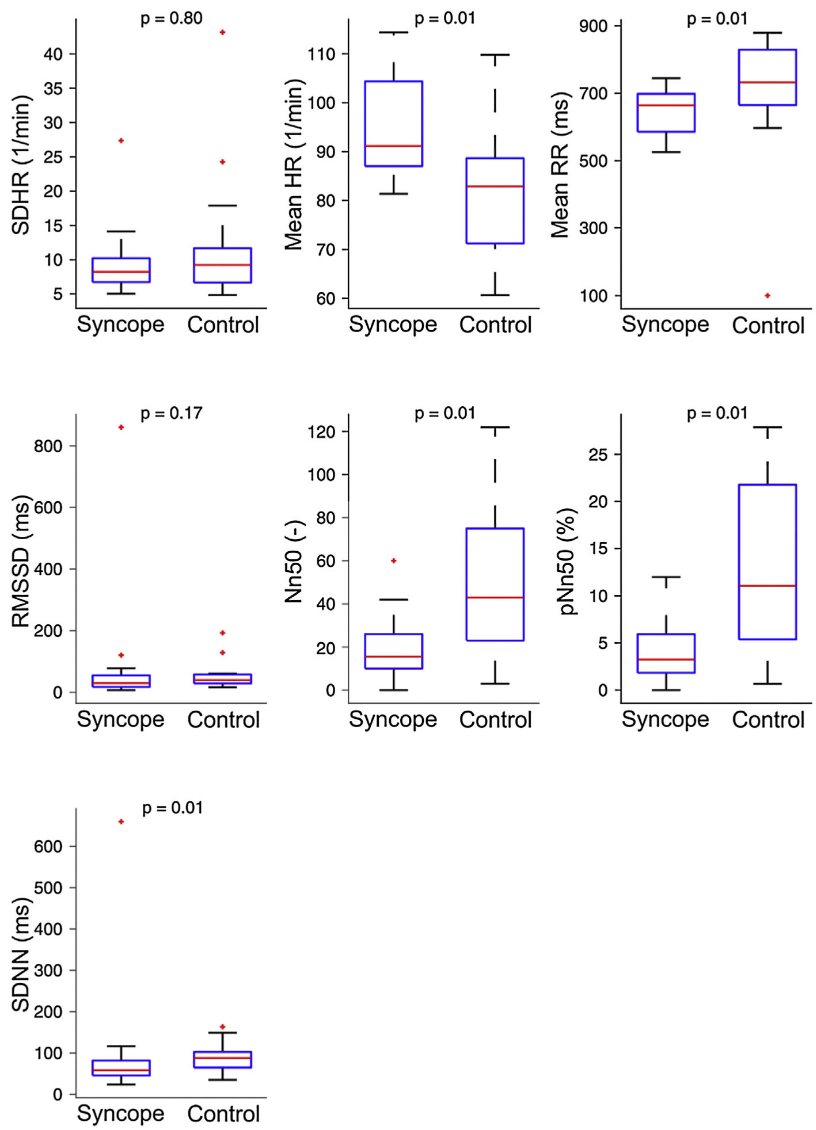

Fig. 3. Box-plots illustrating the comparison of time domain parameters between patients with syncope and control group during standing phase of the active standing test.

Time domain evaluation of R-R interval analysis revealed a significant drop in the values of *SDNN* ($p = 0.0111$), mean *HR* ($p = 0.0018$), *NN*50 ($p = 0.0031$), *pNN*50 ($p = 0.0042$) parameters, and a significant rise in the value of Mean *RR* ($p = 0.002$) parameter in patients with syncope during the second phase of the active standing test in contrast to the first phase where a significant difference was found only in *RMSSD* ($p = 0.0421$) parameter, see Figs. 2 and 3.

On the other hand, spectral analysis of R-R intervals did not identify any significant differences between the groups during the second phase of the active standing test, see Fig. 4. These two groups differed only in the significantly lower ocurrence of LF ($p = 0.0032$) in the syncopal group in the first phase of the test (Fig. 4).

Results of recurrence analysis are depicted in Fig. 1, 5 and 6 and in Tables 2 and 3.

Fig. 1 demonstrates examples of findings in a healthy subject (Fig. 1a) with significant shortening of R-R intervals after standing-up (resting phase on the left, stand-up phase on the right of appropriate graphs in Fig. 1a and b) and with two distinctly separated parts in the recurrence plot. On the other hand, in a syncopal patient (Fig. 1b), no clear heart rate change after stand-up was apparent and both phases of the tests overlap in the recurrence plot.

No significant change was found in RQA measures during the first phase of the orthostatic test (resting in supine position) between both groups. Wilcoxon test showed, that medians of the examined RQA measures were not significantly different (Fig. 5). Table 2 summarizes mean values of all RQA measures in the resting phase of the orthostatic test.

On the contrary, significant differences were found in most RQA measures between patients and the control group in the standing phase of the orthostatic test (Fig. 6). Significantly lower divergence (*DIV*) and significantly higher proportion of points forming diagonal lines (*DET*), length of the longest diagonal line (*LMAX*), points forming vertical lines (*LAM*), the average length of diagonal lines (*AVDL*), *RATIO*, the average length of vertical lines (*TT*) and maximal length of vertical line (*MAXV*) were found in Syncope group.

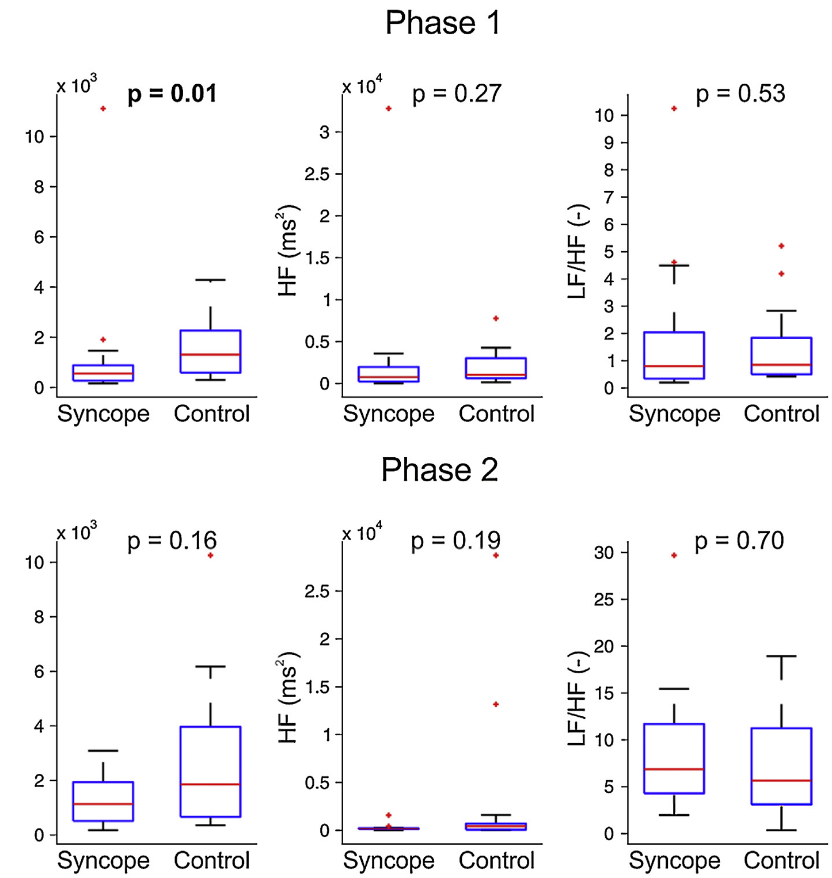

Fig. 4. Box-plots illustrating the comparison of frequency domain parameters between patients with syncope and control group during laying phase (Phase 1) and standing phase (Phase 2) of the active standing test.

Table 2
Overview results: the medians of RQA measures during first phase of active standing test.

RQA measure	Control group			Syncope group			The significance level
	25th	50th	75th	25th	50th	75th	
DET	0.1676	0.2547	0.3191	0.1676	0.2508	0.3191	0.5198
DIV	0.0852	0.0955	0.1607	0.0852	0.1181	0.1607	0.6257
LAM	0.1624	0.3508	0.4646	0.1624	0.2204	0.4646	0.2750
RATIO	6.6927	10.1700	12.7252	6.6927	10.0017	12.7252	0.5198
TT	2.0364	2.3160	2.4785	2.0364	2.1567	2.4785	0.8424
AVDL	2.2603	2.4914	2.7799	2.2603	2.3428	2.7799	0.4380
MAXV	3.0000	6.5000	7.7500	3.0000	5.0000	7.7500	0.1681
LMAX	6.2500	10.5000	11.7500	6.2500	8.5000	11.7500	0.8500
ENTR	0.5836	0.8407	0.9955	0.5836	0.7253	0.9955	0.4380

25th: 1st quartile/25th percentile; 50th: median/2nd quartile; 75th: 3rd quartile/75th percentile.

Table 3
Overview results: the medians of RQA measures during second phase of active standing test.

RQA measure	Control group			Syncope group			The significance level
	25th	50th	75th	25th	50th	75th	
DET	0.4178	0.5232	0.6511	0.6208	0.6743	0.7059	**0.0238**
DIV	0.0171	0.0282	0.0580	0.0102	0.0159	0.0240	**0.0236**
LAM	0.5632	0.6408	0.7412	0.7061	0.7457	0.7943	**0.0099**
RATIO	16.6148	20.9085	26.0312	24.6308	26.9236	28.1627	**0.0153**
TT	2.5700	2.7229	3.1141	2.8882	3.1127	3.3084	**0.0338**
AVDL	2.7310	2.8101	2.9780	2.8636	3.1686	3.4910	**0.0086**
MAXV	8.0000	9.0000	12.7500	10.2500	16.0000	19.5000	**0.0189**
LMAX	17.2500	35.5000	58.5000	41.7500	64.0000	99.2500	**0.0052**
ENTR	0.9889	1.0721	1.2326	1.1299	1.2952	1.3782	0.0649

25th: 1st quartile/25th percentile; 50th: median/2nd quartile; 75th: 3rd quartile/75th percentile.
Significant values (p 0.05) are in bold.

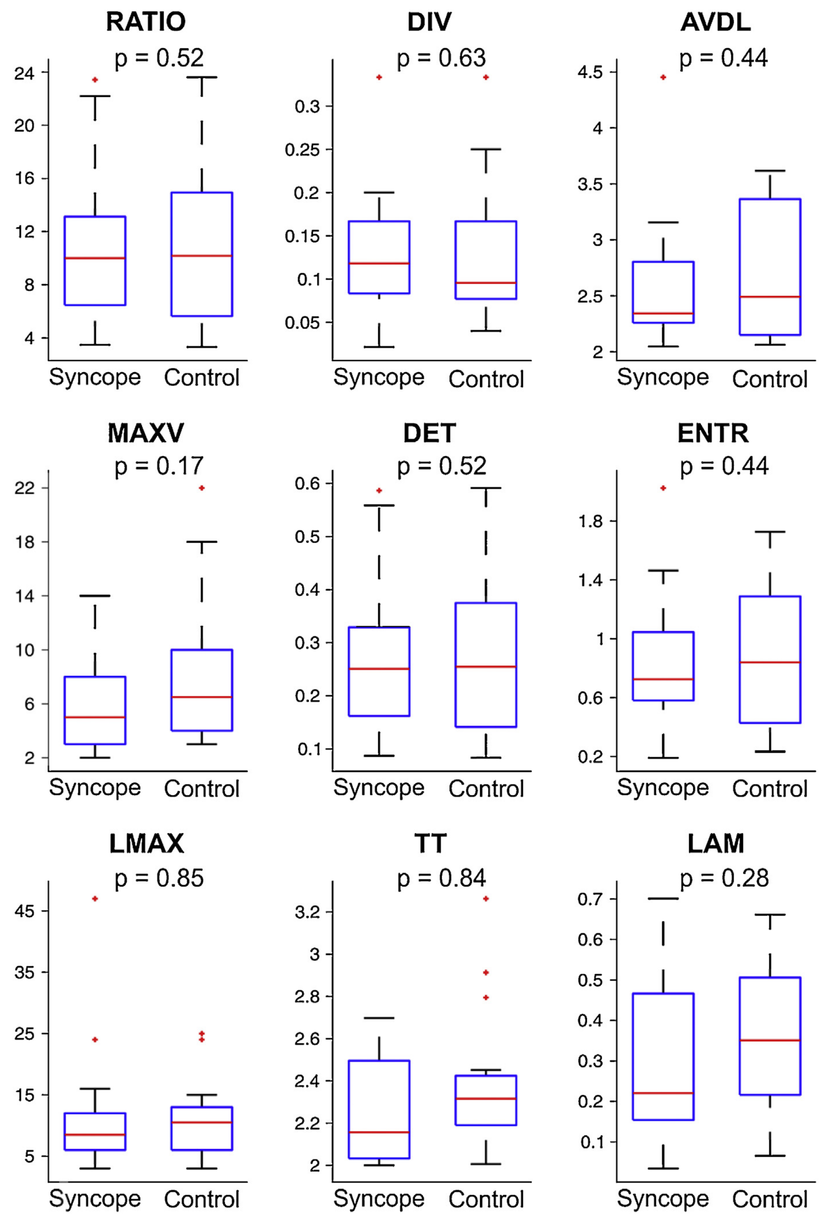

Fig. 5. Box-plots illustrating the comparison of RQA measures between patients with syncope and control group during laying phase of the active standing test.

Higher values of *DET* reflect more frequent return of the system into the previous state reflecting the system's predictability. Significant differences in *TT* and *MAXV* were also identified, see Table 3.

4. Discussion

It is well known that the rigidity of sinus rhythm, i.e. a decrease in HRV is a negative prognostic marker [46,14].

The results of time domain analysis showed significant differences between the groups in the second phase of the active standing test. These findings correspond to results presented in previous studies, e.g. Lagi et al. [47] despite the fact that the analysed record was 24 h long in their study. On the other hand, results yielded by frequency domain analysis did not point to any significant differences between the groups in any phase of the test. Based on our results, it is not possible to verify the claim [29,35] that HRV analysis is capable of identifying differences between patients and the control group, with respect to autonomic nervous system activation as a reaction to orthostasis, or of reflecting changes in the autonomic nervous system related to the onset of vasovagal episodes. In any case, the measuring protocol is partly divided in our study, with the main focus on the total test duration of 10 minutes without using tilt table. With regard to spectral analysis, it is also necessary to take into account a significant interindividual variability [31], which may significantly distort the results with errors.

This pilot study identified significant differences between results obtained from vasovagal syncope patients and healthy subjects using recurrence analysis. Our study demonstrated that the

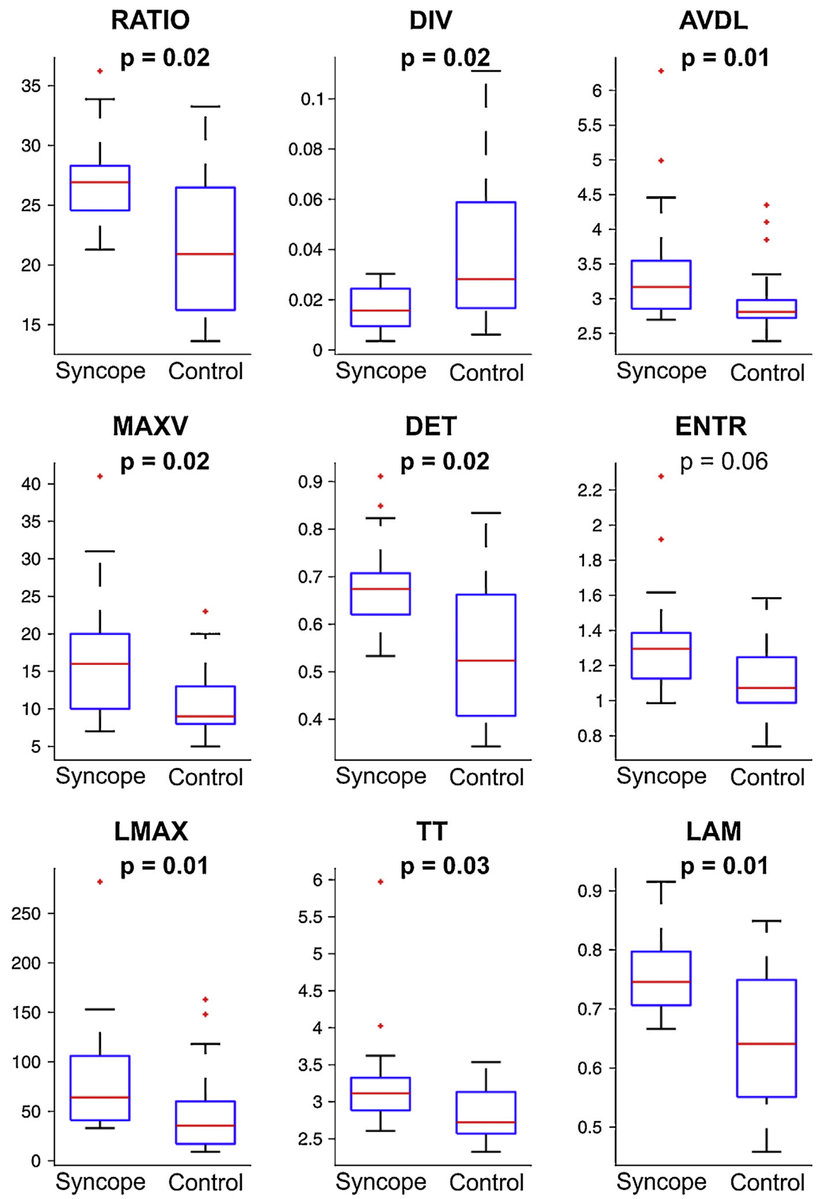

Fig. 6. Box-plots illustrating the comparison of RQA measures between patients with syncope and control group during standing phase of the active standing test.

RQA measures did not differ significantly in the two groups in the first phase of the orthostatic test (resting phase). This finding was predictable, since the activity of ANS between vasovagal syncope patients and healthy population does not differ in resting position [48].

In the second phase of active standing test, expected clinical symptoms typical for syncope patients took place [48]. At the same time, changes occurred in the RQA measures. The Syncope group yielded higher *DET*, *LAM*, *MAXV*, *TT*, *AVDL*, *RATIO* and *LMAX* and lower *DIV* values reflecting lower heart rate variability, which imply pathological conditions.

Increase in *DET* values generally points out to a more frequent return of the system (sinus rhythm) to previous states [49] and at the same time, increase in *LAM* values reflects higher rate of laminar phases in the system [49], and thus an increased intermittence. An increase in *MAXV* value in patients with syncopes points out to the fact that sinus rhythm remains in its previous phase longer [49]. Additional data to *MAXV* is *TT*, which represents the time span of a specific state in the system [49]. Higher values of *AVDL* levels in patients with syncope also reflect lower variability. An average length of an *AVDL* diagonal line represents a state when the trajectory in the phase space runs directly into another segment of the phase space, also called mean prediction time [38].

The significant differences observed between these parameters in healthy subjects and in patients with syncopes after verticalization reflect lower HRV. This means that increase in the parameters implies a higher predictability of the system [50].

The aforementioned observation is caused by the fact that physiological circumstances activate the regulatory function of ANS in terms of the adaptation to the given situation either by increased activity of sympathicus or parasympathicus, to preserve balanced system and to avoid the occurrence of pathological states. These changes in the activation of the two parts of ANS at the same time cause significant deviations in heart rate. However, in the case of syncope, with disorders in regulatory function of ANS (decreased activity of sympathicus), these mechanisms cannot take place, and thus apparent influence of ANS on heart activity in terms of heart beat variability are not as significant.

5. Conclusions

In our study, recurrence analysis was applied for evaluation of HRV with the aim to identify ANS dysfunction that is responsible for orthostatic syncopes in patients. Results from recurrence analysis were compared with the standard HRV analysis that is based on time-domain and frequency domain analysis. Our results suggest that recurrence analysis may be useful tool for identifying patients with autonomic dysfunction that present with orthostatic syncope and that this method may be more sensitive in detecting ANS dysfunction than the measures of HRV derived from time and frequency domain analysis. Since these standard methods of HRV analysis have been demonstrated to be useful in the assessment and identification of high-risk patients with cardiovascular diseases connected to heart attack [15,16,46] or diabetic neuropathy [27,28], recurrence analysis with its possibly higher sensitivity to detect ANS dysfunction may help in the risk-stratification of these patients in the future.

However, since recurrence analysis represents a new method, some questions related to optimal set of input parameters (especially the threshold distance) remain open and widely discussed [42,43]. Moreover, this study represents a pilot project and the demonstrated findings should be perceived in this light, as a relatively small number of subjects in both groups and the lack of gender-matched control group pose certain limitations. Therefore, future studies in this area would be appreciated.

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I Článok 9

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Prediction of Atrial Fibrillation and its Successful Termination Based on Recurrence Quantification Analysis of ECG

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***Abstract*—Atrial fibrillation ranks among the most common heart rhythm disorders. Considering the lack of any trusted method capable of foreseeing possible recurrence of atrial fibrillation after it has been terminated, nonlinear analyses of beat-to-beat heart rate variability demonstrate promising potential. This work focuses on verifying the capability of the nonlinear methods to differentiate patients with early recurrence of atrial fibrillation from those with stable normal sinus rhythm after cardioversion. Both patients groups underwent the active-standing test involving ECG measurement. Recurrence quantification analysis was used to evaluate sequences of intervals between two consecutive heart beats. The data were derived from body surface ECG signal. The results selected those parameters capable of identification of patient groups during the initial phase of the active-standing test prior to cardioversion.**

***Keywords*—active-standing test; atrial fibrilation; cardioversion; heart rate variability; recurrence quantification analysis**

I. INTRODUCTION

Atrial fibrillation (AF), as a remarkably common type of cardiac arrhythmia appears to be a considerable variable in morbidity and mortality rates. The occurrence of the disease rapidly increases with age, and most frequently develops in patients suffering from hypertension, ischemic heart disease, valvular heart disease etc. Patophysiology describes it as a number of re-entry circuits in the atria [1]. The most common symptoms include e.g palpitation, dyspnoe, presyncopes. Standard therapy focuses on three objectives: heart rate monitoring, maintaining sinus rhythm and prevention of thromboembolism and related complications [2]. The focus on heart rate control relies mainly on pharmaceutics. Restoring normal sinus rhythm can be also achieved via medication, however the most efficient alternative is the electrical cardioversion for atrial fibrillation. The short-term efficiency is between 70-90%. The energy required to restore sinus rhythm ranges between 50J and 360J in the case of monophasic shocks, while a significantly lower range (20J-200J) applies for biphasic shocks, reaching nearly 100% efficiency [3], [4]. However, recurrence of atrial fibrillation in the following days or weeks after originally successful electrical cardioversion is quite frequent. Therefore, tools to predict successful restoration of sinus rhythm and its longer-term persistence are of high clinical relevance and importance.

Considering the fact that the autonomic nervous system (ANS) controls the cardiovascular system, it is presumed that autonomic dysfunctions affect the onset and development of AF [5].

Complex behavior of ANS limits our ability to fully understand and describe autonomic regulation. Current methods of ANS testing are based on heart rate variability (HRV) evaluation. Slight changes in heart rate serve as sign of generally normal functioning of ANS, while autonomic dysfunction is characterized by diminished heart rate variability. Since it is believed that autonomic control plays a role in the development and maintenance of atrial fibrillation, study of heart rate variability may give an insight into the functioning of ANS.

The HRV analysis is based on the evaluation of sequence

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of intervals between consecutive beats that are derived from surface ECG as a sequence of so-called R-R intervals (see Fig.1). Various methods are then used for further analysis, while straight-line methods based on the time and frequency domain have become the standard choice [6]–[9]. On the other hand, non-linear methods such as the recurrent analysis and fractal dimension are becoming the point of focus in a growing number of studies due to the non-linear nature of autonomic nervous system behavior [10]. It would be useful for clinical practice to establish reliability of these methods in the prediction of AF recurrence within a certain timeframe.

The objective of this work is thus to apply non-linear methods on R-R intervals analysis and identify paramaters capable of predicting recurrence of AF after it has been successfully terminated.

II. Materials and methods

A. Subjects and measuring protocol

Study population consisted of 66 patients with atrial fibrilation, average age 66 ± 10 (SD) years (as to the date when measurements were performed). Due to the diagnosed AF, all patients underwent delectrical cardioversion in order to terminate the arrhythmia and restore normal sinus rhythm. Before and after the cardioversion, modified orthostatic test with continual ECG recording was performed. During the first phase, a subject was lying still on his or her back for 10 minutes (Ph1), the second phase required a patient to sit for 8 minutes (Ph2), which was followed by returning to horizontal position for 8 minutes (Ph3), and finally, the subject performed upright stance for as long as 8 minutes (Ph4). Figure 2 describes the whole measurement process, which actually represents active-standing test [11], [12].

On the 5th and the 30th day following the cardioversion, the patients underwent a 24 hour ECG monitoring using an ambulatory electrocardiography device (i.e. Holter). Its purpose was to identify recurring arrhythmia (atrial fibrillation). Besides this procedure, patients were continuously monitored by the medical staff via regular medical checkups.

Based on the medical observation as well as Holter records results, patients were further divided into two groups. The first group (Gr1) included those subjects, which did not show signs of recurrence of AF during the observed period of 30 days after successful cardioversion. Patients in which AF recurred between 5th and 30th day represented the second group (Gr2). Patients diagnosed with AF recurrence within 5 days were excluded from further evaluation.

The subject sample for further evaluation was reduced to 42 patients aged 65.9 ± 10 (SD), while Gr1 comprised of 27 subjects (12 women and 15 men) aged 64 ± 8.2 (SD), and Gr2 included 15 subjects (6 women and 9 men) aged 69 ± 13 (SD).

All measurements and the entire experiment was perfomed by professional medical staff at Department of Cardiology of Motol University Hospital using noninvasive methods in accordance with ”Ethical Principles for Medical Research Involving Human Subjects” (Helsinky Declaration [13]).

B. Data processing

The initial stage of processing ECG signals from subjects included the detection of R peaks of the QRS complex (see Fig.1) in Lead II, which is commonly used to record the rhythm strip [14].

Detection of R wave (peaks) from ECG was realized using the Pan-Tompkins method [15], while utilizing a custom designed MatLab software (MatLab R2013b, Mathworks, Inc., Natick, MA, USA). Following the detection of R peaks of the QRS complex, R-R intervals were calculated using the form $R(j+1) - R(j)$, in which $j = 1...n$.

Recurrence quantification analysis (RQA), a method for describing recurrence plots, was then used for quantitative evaluation of the recurrence plots created from R-R interval signal. The method in fact represents a 2D visualization of N-dimensional phase space. The potential of this type of analysis in detecting dysfunctions of ANS has been previously demonstrated in the fields of cardiology, neurology, or epileptology [12], [16], [17].

Thus, reconstruction of the phase space of the signal in form of R-R intervals represented the first step in the analysis process and relied on the time delay method, which is a common choice in similar studies [18]. A method using the first minimum of mutual information was used to determine the optimum time-delay [19]. The choice of the optimum dimension, being the extension of the false nearest neighbour method described in [20], followed as the next step. The final significant attribute affecting the resulting recurrence plot is the threshold value ε, representing the minimum distance

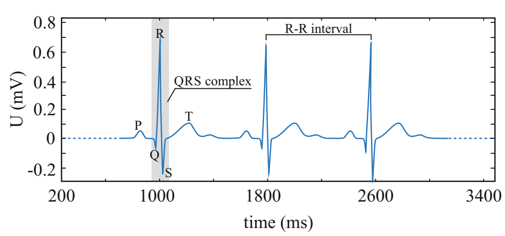

Fig. 1. Example of ECG curve with representation of QRS complex and R-R interval.

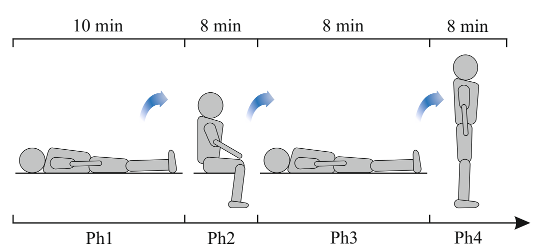

Fig. 2. Illustration of the course of the active-standing test.

between two adjacent points. If this value is lower than ε, logical one is placed in the recurrence plot, otherwise the result is logical zero. The commonly used threshold value represents the fixed percentage of recurrence points with its value ranging between 1.5-15% [21], [22], [23]. Following previous works published by the authors, in this case it was opted for $\varepsilon = 8.5\%$.

Proceeding from the above, recurrence plot of the phase space of R-R intervals was created (see Fig.3). Parameters describing the dynamics of HRV were derived from the recurrence plot [18], namely RR, DET, LAM, RATIO, AVDL, TT, MAXV, LMAX, DIV, ENTR and TREND.

RR - recurrence rate measuring the density of recurrence points within the recurrence plot. DET represents the proportion of recurrence points which results in the formation of diagonal lines, reflecting the system‘s recurrence into the identical or similar state. LAM is understood as an analogy (for vertical lines) to the definition of DET and describes laminarity of the system. RATIO represents the ratio between DET and RR, describing the system‘s dynamics. AVDL is defined as the average length of diagonal lines. TT trapping time is an analogical parameter of AVDL for vertical lines. MAXV is

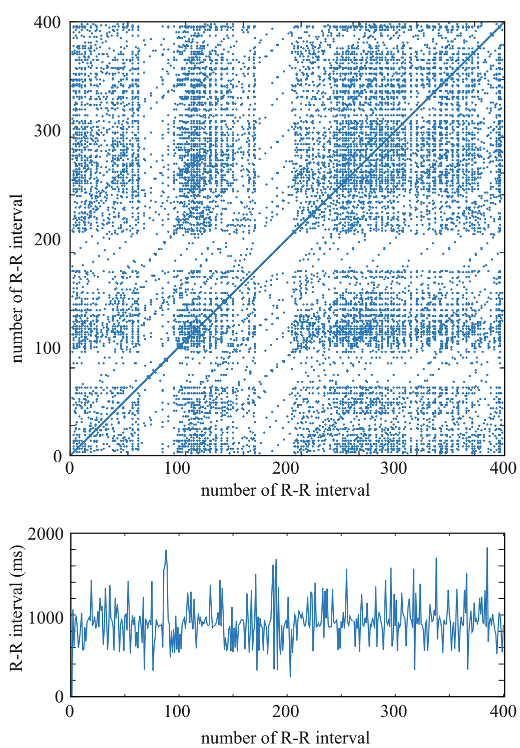

Fig. 3. Example of recurrence plot (top) created using phase space reconstruction of the signal in the form of R-R intervals (bottom). Recurrence plot is formed by recurrence points, which forms lines and structures that are basis for recurrence quantification analysis.

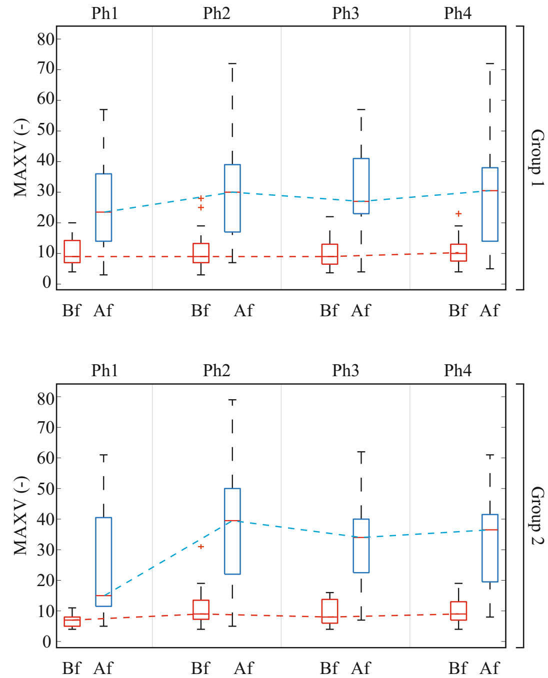

Fig. 4. Example of the MAXV parameter distribution and the course of active-standing test in Gr1 and Gr2 before (Bf) and after (Af) cardioversion.

the acronym for the length of the longest vertical line as well as its analogical value for diagonal lines LMAX the length of the longest diagonal line (maximum time of recurrence). DIV represents the inverse value of LMAX. ENTR measures the Shannon entropy of the probability distribution of the diagonal line lengths. TREND is a linear regression coefficient over the recurrence point density assesing non-stationarity in the process. The parameters are further described in [24].

The above parameters were calculated for each measurement phase in every subject in either Gr1 or Gr2 both prior to and following the cardioversion.

C. *Statistical analysis*

Statistical assessment was performed with datasets characterized by the evaluated RQA parameters for the respective patient groups in individual test phases before and after cardioversion. The objective of the statistical evaluation was the comparison of the patient groups within the entire course of the test. The initial stage of the statistical analysis was the evaluation of data distribution in the datasets. Kolomogorov-Smirnov [25] test of normal distribution was performed in the MatLab environment at the significance level of $p = 0.05$, which verified the normal data distribution hypothesis for $p < 0.05$. Normal distribution was found only in two datasets. Due to this fact, nonparametric Wilcoxon test [26] was chosen for further evaluation. The hypothesis of significant intergroup

TABLE I. RESULTS IN FORM OF WILCOXON TEST P-VALUES FOR COMPARISON OF GROUP 1 AND 2.

Parameter	**p-values of Wilcoxon test**							
	Ph1 Before	***Ph1 After***	***Ph2 Before***	***Ph2 After***	***Ph3 Before***	***Ph3 After***	***Ph4 Before***	***Ph4 After***
RR	0.753307	0.587833	0.004349*	0.807875	0.006521*	0.167261	0.866010	0.385621
DET	0.016473* ⇓	0.985624	0.136566	0.134769	0.138675	0.246583	0.429538	0.576448
DIV	0.003499* ⇑	0.880945	0.573815	0.029306*	0.127963	0.194148	0.056028	0.050034
LAM	0.655641	0.250851	0.302549	0.149634	0.155318	0.465531	0.298389	0.652372
RATIO	0.016473* ⇓	0.985624	0.136566	0.134769	0.138675	0.246583	0.429538	0.576448
TT	0.100256	0.142741	0.402869	0.860952	0.179486	0.525549	0.483450	0.652372
AVDL	0.003414* ⇑	0.121776	0.095394	0.925459	0.055334	0.495731	0.960506	0.774556
MAXV	0.018548* ⇑	0.613594	0.390779	0.154717	0.847802	0.564031	0.739548	0.294212
MAXD	0.004888* ⇑	0.730938	0.520431	0.111298	0.017732*	0.730961	0.234591	0.090263
ENTR	0.003927* ⇑	0.041039*	0.287033	0.871173	0.090156	0.311528	0.940789	0.745476
TND	0.138651	0.321247	0.881659	0.304388	0.000619*	0.635927	0.928932	0.381133

* Intergroup significant difference ($p < 0.05$); ⇑ - median of the parameter is higher for Gr1 compared to Gr2; ⇓ - median of the parameter is lower for Gr1 compared to Gr2

difference between the observed phases and groups was verified for $p < 0.05$.

Demonstration of the results via figures illustrates only one example (due to the rather extensive number of diagrams), describes the course of test phases for Gr1 and Gr2 for the MAXV parameter (Fig.4). More specifically, Fig.4 presents boxplots describing the distribution of an observed parameter for a subject group (vertical lines from the bottom - minimum, first quartile, median, third quartile, maximum) in the respective phases of the active-standing test both before and after cardioversion.

The major objective is to compare the course between the groups of Gr1 and Gr2 in order to determine the most significant parameters and phases of the active-standing test, based on which, atrial fibrillation and its successful termination may be predicted.

III. RESULTS

The results pointing to significant intergroup difference are presented in Tab.I, in the form of p-values calculated by the application of Wilcoxon test. Values of $p < 0.05$ describe intergroup difference in a given parameter for a given phase of the active-standing test. It is specifically apparent that the significant difference between the Gr1 (subjects in which the arrhythmia did not recur) and Gr2 (recurrence between 5th and 30th day following the cardioversion) demonstrates during Ph1 before the cardioversion. Significant differences for Ph1 were thus found for DET, DIV, RATIO, AVDL, MAXV, MAXD and ENTR.

Significant difference was also found for the ENTR parameter during Ph1 after the cardioversion. Ph2 of the active-standing test did not identify any remarkable intergroup differences considering the observed parameters except for the RR and DIV parameters. The evaluation of Ph3 before the cardioversion suggests significant intergroup differences in RR, MAXD and TND. Ph3 after the cardioversion failed to identify any significant differences for any of the parameters.

During the phase of the test which involved moving to the upright stance, no intergroup differences were found in any of the parameters, neither before, nor after the cardioversion.

The results thus show, that the most appropriate phase for the identification of patients with successful AF termination is Ph1 before cardioversion, while the most differentiating RQA parameters are DET, DIV, RATIO, AVDL MAXV, MAXD, ENTR. Significant changes in the observed parameters were hardly seen during the remaining phases.

IV. DISCUSSION

Based on presented results it appears, that there are not visible differences between two patients groups with diagnosed AF after performed cardioversion. This finding would be presumable as, in fact, physiologically normal sinus rhythm was restored in each examined patient.

The results further suggest that it is possible to separate the group of patients with AF and with the expected recurrent fibrillation within 30 days from those patients who will not experience recurrence. Identification of differences between Gr1 and Gr2 is the clearest during the first phase of the active-standing test while RQA parameters point to changes in HRV between the observed groups.

Increased values of the DET and ENTR parameters in Gr2 indicate lower variability compared to Gr1. The determinism in Gr1 suggests that the system tends to return to the previous states more frequently than in the case of Gr1. Entropy suggests higher variability diagonal line lengths in Gr1 compared to Gr2, i.e the system is more predictable. On the other hand, higher values of MAXV, MAXD and AVDL in the case of Gr1 indicate that once Gr1 system returns to the same or similar state at a different time, the state is kept longer compared to Gr2. Higher values of RATIO, and vice versa lower values of the DIV parameter in Gr2 than in Gr1 suggest lower HRV. Similar results can be observed in the case of vasovagal syncopes [12].

Increases or decreases in the median of the observed significance parameter during the first phase of the active-standing test before the cardioversion is presented in Tab.I.

V. Conclusion

Having the results presented and discussed, we arrive at the conclusion that prediction of AF and its successful termination does not depend on the evaluation of the active-standing test phases. It follows from the results that for this purpose, ECG measurement of a patient lying in a horizontal position is sufficient. The most significant markers capable of prediction of successful AF termination might be the parameters of RQA (in the case of our study DET, DIV, RATIO, AVDL, MAXV, MAXD and ENTR).

The results of the recurrence analysis indicate the potential of the method in the prediction of successful AF termination. Nevertheless, future studies might require more specific division of subjects into individual groups, based on diagnoses and risk factors triggering pathological conditions of the myocardium and consequent onset of atrial fibrillation.

Opportunities in this field appear also for the use of other nonlinear methods such as analysis of fractal dimensions, or Lyapun exponents.

The possibility to succeed in complex predictions of cardioversion success using simple tests and RQA analysis would open up for alternative treatment methods (pharmacological, surgical etc.) which would facilitate the decision making of doctors. Last but not least, this might also reduce the duration of the treatment period in patients with AF.

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Evaluation of Pilots' Psychophysiological Condition Using Recurrence Quantification Analysis of Heart Rate Variability

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Abstract

Psychological discomfort or increased stress can negatively influence performing specific activities mainly concerning professions which are responsible for human lives. Such group of professionals includes aviation specialists, especially pilots. Psychophysiological state is indicated by certain physiological parameters by means of which it is possible to describe it. There is a wide range of methods for signal processing of measured physiological parameters which are, however, based on linear methods. This paper deals with application of non-linear method, the so-called recurrence quantification analysis for evaluation of psychophysiological state of pilots. For this purpose, R-R interval recording of pilots in training was conducted by the means of wearable telemetric system. Research sample consisted of 35 beginner pilots and measurements were performed during both simulated and real flights. Measured signal processing was done using standard time-series analysis (Mean R-R and SDNN) and also using recurrence quantification analysis. The results indicate that both standard and recurrence quantification analysis parameters were able to distinguish between two groups of measurements (simulated vs. real flights) at the significance level of $p < 0.05$. Apart from that, the results indicate considerable increase of heart rate frequency and decrease in its variability during real flights.
KEY WORDS: *recurrence quantification analysis, heart rate, piloting, pilot training, flight simulator*

1. Introduction

In the domain of aviation, air carriers are willing to achieve maximum comfort and safety of passengers. Achieving this depends on pilot, his co-pilot but also on various aviation employees or flight parameters. Flight parameters are influenced by the effect of environmental conditions on pilot and so it is flight safety. There are plenty of specific influences on human organism during flight, which depend on physical properties of surrounding environment, aircraft performance, demanding nature of required actions and on mutual effect of these influences on physiological functions of individual organs [1]. The goal of all human factor studies in aviation was and still is increase of flight safety. Owing to the acquired knowledge, awareness of pilot's stress load during flight is expanding also in terms of how to resist it or how to cope with it.

Individual aviation accidents statistics differ regarding the number of accidents caused by human factor. According to PlaneCrashInfo.com, 67.57% of aviation accidents are caused by human factors whilst almost 54% is caused by fatal piloting error. Majority of these errors emerges during approach and landing phase but almost 28% take place during routine flight phases [2]. Piloting errors are caused by various factors, for instance fatigue accompanied with reduced awareness, stress, flight crew's psychological state or inexperience in critical situations. The very pilot's state is indicated by his or her physiological parameters by means of which it is possible to evaluate his or her psychophysiological condition. In this field, majority of studies is focused on stress evaluation using heart rate variability (HRV) [3], [4]. The reason is that HRV reflects autonomic nervous system (ANS) modulation, which allows differentiating between connection of sympathetic and parasympathetic elements. With the help of ANS (sympathetic and parasympathetic) behavioural specification, it is possible to partly objectivise the effect of stress on human organism. From short-term perspective, the stress itself brings some benefits to organism. During long-term persistence, however, all benefits are lost and it can lead to fatigue or possible pathological consequences [5]. Such state is for pilots unacceptable.

As mentioned, most studies use HRV regarding identification of load, stress or more precisely adverse psychophysiological condition. Obtained signal evaluation methods are mainly based on time-series or spectral analysis

[6], [7], which are linear methods. Autonomic nervous system is characterised as non-linear deterministic system though [7]. The goal of this paper is to verify non-linear method application (recurrence quantification analysis (RQA)) on pilots' psychophysiological state evaluation. The concept of HRV evaluation using RQA is expanding but it was never used for pilots' evaluation.

2. Materials and Methods

For the purpose of verification of RQA suitability for its application on evaluation of psychophysiological state of pilots, heart rate frequency measurement was used for pilots in training. Research sample consisted of 35 subjects (27 men and 8 women) put in flight simulator (type TRD40) training and real flight training on Diamond DA40 aircraft. The pilots were students at Technical University of Kosice and at the age of 23 ± 4 years. Selection of research sample was conditional on medical fitness and theoretical knowledge of flight fundamentals. Specifications of the training are described closer in preceding study (see [8]). In essence, the point was to experimentally set the training for beginner pilots with the main emphasis put on simulator training with implemented real flights. Members of the sample completed continuous preparation covering 11 flight simulator hours followed by one flight hour on Diamond DA40 aircraft and then next 3 flight simulator hours were followed by another two flight hours finishing the training. Individual flights were uniform and consisted of series of precisely predefined manoeuvres. For the purpose of this study, it was the first transfer between simulated and real flying which was monitored. Estimated stress load was tracked and it was assumed that it would follow ascending trend concerning simulated and real flight comparison.

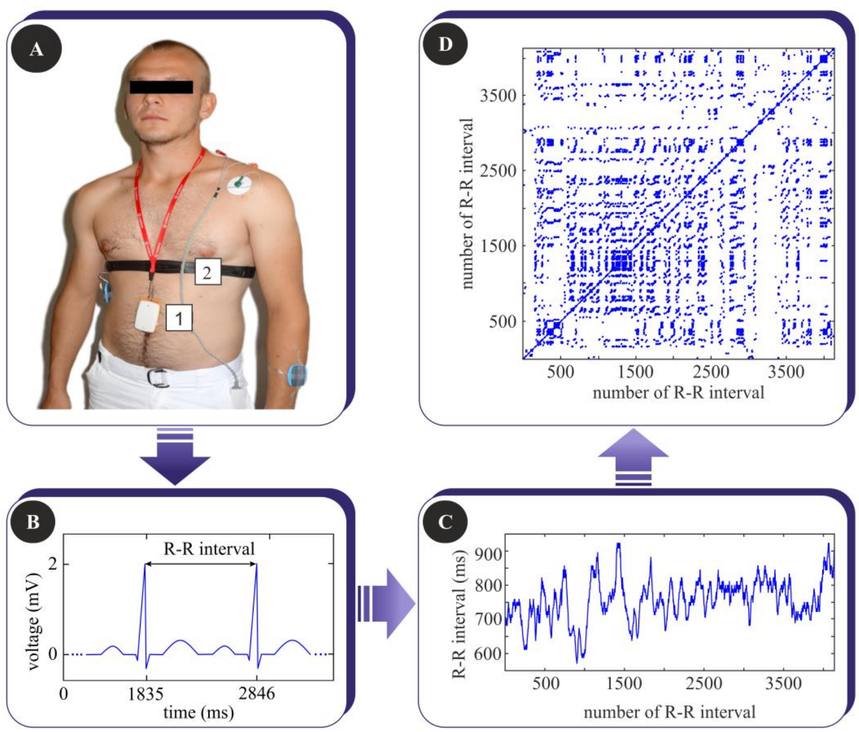

Fig. 1 Data processing: A - system FlexiGuard with central collection unit (1) and chest strap for heart rate monitoring (2); B – example of R-R interval; C – example of heart rate frequency signal in the form of R-R intervals; D – example of recurrence plot)

To verify the increase or decrease in stress load, ECG recoding was performed at 11^{th} (simulated flight - SF) and 12^{th} (real flight - RF) hour of training. FlexiGuard (FG) system (Fig. 1, A) was used for data recording. It is a wearable telemetric modular system designed for this purpose by Faculty of Biomedical Engineering, CTU in Prague (see [9]). The system is capable of continuous data recording of several physiological parameters but for the purpose of this study, only heart activity data were used, recorded by means of Garmin® chest strap. FG system recorded R-R interval data (Fig. 1, B) tracking time intervals between two characteristic ECG peaks. This concept is used mainly for heart rate variability evaluation, which could indicate various pathophysiological states such as stress [10]. R-R intervals measurement was performed during entire flight where the measurement begun at the time of take-off roll initiation and stopped at the time of touchdown.

The recorded signal (Fig. 1, C) was processed in two ways. The first way consisted of standard variables calculation used in clinical practice. Calculated were mean R-R, indicating average heart rate, and heart rate variability throughout standard deviation of N-N intervals (SDNN) which means SD of R-R intervals in our case [6]. This calculation was performed with regard to the verification of RQA suitability. The second way of data processing and evaluation consisted of procedures for creating recurrence plots (Fig. 1, D) which are essential for RQA. Detailed description of R-R interval signal processing by the means of recurrence analysis is presented below.

2.1. Signal Processing - Recurrence Analysis

In the domain of medicine research, non-linear analysis is becoming widespread. It is based on signal trajectory reconstruction in phase space [7]. One of non-linear analysis methods is recurrence analysis, which stems from theory of chaos. Recurrence analysis allows visualising recurrence of dynamic systems. For this visualisation, a time-series is needed with no requirements for its length, stationarity or distribution. It is possible to monitor dynamics of the entire system by means of this multidimensional method. First step is to establish multidimensional system, which relates to the original phase system. Phase space and distance matrix (DM) are to be computed here. Then points are identified which are distant in time but in terms of selected radius they are space neighbours. This creates recurrence plot (Fig. 1, D). The last step is evaluation of recurrence plot with the help of RQA.

Trajectory in phase space expresses dynamics of the entire system and with the help of several methods it can be reconstructed from just one scalar time-series. The most commonly used method is time delay embedding method, which prescribes following signal reconstruction [11]:

$$x(t_i)=\left[x(t_i),\,x(t_i+\tau),\ldots,\,x(t_i+(m-1)\tau)\right], \tag{1}$$

where $i = 1 \ldots M$; m is embedding dimension; τ is time delay and $M = N - (m - 1)\,\tau$, where N is amount of samples. Reconstructed phase space in this way is not identical with the original phase space but under certain conditions, dynamics of both systems are the same [11]. Basic condition for this is sufficient embedding dimension m and appropriate time delay τ. It was proved that for attractor of dimension D, the sufficient embedding dimension is $m \geq 2D + 1$. This knowledge works for infinite and accurate time-series which are, however, not measurable in practice. Because incorrect initial parameter selection can significantly affect the results and so the data may be misinterpreted, it is important to be careful when selecting m and τ.

For purpose of this study, time delay τ was selected so that the interactions between points of time-series would be minimised. This way is the attractor verified if it exists. Time delay τ states the distance between two neighbouring points of the time-series, which is to be reconstructed. For low τ is the difference between reconstructed vectors minimal and the information obtained about the dynamics of the system is not much enriched (it is so-called redundant state). Too much time delay causes the system's behaviour to become chaotic and complicated. In that case it is called irrelevant state. For optimal time delay τ setting, I was selected by means of minimal mutual information. It shows interdependence between two dependent quantities where the higher the dependence, the more information is obtained. Mutual information (I) calculation stems from entropy and is given by following:

$$I(A,B)=H(A)+H(B)-H(A,B), \tag{2}$$

where A and B are individual variables, $H(A)$ and $H(B)$ are their entropies and $H(A,B)$ is their combined entropy. The most appropriate time delay for measured signal was selected as the first minimum of mutual information. The first minimum of I corresponds to time step where measurement/observation $x(t_i + \tau)$ contributes on average with maximum information to the information which is already known from measurement/observation $x(t_i)$. If there is no minimum of mutual information, the value of τ was selected such where $(\tau) / I(0) = 0.2$, (see [11]).

The goal of phase space reconstruction was to ensure that there would be no trajectory intersecting. With small dimension, in majority of cases the trajectory intersects itself whilst increase in dimension causes the trajectory to cease this phenomenon. As a result of trajectory intersecting there are so-called false neighbours. One of the most commonly used methods for proper dimension m selection is method based on the number of false neighbours. It is about linear increasing of phase space dimension and monitoring of false neighbours. The disadvantage of this method is the selection of threshold at which two points are still considered as neighbouring. This problem was partly solved by Cao [12] who introduced following equation:

$$a(i,m)=\frac{\|x_{m+1}(i)-x_{m+1}^{NN}(i)\|}{\|x_m(i)-x_m^{NN}(i)\|}, \tag{3}$$

where $\|.\|$ is Euclidean distance; $x_m(i)$ is i-th reconstructed vector with dimension m and $x_m^{NN}(i)$ is his closest neighbour with non-zero distance from point $x_m(i)$. Cao also introduced $E(m)$ as average of all values $a(i,m)$ which can be calculated as:

$$E(m)=\frac{1}{N-m\tau}\sum_{i=1}^{N-m\tau}a(i,m). \tag{4}$$

From Eq. 4 it is apparent that first time delay is to be set. The difference between the number of false neighbours between two neighbouring dimensions is specified by comparison of values $E(m)$ and $E(m+1)$. This difference is given as a fraction $E_1(m)$ of individual averages (Eq. 5). At sufficiently high embedding dimension is the value of $E_1(m)$ stabilised at around 1.

$$E_1(m)=\frac{E(m+1)}{E(m)}. \tag{5}$$

By the above stated means, phase space with optimal time delay τ and embedding m dimension was reconstructed for each signal. For further processing it was necessary to create recurrence plot which characteristics were used for quantification analysis.

Recurrence plot (Fig 1-D) can be comprehended as two-dimensional depiction of N-dimensional phase space. The basis for recurrence plot (RP) creation is distance matrix (DM) which is squared matrix symmetric with respect to the main diagonal and from which the RP is obtained by thresholding. For DM calculation, Euclidian norm was used where the very prescription for DM is as follows:

$$DM(i,j)=\|x(i)-x(j)\|, \tag{6}$$

where $\|.\|$ is Euclidean distance, $x(i)$ and $x(j)$ are system's states in time i or j respectively and $i, j = 1,..., N- \tau(m-1)$, where N is the number of points, τ is time delay and m is embedding dimension. Recurrence matrix (RM), or more precisely RP as visualisation of RM, is derived from thresholding DM. RM can be described mathematically as follows:

$$R(i,j)=\Theta\left(\varepsilon-\|x(i)-x(j)\|\right), \tag{7}$$

where Θ is Heaviside function (i.e. $R(i, j) = 0$ for $\|x(i) - x(j)\| > \varepsilon$) and ε is distance threshold. Graphical depiction of RP is therefore binary coded, i.e. recurrence states are represented by points in RP. From Eq. 7 it is apparent, that thresholding directly influences the number of recurrence points. That implies that the threshold selection is one of the key factors of recurrence analysis. However, the optimal threshold setting is still subject of discussion. The most simple and used way for thresholding is selection of fixed percentage of recurrence points, i.e. such threshold setting which ensures the percentage value set for recurrence points in RP. When setting the threshold in this way there are several recommendations. One of them is that the recurrence points' percentage in graph should be kept at low values, i.e. no more than 5%. Other studies state that fixed recurrence points' percentage should be between 1.5% and 15% [7]. Because previous studies dealing with heart rate recurrence analysis often used fixed recurrence points' percentage set at 2.5% [7], this study used the same setting.

After recurrence plot creation (with selected thresholding), recurrence quantification analysis (RQA) was used for RP evaluation for each measured R-R interval signal obtained from heart rate measurements. Explicit mathematical definition for distinct RP properties allows in general analysing multidimensional, non-linear or noisy signals. The definition and procedures for RP structures quantification are based on horizontal, vertical and diagonal structures evaluation in RP. Currently, 9 variables are used for RP description. They are recurrence rate, which shows point density in RP, determinism (DET), laminarity (LAM), longest diagonal line (LMAX), divergence (DIV), average length of diagonal lines (AVDL), ratio between DET and recurrence rate (RATIO), Shannon entropy (ENTR) and maximal length of vertical line (MAXV) [13]. Because for the purpose of thresholding a fixed percentage setting for recurrence points was used, the parameter recurrence rate was discarded from the evaluation. Another reason for discarding this parameter was that it is covered in RATIO and so it would exhibit direct dependence. For the other above stated RQA parameters, which were calculated for each measured signal of R-R intervals, a statistical evaluation was performed.

For the above stated signal processing, an own-designed software in Matlab environment was used (MATLAB R2013a, MathWorks, Inc., Natick, MA, USA).

2.2. Statistical Analysis

Statistical analysis was used to evaluate the intergroup differences in standard parameters (Mean R-R a SDNN) and individual RQA parameters. The goal was to find those parameters, which were able to distinguish between the two groups of measurements during simulated and real flight. Statistical test selection was determined by probability distribution. Because the measured and tested data groups (represented by RQA parameters, Mean R-R and SDNN) obey normal distribution, Jarque-Bera test was used. Null hypothesis was that the data originate from normal distribution at the 5% significance level against alternative hypothesis that the data do not originate from normal distribution ($p < 0.05$). The testing did not indicate normal distribution for any data vector containing measured parameter. With respect to this finding, Mann-Whitney U nonparametric test was used for intergroup testing with null hypothesis stating that two samples originate from distribution with the same median at the 5% significance level. Alternative hypothesis stating that two samples originate from distributions with different median was accepted for p<0.05 and so it is possible to tell that between the two measured samples there is statistically significant difference.

Statistical testing was performed in Matlab environment (MATLAB R2013a, MathWorks, Inc., Natick, MA, USA).

3. Results

Graphical representation is realised in form of boxplots, where one boxplot demonstrates data distribution of measured parameter within measured group (SF or RF). Each boxplot shows (from lower horizontal line) minimum, first quartile, median (red), third quartile and maximum value of measured parameter in measured group.

The results of standard analysis, i.e. Mean R-R and SDNN evaluation, indicate statistically significant ($p < 0.05$) increase of average R-R interval values for SF compared to RP. Mean R-R value was 732 ms for simulated flights compared to 598 ms for real flights. This can be interpreted also by means of heart rate frequency in beats per minute (bpm) units (see Fig. 2). It is possible to tell that the average heart rate for researched sample of pilots is considerably lower for simulated flights than for real flights.

Significant differences between SF and RF were found also for heart rate variability by the means of SDNN. In case of SF, this was parameter 48 ms whereas for RF it was 32 ms. It is possible to see this considerable decrease in heart rate variability for RF compared to SF.

The results of statistical testing also indicated that there are significant differences ($p < 0.05$) between SF and RF between all measured RQA parameters. Statistically significant increase or decrease of measured parameters is depicted on Fig. 3. The importance of increase or decrease in respective parameters is the subject of discussion.

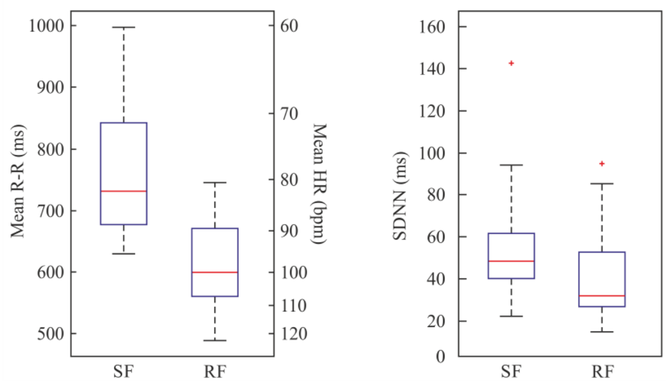

Fig. 2 Graphical representation of Mean R-R and SDNN distribution for pilots' heart rate during performing simulated (SF) and real flight (RF)

4. Discussion

The results of standard analysis demonstrated that in the research sample, psychophysiological stress load is higher in case of RF. During RF, significant increase in heart rate frequency with simultaneous decrease in heart rate variability was observed, what clearly indicates higher pilots' stress load [5]. This was in line with expectation.

RQA parameters support these finding. RP average length of diagonal line (AVDL) reflects average time during which two trajectory segments in phase space are close to each other (in distance =< ε). Regarding R-R intervals measurement, greater AVDL value indicates lower variability for group of subjects performing RF. In other words, RF group subjects exhibit less variance from mean heart frequency. LAM parameter indicates laminar state duration. It is a state where the dynamics of the system does not change or it changes only marginally. In case of a signal given by R-R intervals, the LAM parameter indicates decreased heart rate variability for RF.

DET (percentage of points comprising diagonal lines in RP) indicates that the system is more frequently returning to its previous states. The higher the determinism, the more frequently the system returns to its previous state. This is relates with system's foreseeability, i.e. the greater the DET the more foreseeable the system. Regarding the signals measured, DET indicates lower RF variability compared to SF.

RATIO is the ratio between DET and recurrence rate. In this case, DET is divided by constant (due to the fixed setting for percentage of recurrence points in RP) which means that, in terms of this study, the parameter has no special significance and its interpretation is similar to DET. In case of other type of thresholding (which will not ensure fixed setting for percentage of recurrence points in RP), the ratio between DET and recurrence rate could be used for revealing of hidden transitions [13].

ENTR parameter is derived from Shannon entropy where greater entropy means wider span of diagonal lines length (demonstrable in histogram) in RP. Greater ENTR value for RF group would mean greater variability in length but it is necessary to realise that average lines length for this observed group is greater thus more span for variation of diagonal lines length exists. In essence, this parameter points to previous findings concerning AVDL and DET. ENTR parameter is in case of this study a side-effect, complementing and confirmative figure. Information value of this parameter would be higher for system descriptions, where average length of diagonal line and number of points comprising diagonal lines would be comparable, i.e. statistically indistinguishable.

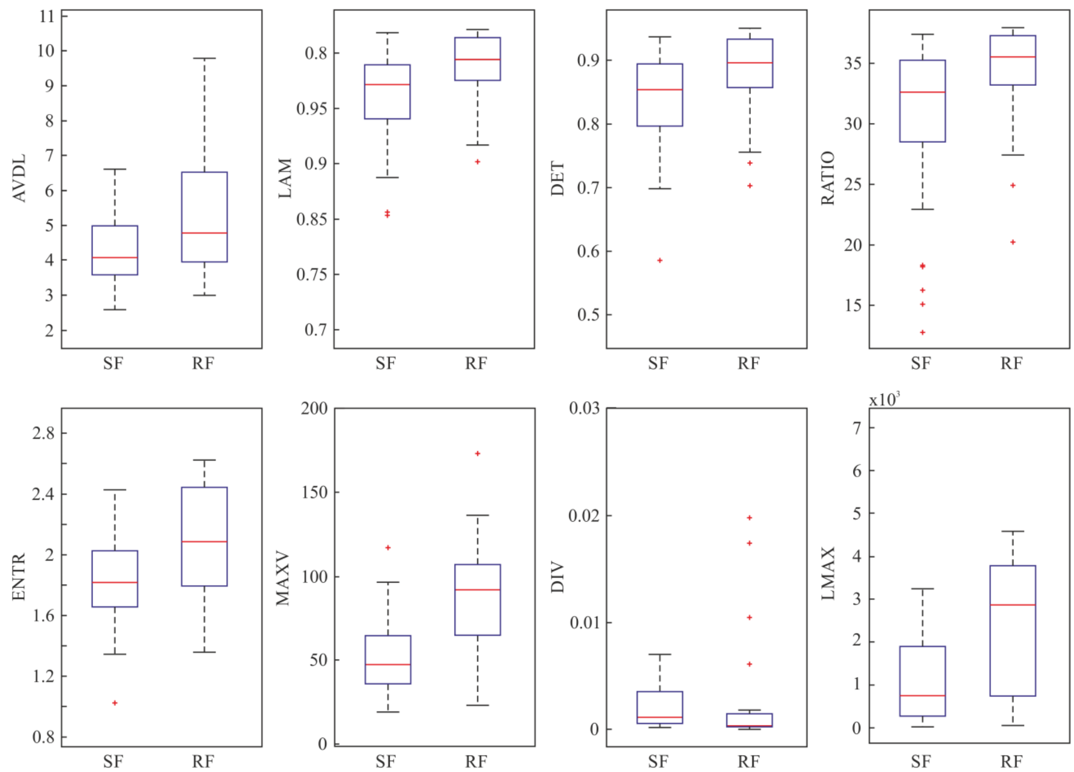

Fig. 3 Graphical representation of RQA parameters' distribution for pilots' heart rate during performing simulated (SF) and real flight (RF)

MAXV parameter denotes value of shortest vertical line. This value determines longest stay in specific state. In terms of evaluating signals of R-R intervals it is possible to tell that in case of RF the system remains in specific state longer compared to SF, what also indicates lower variability of heart rate for RF.

Maximal length of diagonal line (LMAX) in RP denotes longest time period during which the trajectory in phase space runs parallel to other segment (at distance $=< \varepsilon$). LMAX is closely related to divergence (DIV) where DIV is inverse value of LMAX. Both DIV and LMAX relate to the maximal Lyapunov exponent. Chaotic attractors are characteristic for their high sensitivity to initial conditions. It is possible to quantify the degree of chaotic nature by means of Lyapunov exponent. The exponent shows whether trajectories close to attractor converge or diverge. There are several of such exponents for each system or more precisely exactly one for each its dimension. The most important is the maximal one. In simple terms, maximal Lyapunov exponent is mostly influenced by long-term system behaviour and it is used as one of the indicators of chaotic nature. LMAX and DIV parameters then describe foreseeability of the system where greater DIV (lower LMAX) indicate lower foreseeability and vice versa.

Generally, the results in both cases (standard parameters and RQA parameters) demonstrate decrease in heart rate variability when performing real flights. Taking into account that at higher psychical or physical load, the heart rate increases with simultaneous decrease in its variability [5], it is possible to say that RQA parameters are capable of distinguishing such state. RQA parameters provide relevant information about psychophysiological condition of monitored pilots and they are able to describe complex system's behaviour based on R-R interval monitoring.

5. Conclusion

Aviation accidents are mostly caused by human factor, i.e. by pilot, co-pilot or the rest of flight crew. Due to this, it is suitable to monitor mental state of flight crew to ensure safety. The goal of this study was monitoring of pilots' psychic state during simulated and real flights using physiological data, i.e. ECG signal. Such monitoring can timely point out the change in pilot's physical state what makes it possible to prevent errors emerging for instance from higher mental load.

The study utilised standard ANS activity evaluation methods – mean R-R and SDNN. Non-linear data analysis RQA was used. The results indicate that during transition from SF to RF there is increased heart rate coupled with decrease in its variability what indicates higher stress load for RF. Identical results were achieved during all three types of analysis. This confirms suitability of RQA application for stress quantification. Although the RQA is not used for evaluation of pilots' mental state, compared to standard methods it provides the ability to monitor entire dynamics of the system, i.e. its behaviour description. RQA utilisation thus can lead to flight safety improvements.

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K Článok 11

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Determining Importance of Physiological Parameters and Methods of Their Evaluation for Classification of Pilots Psychophysiological Condition

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***Abstract*— At present, several studies exist describing the relevance of human factor in air transport with main focus on pilots and flight safety. Within such studies, monitoring of physiological functions is used. There are lot of physiological parameters and methods of their assessment; however, they are mostly based on principles originating from clinical practice. Yet, sensitivity and specificity of these methods with regard to assessment of aviation professionals - pilots is unknown. Therefore, this paper is oriented towards description of the most common methods for physiological parameters assessment. The paper also describes evaluation methods, which are on experimental level in terms of physiological data evaluation, namely recurrent quantification analysis. Within the research carried out, sample group of pilots was subjected to measurement for evaluation of their psychophysiological condition and performance. Selected evaluation methods were applied on the collected data and importance of those parameters and methods, which provided best classification for level of psychophysiological stress, was evaluated by means of statistical analyses. The results indicate that the most important physiological parameter for psychophysiological condition assessment of pilots is heart electrical activity where the possibility to perform signal processing whilst preserving its importance is provided by linear methods in the time and frequency domain, or alternatively by non-linear methods utilizing recurrent quantification analysis.**

***Keywords*— air transportation; biomedical signal processing; biomedical telemetry; decision trees; nonlinear dynamical systems; regression analysis**

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I. Introduction

In the domain of aviation, whether military of civil transport, operators are making efforts to achieve maximum comfort and safety for passengers. Available statistical data dealing with aviation accidents are varying in the number of accidents and their causes, but it is possible to claim that pilot error contributed to 60 % of fatal accidents. For example, according to the statistics of PlaneCrashInfo [1], 58 % of aviation accidents from 1/1/1960 up to 12/31/2015 was caused by fatal piloting errors. Most of these errors occur during landing phase, but almost 28 % takes place during routine flight phases [1].

Piloting errors are caused by different factors, for example by fatigue accompanied with reduced attention, stress, pilots' psychical condition and also by insufficient experience with critical situations. Timely recognition of limit pilot fatigue, drop of situational awareness or stress by means of monitoring physiological parameters could prevent aviation accidents. This stems from the fact that during a flight, number of specific effects influence human organism and they depend on physical properties of the surrounding environment, aircraft technical properties, demanding character of required activity as well as mutual influence of the mentioned and other effects on physiological functions [2]. It is possible to obtain information about pilot's psychical and physiological condition [3] by measuring his/her physiological parameters.

There were lot of studies with the goal to improve safety and effectivity of military and civil aviation flying regarding its control and monitoring [4], [5]. In this sense, most of the studies were focused on mental and physical condition of aviation professionals (pilots, air traffic controllers etc.) by means of monitoring heart rate, breathing, blood pressure, blood saturation with oxygen, electrodermal activity etc. [6], [7], [8], [9]. Stress emerging from actual situation, which respective subject is confronted with, plays the key role [10]. Physiological function, such as heart rate, unfold from this condition, originating from human neural system. Part of the neural system is autonomic neural system (ANS), consisting of parasympathetic and sympathetic elements, which serve control of internal organs activities. Even small deviations from the so-called sympathovagal balance may be caused by stress situation. Therefore, it is important to timely identify changes in ANS and take adequate measures to reduce or eliminate stress situation and its negative effects on human activity.

In this way, many studies concentrate on individual parameters, which may have insufficient explanatory value, but the measurement of physiological parameters is more effective if multiple physiological measurements, which are mutually relevant, are merged. Analysis of such data and subsequent possibilities are extensive and there are many methods for biological signal processing; important is, however, which parameter is concerned, how to measure it and how to process such signal. Nevertheless, ordinary and clinically utilized systems appear not suitable for recording of such signal during performance of piloting activities. For majority of cases, the reason is their robustness and potential restrictions for working activities. With regard to this, mobile biotelemetry systems come to the fore which are, due to the mentioned reasons, used also in this study.

Based on the above-mentioned, experimental measurements were carried out to identify optimal usage of measured physiological parameters and methods of their evaluation to describe psychophysiological condition of pilots. Within the presented research concept, monitoring of piloting precision was used as comparative indicator of pilot's stress and performance.

II. Materials and Methods

A. Participants

For the purpose of this study, selection of candidates from students of Technical University in Košice was performed. The goal was to select representative sample of subjects (consisting of beginners) with the largest level of uniformity possible. The selection was conditioned by meeting selection criteria, which consisted of successfully passing psychological and intelligence tests. Intelligence tests were focused on aviation regulations and basics of flight. Apart from that, participants had to meet the criteria for medical fitness according to Commission Regulation (EU) No 1178/2011, Annex IV [11] and could not be holders of a pilot license of any type (ULL, PPL or higher). This way, 35 subjects were selected (27 men and 8 women of average age 2 $\pm$ 4 years), who met the above-mentioned criteria.

B. Measurement Procedure

The general measurement methodology, regarding flight execution and evaluated subjects, was the same as in the previous study (see [12]). First part of the training took place on TRD40 flight simulator equipment, second (real flights) was executed on Diamond DA40 aircraft. During individual flights, the participants had to perform three precisely defined flight manoeuvres series during which they had to maintain prescribed flight parameters. Each of the series consisted of four flight tasks in predefined sequence: horizontal steady flight (HPL), horizontal 360° turn (H360) with 30° bank angle, 180° climb and descent turn with 15° bank angle and vertical speed of climb/descent equal to 500 ft/min. The entire flight consisted of the following: departure, three HPL series, H360, C180, D180 and landing. Obeying the prescribed flight sequence, uniformity of training and measurements was assured.

The entire training consisted of 17 flight lessons, where the above described series were repeated in each flight lesson. The subjects first finished the training part on flight simulator (11 lessons), then completed 1 real flight lesson followed by another 3 flight simulator training lessons and the training was finished by 2 lessons of real flying. Maximum time span between individual training lessons was 2 days. The entire training was done with analogue flight, navigation and engine gauges in the flight deck of both the simulator and real aircraft. For uniformity assurance, all flights were executed under uniform meteorological conditions with no or few clouds, ground visibility and in terminal manoeuvring area of Košice International Airport (ICAO code: LZKZ).

During selected flight lessons, a pair of measurements was conducted where piloting precision of individual manoeuvres was monitored and list of physiological parameters was recorded. Within the training, these measurements were conducted during lessons 2, 6 and 11 (simulated flights) and during lessons 12 and 17 (real flights), see Fig. 1.

Physiological parameters measurements were performed using modular telemetry system FlexiGuard [13], [14]. This system was conceptually aimed to build sensory network allowing wireless transmission of physiological and environmental variables measured on the body of its user. Sensory base for performing measurements was, owing to system modularity, adjusted for application purposes and based on typically measured variables [15], [16], heart rate, respiratory rate and myopotential measurement sensors were selected. The location of individual sensors was picked to acquire signal of the highest quality. Sensors location on test subject is depicted in Fig. 2.

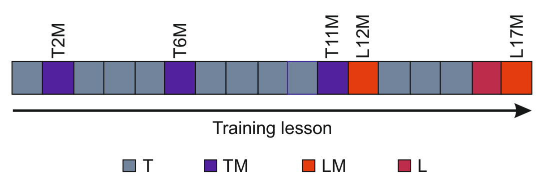

Figure 1. Training schedule (T – flight simulator, TM – flight simulator measurement, LM – flight measurement, L – flight).

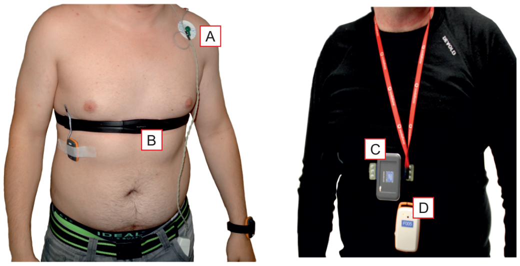

Figure 2. Location of FlexiGuard modular telemetry system sensors on test subject (A – myopotential sensor, B – heart rate sensor, C – respiratory rate sensor, D – modular sensing unit (MSU)).

On the figure, respiratory rate sensor is put on inner layer of test subject clothes because it did not require direct contact with skin.

C. Physiological Parameters Evaluation Methods

For heart rate data processing, only the values of RR intervals were used (time intervals between R peaks of QRS complex of ECG recording). Although the Flexiguard system offers data on heart rate also in bpm (beats per minute) units, the rate can be calculated using RR intervals, not to mention that most studies dealing with ECG processing use the above mentioned time difference between RR peaks [17].

RR intervals recording was evaluated using standard methods of time series analysis. Specifically, an average value of measured RR intervals, standard deviation of RR intervals (SDNN) and root mean square of the successive differences (RMSSD) [18] were calculated. Further, Kubios® software environment was used for data processing using spectral analysis [19]. Other output parameters were obtained as performance in frequency bands describing three basic spectral components: very low frequency (VLF), low frequency (LF) and high frequency (HF). The VLF band ranges between 0.01 – 0.04 Hz and describes the slow mechanisms of sympathetic system. The LF band is in the range of 0.04 – 0.15 Hz and characterizes both sympathetic and parasympathetic system, but, in general, it is considered as a strong indicator of sympathetic activity. The HF ranges between 0.15 – 0.4 Hz and reflects parasympathetic activity. Another parameter characterizing the spectral analysis is total performance (TP) which is an estimate of total spectral performance, i.e. all bands of 0.01 – 0.4 Hz, indicating overall ANS activity. However, the initial parameter is a low to high bands ratio (LF/HF) because it describes the total balance between sympathetic and parasympathetic component of ANS.

Data characterizing the number of breaths and myopotential activity were processed using standard analysis in time series domain, i.e. average respiratory rate and its variance were calculated. Pulse, respiratory rate and myopotentials data were also processed by recurrent quantification analysis (RQA). Recurrent analysis is one of the non-linear data analyses derived from chaos theory. Recurrence is an essential property of such dissipative dynamic systems. Recurrent graphs, the basic recurrent analysis tool, allow repetitive behaviour visualization of dynamic systems. The method is also suitable for non-linear analyses of short-term and non-stationary data [20]. This method of signal processing was used due to non-linear nature of autonomous neural regulation. Recurrent analysis procedure could be divided into three parts. The first step is, as for most of non-linear techniques [20], reconstruction of phase space. The second step is production of recurrent graph using threshold distance as an input parameter (see [21], [22]). Calculation of RQA variables is the last step of the analysis. It is a percentage of recurrent RR points, which form the recurrent graph. This parameter corresponds to the probability that particular condition will recur. Higher recurrence means a lower system variability and vice versa [23], [24]. Determinism DET is a parameter, that represents a percentage of recurrent points that form diagonal lines. Diagonal lines indicate that the system is returning to previous state at a different time. The determinism parameter is related to the predictability of dynamic systems. Laminarity LAM refers to the percentage of points that form vertical lines. This parameter is used for detection of laminar states, i.e. states, when the system does not change or it changes very little. Trapping Time TT is a parameter that labels an average length of vertical lines. This parameter denotes how long the system remains in a particular state and it includes information about frequency and length of laminar states. Low LAM and TT values indicate significant system complexity, i.e. the system returning to previous state only for a short period of time [24]. Other parameters of RQA include maximum length of diagonal line $Lmax$, divergence DIV (inverse value of $Lmax$), average length of diagonal line $AVDL$, ratio $RATIO$ (ratio between DET and RR), Shannon entropy $ENTR$ and maximum length of vertical line $Vmax$. To evaluate data using the described analysis, MATLAB environment was used to create software according to mathematical definitions [21].

D. Piloting Error Rate Evaluation

For piloting precision processing, two types of data sets were available, namely instructor notes and flight records.

Each manoeuver had prescribed flight parameters or more precisely rules, about which the subjects were informed during theoretical preparation. In case of HPL manoeuver and with regard to the precision, the most important was to maintain constant altitude whilst the altitude itself (its value) was not important. Further, it was important to maintain constant heading whilst the heading itself (its value) was again unimportant.

In case of H360 manoeuvre, the pilot was supposed to perform horizontal turn, whilst aircraft bank angle had to be constant at the level of 30°. The pilot had to maintain also constant altitude. During C180 or D180 manoeuvre, all subjects performed climb or descent 180° turn where the vertical speed of climb or descent was prescribed as constant to 500 ft/min and the prescribed bank angle was 15°.

The precision evaluation itself for data gathered from flight simulator was described in detail within conference paper named "Evaluation of relationship between the activity of upper limb and piloting precision" [25]. The evaluation methodology relies on the assumption that in case of sufficient number of recorded values for respective flight parameter (n $\rightarrow \infty$), arithmetic mean of monitored parameter will approach real prescribed value. In essence, it is then possible to quantify error rate by calculating standard deviation.

The problem occurs when assessing real flights because for the research there were no data available from aircraft flight data recorder. This problem is partly resolved by instructor notes on piloting precision. Instructor manually recorded deviations during each individual manoeuvre. The deviations were recorded as maximal deviations from prescribed values (altitude, bank angle, vertical speed etc.), which were to be maintained by respective subject. In the previous study, piloting precision evaluation was compared with calculated deviations. Authors used the same data as in case of this work. The analysis showed that error rate calculated and evaluated by instructor mutually correlates and so it is possible to use only instructor notes for further evaluation.

For piloting precision evaluation, only instructor notes were used in this work. The data were divided into data sets describing precision when executing prescribed flight parameters and subsets defining measurements (T2M, T6M, T11M, L12M a L17M). In other words, all error rates from all subjects were included in the measurement categories. Within the statistical evaluation during the first phase, sub-data sets normality was evaluated by means of Kolmogorov-Smirnov test. The testing was performed on level of significance $p = 0.05$, where the hypothesis of normality was concluded with $p < 0.05$. Normal distribution was not identified in any case, i.e. for any sub-data set. Due to this, Wilcoxon test was used for further statistical evaluation to identify significant differences between groups. Hypothesis of significant difference between sub-data sets was concluded with $p < 0.05$, where all groups of measurements were compared with each other.

Overall progress of the training with regard to piloting precision as an indicator of performance, or more precisely pilot experience, is described more in detail within complex study dedicated to this issue [12]. For the purpose of this study, however, it was necessary and sufficient to consider normalized training progress. It was possible to calculate normalized progresses based on statistically significant differences between medians of individual training phases. These progresses were established based on error rate medians for specific manoeuvre and monitored flight parameter. They were then recalculated into single scale according to the maximum value from monitored data set. The normalization took place in line with equation:

$$N_i = \frac{med_i}{max(med_1, med_2, \ldots, med_n)}, \quad (1)$$

where N_i is i-th normalized value, med_i is i-th median from monitored data set (where $i = 1 \ldots 5$, for each measured training phase) and max is maximum of observed medians. Normalized progresses are depicted in Fig. 3 together with resulting average progress of piloting precision. The average progress was used as standard for evaluation of data gathered from evaluation of selected physiological parameters.

E. Statistical Analysis

Progressive regression method was selected for the choice of the most important parameters. The method performs the so-called stepwise regression, which is a systematic method for adding and removing terms from multilinear model based on their statistical significance in a regression. The method begins with an initial model and then compares the explanatory power of incrementally larger and smaller models. At each step, the p value of an F-statistic is computed to test models with and without a potential term. If a term is not currently in the model, the null hypothesis is that the term would have zero coefficient if added to the model. If there is sufficient evidence to reject the null hypothesis, the term is added to the model. Conversely, if a term is currently in the model, the null hypothesis is that the term has zero coefficient. If there is insufficient evidence to reject the null hypothesis, the term is removed from the model [26].

Basic classification criterion (or more precisely classification vector y) was, in case of addressing the mentioned issues, established based on piloting precision evaluation. Monitored parameters progresses, within statistical evaluation of piloting precision, pointed to behaviorality of tested subjects. To establish optimal classification vector y, median progresses for each monitored parameter were averaged and normalized. The result was vector $y = [0.7426\ 0.4041\ 0.2571\ 1.0000\ 0.6880]$. The values correspond to individual training phases, their progress

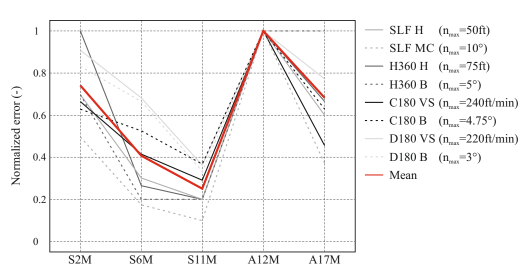

Figure 3. Depiction of normalized error rate courses for monitored flight parameters during executed flight manoeuvers (SLF – steady level flight; H360 – horizontal 360° turn; C180 – 180° climb turn; D180 – 180° descend turn; H – height; MC – magnetic course; B – bank angle; VS – vertical speed; nmax – normalization coefficient representing the maximum in given dataset) [12].

is logical and, in essence, it corresponds to logical assumption about the training. It is possible to describe the assumption as:

"All monitored training phases will exhibit statistically significant difference where the total psychophysiological stress during training on flight simulator will significantly decrease and during first flight on real aircraft then significantly increase compared to previous measurements. At the final stage, i.e. during second flight in real aircraft, psychophysiological stress will significantly decrease in comparison with the previous fight."

The above-mentioned classification criterion "y" is thus criterion established based on exact results from piloting precision evaluation and it also meets logical consideration, which can be named as base hypothesis.

The classification criterion was further used to select the most statistically significant parameters. The selection was performed in MATLAB environment using function stepwisefit. Based on the performed analysis and within the indicated steps, the parameters from data matrix listed below were selected as the most significant.

- Step 1, added column 1, $p = 2.5311 \cdot 10^{-06}$
- Step 2, added column 2, $p = 0.0416275$
- Step 3, added column 9, $p = 0.0170257$
- Step 4, added column 18, $p = 0.0302947$
- Step 5, deleted column 2, $p = 0.17803$
- Final selection of columns: 1, 9, 18

Column 1 represents Mean RR, column 9 is HR RATIO and column 18 is HF. SDNN parameter (column 2) was deleted by backwards elimination. The testing was conducted at the level of significance $p = 0.05$. Parameters, which will be used for further evaluation are thus Mean RR (mean value of R-R intervals, i.e. intervals between individual heart beats) or Mean HR (mean heart rate), HR RATIO (RATIO parameter for heart rate from recurrent analysis) and HF (high-frequency band spectral density for R-R intervals). From the nature of the processing, it follows that the selected parameters are linearly independent.

Subsequently, importance for the selected parameters was determined. Importance calculation was formulated by Friedman [27]. The calculation is based on frequency of variable for splitting and it is weighed by the squared improvement to the model, which is a result of each splitting followed by averaging across all trees. If needed, predictor importance was scaled according to their portion so that the total importance was 100 % [28].

III. Results

Tables presented below show the distribution of Mean RR parameter (average time between RR intervals – heart beats), which was marked as the most important by progressive regression. The parameter is presented as sample, due to the assumption of corresponding progress with other selected parameters, i.e. HR RATIO (RATIO from heart rate recurrent analysis) and HF (evaluation parameter of sympathovagal activity symptoms using frequency analysis). Interpretation of training progress based on psychophysiological condition is, therefore, comprehensively assessed using the example of Mean RR. Graphical representation of the results is in form of box-plots showing distribution of monitored parameter for all subjects from evaluated training phases (T2M, T6M, ...).

The tables represent results from Wilcoxon text in the form of p-values. The test was selected considering the normality of data (examined by Kolomorgov – Smirgov test), where the hypothesis about normality on the level of significance $p < 0.05$ was not concluded for all observed groups. Therefore, this condition determined non-parametric form of testing of inter-group similarity. The testing was done on level of significance $p = 0.05$, where values of $p < 0.05$ concluded the hypothesis about statistically significant inter-group difference.

When evaluating Mean RR parameter, significant differences between T2M and T11M, T2M and L12M, T6M and L12M, T6M and L17M, T11M and L12M, and T11M and L17M (Tab. I) were discovered. The interpretation of the discovery can be following. The mean RR interval increased between the first and second measurement on flight simulator. This increase, however, is not statistically significant, although the testing showed that resulting level of significance of inter-group difference is $p = 0.084$, which is a value not too different from 0.05. Subsequently, the median of average time between RR intervals decreased minimally. The decrease, however, is not statistically significant compared to T6M. On the other hand, statistical significance became evident in comparison to T2M measurement. During the first measured flight on DA-40 aircraft, rapid decrease in Mean RR parameter was recorded and this decrease exhibits statistically significant difference from previous measurements. Measurement L17M is, with regard to the evaluated parameter, on the same level as T6M measurement. Described progress is shown in Fig. 4.

Regression trees providing information about strength of classification predictor were used for backwards classification of subjects into individual groups. Testing and training group were randomly selected in a ratio of 70:30. In case of this analysis, the classification predictors were the above-mentioned selected parameters. The analysis was carried out with regard to verification of parameters significance and their capability to assign subjects into respective phase of training.

In the case presented in Fig. 5, the subjects were classified into individual groups. The importance of predictors

TABLE I
Wilcoxon Test Results for Heart Rate Mean RR Parameter

	T2M	T6M	T11M	L12M	L17M
T2M	1	0.0844	0.0318	0.0038	0.2447
T6M	0.0844	1	0.7177	0.0007	0.0207
T11M	0.0318	0.7177	1	$9.74\ 10^{-06}$	0.0021
L12M	0.0038	0.0007	$9.74\ 10^{-06}$	1	0.1719
L17M	0.2447	0.0207	0.0021	0.1719	1

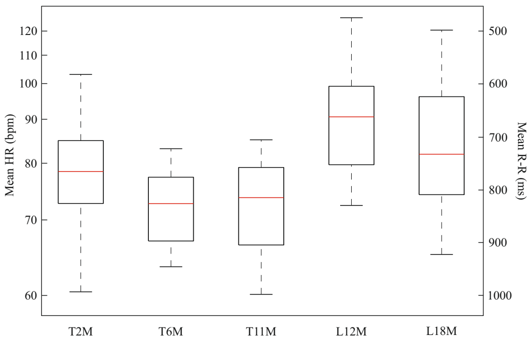

Figure 4. Mean RR and Mean HR parameters distribution for heart rate in the form of box-plots for each measured flight lesson.

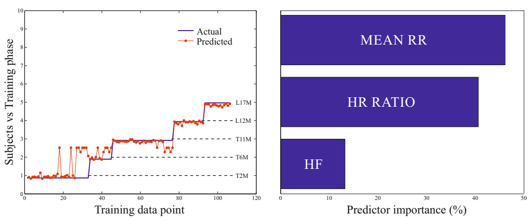

Figure 5. Backwards classification of subjects into groups using selected heart rate parameters (left) and their importance (%) (right).

was in the following sequence (from highest to lowest): Mean RR (or Mean HR), RATIO and HF.

IV. Discussion

The study results show that change of psychological stress was not reflected by each monitored physiological parameter but only by evaluated parameters based on heart activity. Based on the performed multi-regression analysis, no relationship between all monitored parameters was found, except between mean value of heart rate R-R intervals (Mean RR) or mean heart rate (Mean HR), RATIO parameter for heart rate from recurrent analysis and high-frequency band spectral density of RR intervals for heart rate.

Based on the results, monitored Mean RR parameter can be pronounced as characterizing pilot training progress with regard to psychophysiological stress, describing it as continuously decreasing during flight simulator training. The stress significantly increased during the first flight on DA-40 aircraft and during next flight lesson (L17M) it decreased to the level of T6M.

Interpretation of Mean RR parameter progress is the same as for Mean HR. Mean RR parameter is one of the main indicators of heart rhythm variability, which increase indicates higher psychophysiological stress [29]. It means that graphs presented in Fig. 4 exibit inverted progress compared to the progress of Mean HR.

The results also show that the parameters characterizing heart rate as an indicator of psychophysiological condition are more significant than all other parameters considered in this work. HF parameter itself reflects parasympathetic activity of autonomic nervous system of human organism. RATIO parameter represents return of the system to previous states, i.e. for RR intervals analysis this parameter reflects heart rate variability.

V. Conclusion

The goal of this study was to determine the utilization of selected physiological parameters and methods of their evaluation with regard to description of pilots psychophysiological stress. The measurements of physiological parameters of group of subjects undergoing flight training took place according to defined training methodology. To ensure measurement uniformity, research sample selection was performed based on psychological testing, comparable age, flying experience and health conditions of the subjects. During the training, data collection consisting of selected physiological parameters (respiratory rate, heart rate, myoelectric activity) and evaluation of piloting precision of selected flight tasks were carried out in accordance with training methodology.

Data evaluation was performed at two levels – assessment of piloting precision and evaluation of physiological parameters. Standard and experimental methods, regularly used for the purpose of physiological parameters evaluation, were chosen. From standard methods, methods for evaluation in the domain of time-series and frequency were used. In addition, a method not typically used for evaluation of physiological parameters was selected. It is called recurrent analysis and it is based on investigation of chaotic signals seasonality. Using statistical methods and approach, separation of the most important physiological parameters and methods of their evaluation was achieved. Also, importance of monitored parameters with regard to classification prediction was determined.

Based on the results, it was possible to determine suitable methods for evaluation of physiological parameters and to determine suitable physiological parameters serving as indicators of psychophysiological stress, which enables starting points for further practical research in this field.

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L Článok 12

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"Generating synthetic aviation safety data to resample or establish new datasets"

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Generating synthetic aviation safety data to resample or establish new datasets

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ABSTRACT

Aviation safety data are limited in availability due to their confidential nature. Some aggregated overviews already exist but in order to effectively use the data, it is important to fill the gaps of their existing limitations. For some data, there are not enough data points in order to process them through advanced analysis. For other, only expert assumptions can be obtained. In both cases, these shortcomings can be addressed via proper data resampling or simulation where little effort can make the data suitable for various research and development initiatives. Examples of real aviation safety data made public are demonstrated together with key principles of how to perform their resampling. Then, for cases where only expert assumptions are available, general solution to the transformation of the assumptions into simulated data is introduced. The goal is to demonstrate how to transform accessible data or knowledge about aviation safety into data samples with sufficient granularity. The results provide general solution suitable not only for aviation safety data and knowledge, but also for similar transportation or high-risk industries related data issues, indicating that both the data resampling and simulation provide an option for generating datasets, which can be used for statistical inferential methods, linear regression modelling, recurrent analysis etc. Example of data resampling application is included in Aerospace Performance Factor calculation for years 2008 up to 2015.

1. Introduction

To date, aviation safety is subject of intensive research in terms of new information technology deployment. It is recognised, that further progress in this domain can be achieved by implementing technology, which collects, processes and analyses safety data in order to produce system-wide information of how the system performs on safety (ICAO, 2013). This information is to be used for safety-critical decision-making within safety management system as far as the aviation is concerned, but this principle is generally true for other high-risk industries as well (Niu and Song, 2013; Klein and Viard, 2013). One of the features of the system-wide information is that it cannot be reliably derived by individuals from the data available because aviation became very complex, i.e. hardly manageable for humans. The industry is distributed system of many types of stakeholders (airspace users, organisations, regulators, manufacturers, policy makers etc.) which use different technologies, different procedures and which overlap with each other to various extent. As a result, safety performance of one stakeholder may be severely affected by how safety is managed by other stakeholder and it can be difficult to identify this from either side.

Today's accidents only support this claim. They consist of long chain of events and contributing factors, which typically exceed responsibilities of one stakeholder and its safety management (Socha et al., 2014). From the perspective of managing safety, it is important to have some sort of full picture to be able to apply effective measures to prevent modern accidents. The distributed character of aviation, however, sets constraints for achieving such a full picture. Not only are the data and the full picture to be established distributed in parts among the stakeholders, but also the nature of both is often confidential and may have potential to damage someone's position on the market, if misused. Aviation authorities encourage organisations and other stakeholders to share safety data, experience and safety knowledge (ICAO, 2013; European Commission, 2010) but the degree of these activities is still not perceived to be satisfactory. This paper does not aim to resolve this issue but rather address its consequences, namely limited safety data availability.

Research and development initiatives in the domain of aviation safety are restricted by the safety data not being available. Whilst it may be possible to sign some bilateral confidential agreement between two parties, this is still rather difficult to achieve for multiple

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stakeholders at the time. Fortunately, some of the data are regularly (annually) published by authorities in form of aggregated overview of key safety issues (such as Safety Regulation Commission, 2016; EASA, 2016 or Federal Aviation Administration, 2015), but this is true only for some segments of the industry, e.g. for air navigation services providers (ANSPs). These providers have a lot of advanced technology and data at their disposal and they are typically state-owned monopolies, which are not subject of market competition. The latter was likely the key factor for making some of their data publicly available.

To better understand the issue, it is important to note basic facts of data evolution in this domain. Safety was always measured indirectly, i.e. through its absence (Reason, 2000). It is quite hard to find any effective way to measure it directly as it is the case for conventional measurements related to more tangible issues (Hanakova et al., 2017). Overall safety is intangible system property and even where it is possible to measure it directly, it is often impractical because measuring the things which go right simply means a lot of effort to be spent in order to have meaningful records. Unlike safe state, unsafe outcomes are not only less frequent but they are much more tangible thus considerably easier to track (Hollnagel, 2014). Aviation accidents and incidents attract society from early days of its existence and for decades they were the best driver for safety improvements. As soon as they became rare, the focus just shifted to incidents and safety occurrences with their contributing factors, which, according to investigations, lead to the accidents.

Recently, a new type of data emerged in this domain. Tracking back the root causes of accidents led to the discovery of the so-called organisational factors denoting those contributing factors, which stem from how safety management and safety oversight work (ICAO, 2013). Until the discovery of the importance of how aviation organisations and regulatory bodies are set up as entities, no safety management system nor any sophisticated safety oversight were needed. Progressive requirements for gathering how organisations and regulatory bodies approach safety from management perspective appeared first around the year 2010 (European Commission, 2010; EASA). These requirements established datasets different in their very fundamentals; they assess activities which can hardly be associated with specific unsafe behaviour but which are capable of generating background on which unsafe behaviour emerges. Starting to collect this type of safety data was significant milestone for aviation safety as it brought the industry closer to generate the full picture.

Nowadays, we are closer to the full picture as the content of collected data evolved, but due to the insufficient data sharing and confidentiality restrictions, they are typically not available for research and development initiatives. This inhibits the progress of introducing new technology which could integrate and process the data so that all parties would benefit from industry-wide, open data based knowledge. So has the progress to be achieved the other way. Current research initiatives have to make the best use of public but restricted data samples to come with solutions that aviation organisations may trial and which would expedite establishing the full picture.

Data scarcity, however, is not a new issue. There are several studies available to date, which propose methodologies to overcome this issue in different applications. In fact, very few deal with this problem in scope of safety (such as Yu et al., 2017; El-Gheriani et al., 2017, which are only oriented to major accidents); much more frequent are studies oriented to system reliability, failure and risk assessment in terms of data uncertainty and its reduction. Both safety and reliability oriented studies are typically using Bayesian approach in some variations to produce a posterior distribution by combining data, expert knowledge or various simulation results. Among other methods, first order reliability method and Monte Carlo simulation (Awadallah et al., 2016), or grey system theory (Wen et al., 2011) are used in respective applications. Special attention in the literature is paid to expert elicitation, which was already formalised in several publications (such as Meyer, 2001; Keeney and von Winterfeldt, 1991 or Aven and Guikema, 2011). All the methodologies are, however, difficult to apply directly on the problem in this work as they require various inputs which are out of the scope of this paper. The problem here is of more generic nature, even though it can be complemented with the methods from other studies.

With respect to the afore-mentioned, this article describes the public aviation safety data in detail and provides solutions for how to overcome their limitations. It suggests generating either synthetic aviation safety data or resampling the data already available. The motivation to use data resampling is based on the need to decompose existing signals to increase their granularity for the purpose of further processing and analysis. Data simulation complements this approach by extending the possibility to generate entirely synthetic signals.[1] Synthetic data have their apparent limitations but the important aspect is that they can enable application of advanced analyses, even for experimental or learning purposes only, where real data do not allow it. Direct application of mathematical tools and methods, such as statistical inferential procedures, autoregression or recurrent analysis, to make inferences about safety performance (the full picture) would be otherwise impossible. To enable the tools and methods, it is important to resample the data, i.e. to transform annual figures into month, week or day distribution. For cases where no data are available, simulation based on expert assumptions can provide the solution.

Taking into account the goal, this paper deals with methodology of both data resampling and simulation. It describes data and identifies the gap for improvement. The methods are applied on selected figures from real datasets in the domain of aviation safety. At the end, aviation safety performance is computed using the resampled data to exemplify the contribution of the proposed solution.

2. Methods

This section details the proposed methodology to achieve the goal of this paper. At first, aviation safety data are specified, including their sources, relevant issues and examples. At second, data resampling follows with description of key principles of how to combine expert knowledge and real datasets to increase data granularity by the means of mathematical functions. Lastly, after the outline of data resampling principles, the methodology further specifies data simulation in order to extend the principles of generating synthetic data to situations where no real data are available.

2.1. Data characteristics

Aviation safety data comprise accidents, incidents and safety occurrences. The data are available in form of aggregated figures denoting number of observations of respective accident, incident or occurrence during given time interval. Additionally, new data types were recently introduced to aviation through the European Union-wide (EU-wide) safety key performance indicators (SKPIs) (European Commission, 2013), which are based on the so-called organisational factors. However, these are using artificial scores and due to their novelty, inherent bias and lack of relevant expert assumptions, they are not considered in the methods of this study.

Aviation accident records were gathered reliably till now and they are publicly available together with investigation reports, including conclusions and corrective measures. These data can be found on website of responsible body for respective investigation.[2] But because aviation accidents became rare, they solely cannot be used for safety management today. In terms of any research and development initiatives, much more valuable are data concerning incidents and safety

[1] For further reading on data resampling and simulation methods refer to Lahiri (2003) and Carsey (2014)).

[2] Such as Air Accidents Investigation Institute (2017) in the Czech Republic or Bundesstelle für Flugunfalluntersuchung (2017) in Germany.

occurrences. These data are published on websites of some aviation authorities, but there are not many yet.

One of the most useful data repositories is provided by European Organisation for the Safety of Air Navigation (EUROCONTROL) on its dedicated performance monitoring websites [3,4,5] and in annual safety- and operations-related reports (Safety Regulation Commission, 2016; EUROCONTROL, 2016). EUROCONTROL provides EU-wide aggregated overview of the most common safety issues in the domain of Air Traffic Management (ATM) and ANSPs in form of interactive dashboards (see Fig. 1) together with many other overall performance-related indicators, such as complexity scores, flight delays, traffic distribution etc. Because the most detailed aviation safety data are provided from this domain, they are used to exemplify generating synthetic data.

At the highest level of detail, ATM related safety data are published on (a) Separation Minima Infringements; (b) Unauthorised Penetrations of Airspace; (c) Runway Incursions and (d) ATM Specific Occurrences. The data include severity distribution for the most severe events (severity A - serious incident and severity B - major incident, as defined in (EUROCONTROL, 1999)) and are available back to the year 2004. Federal Administration Authority (FAA) publishes regularly reports of similar quality in the U.S., but unlike in Europe, no data on organisational factors (structure) are provided. In Europe, the data can also be obtained directly from providers' annual reports but these are not all consistent in their content. Some providers are more advanced in safety and others are less, which results in each ANSP publishing different data.

Table 1 demonstrates the Separation Minima Infringements (SMI) in total numbers from year 2008 to 2015. It shows EU-wide figures of these occurrences, where severity A and B Infringements are extracted and stated separately because they represent the most severe outcomes of this type of occurrence.

For aviation organisations other than ANSPs there are almost no data accessible. Owing to the recent initiatives to establish common reporting scheme in the EU (European Commission, 2014), some data from other organisations are already available on the EU level and basic statistics and knowledge were extracted into newest annual safety review by European Aviation Safety Agency (EASA) (EASA, 2016). Compared to the EU-wide data published by EUROCONTROL, however, it does not provide much level of detail, such as distribution per year and month, or per country and airport.

With respect to the mentioned facts, this study demonstrates the basic principles of resampling using data from EUROCONTROL's repositories, which relate to the listed occurrences measured at the highest level of detail. In fact, its data exclusively can be resampled with no need for complementing them with data from other stakeholders to be able to test, for instance, statistical and stochastic tools to analyse the data.

2.2. Data processing

Data processing can be performed using two methods: data resampling and data simulation. The selection of appropriate method depends on following conditions. The first is real data accessibility and the second is expert assumptions availability. In this study, data resampling is used only if real data are accessible and at least some expert assumptions are provided. Data simulation is used to synthesise data vectors where no real data are accessible but expert assumptions exist. It is possible to use the simulation also in case where no data nor any expert assumptions are available but then the output may be highly questionable.

[3] http://ansperformance.eu/.

[4] http://www.eurocontrol.int/prudata/dashboard/eur_view_2014.html.

[5] http://www.eurocontrol.int/prudata/dashboard/rp2_2015.html.

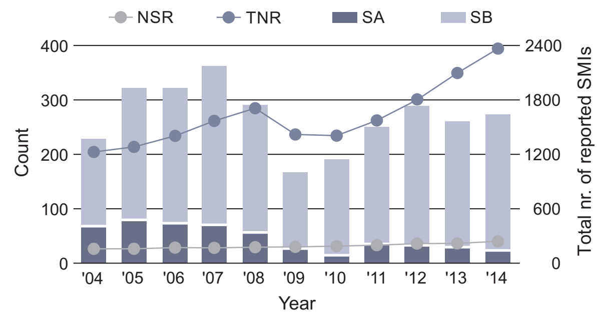

Fig. 1. Separation Minima Infringements (SMI) dataset with number of states reporting (NSR), total number of records (TNR), number of reports with severity "A" type (SA) and severity "B" type (SB).[1] Note that only TNR refers to the right-most y-axis.

Table 1
Separation Minima Infringements (SMI) distribution per year and highest severity.

	2008	2009	2010	2011	2012	2013	2014	2015
SMI severity A	56	24	16	35	29	30	23	20
SMI severity B	236	141	178	217	258	232	250	228
SMI total rep.	1711	1418	1402	1571	1796	2161	2359	2316

2.2.1. Data resampling

First method transforms real data into desired distribution with the help of expert assumptions. Typically, resampling is needed when data granularity is to be increased; even the most detailed data on safety occurrences in aviation are public only as annual figures of occurrence observations but at least distribution by month or week is needed for the deployment of advanced mathematical methods. To resample the data, expert assumptions are to be made before the resampling process starts. In general, regarding safety occurrences similar to SMI, it is true that (a) occurrence rate is higher in summer than in winter; (b) the higher the total amount of reports per year the bigger the difference between peak and trough values; (c) occurrence observations should correspond to the traffic distribution, i.e. maximum number of observations is most likely in July and minimum in January and (d) values are to be natural numbers or zero.

The assumptions are based on following facts. Occurrence rate assumption stems from the fact, that the higher the traffic saturation, the higher the probability of a conflicting situation. This is especially true for today's volumes of traffic reaching maximum capacity of existing airspaces in Europe (Lehouillier et al., 2016) and it is indicated by increasing complexity scores of Europe's ANSPs (EUROCONTROL, 2017). Traffic saturation is known to be seasonal, what can be inferred from traffic figures clearly indicating regular peak values around July and troughs around January, justifying the second assumption. Absolute difference between peak and trough values of occurrence observations during a year can hardly be constant for all safety occurrences; occurrences with hundreds of observations per year should have the difference amplified by their magnitude, causing it to increase. Occurrences with no more than 10 observations per year must remain within their limits. Last assumption relates to the format of occurrences. Any occurrence is a binary variable; either there is an occurrence or there is no occurrence. It is clear that there cannot be negative number of observations and any other than natural number or zero is not conceivable in real world. All these assumptions are general enough to be universal and valid for all safety occurrences similar to the SMI, i.e. for all occurrences on which the data are currently accessible. This is mainly due to the binary property of monitored safety occurrences and their close relation with traffic saturation, especially when reaching limits of given airspace.

Taking into account all these assumptions, following equation provides basic solution to the problem, where the goal is to resample data into any other distribution with higher granularity:

$$N = \int_0^M k\cdot f(x)dx, \quad (1)$$

where N is annual total number of selected occurrence observations, M is scale determined by the new distribution to be produced, k is coefficient of seasonal variance, x represents time and $f(x)$ is time-dependent mathematical function capturing expert assumptions. Scale M is determined by total number of data points to be produced (e.g. $M = 12$ for data distributed by month whilst N is the total figure per year). Coefficient k may be calculated in many ways but it should be in line with provided expert assumptions. If there are no expert assumptions on the coefficient, one of the possible ways to calculate it is to use average occurrence rate N/M as a starting point because the variance typically depends on this rate: the higher the number of observations per event type, the higher the variance. For datasets by EUROCONTROL, the variance is unknown and no expert assumptions can be considered, so the problem is then shifted to the coefficient k. Based on empirical testing in MATLAB environment (MATLAB R2015b, MathWorks, Inc., Natick, MA,USA) for the purpose of this study, reasonable results with the data samples from Table 1 were achieved with $k = 0.25\cdot N/M$ (k amplifies $f(x)$ by 25% of the average occurrence rate N/M). The coefficient may be set differently at ones discretion so that the results copy as much as possible what is supposed to be real.

With regard to the Eq. (1), new data distribution can be calculated as follows:

$$N_i = [k\cdot F(x)]_{i-1}^{i}, \quad i = 1,2,...,M, \quad (2)$$

where N_i is number of occurrences during selected time interval i and $F(x)$ is anti-derivative of the integrand (function $f(x)$). Obviously, N_i needs to be rounded in order to fulfil the last assumption about natural numbers or zero. If deemed appropriate, Eq. (2) may be complemented with white noise, which makes the resampling more realistic. The noise can be of any distribution but because Gaussian white noise is good approximation of many real-world situations (Yanushevsky, 2007), it is preferred in this study. Gaussian white noise can be generated using pseudorandom component of Gaussian distribution with mean 0 and variation equal to 1 (such pseudorandom numbers can be produced by MATLAB or similar software). The component is based on the following equation:

$$\vec{\epsilon} = p\cdot\vec{u_i}, \quad \vec{u_i} \sim N(\mu,\sigma^2), \quad (3)$$

where $\vec{\epsilon}$ is vector of final white noise components, $\vec{u_i}$ is vector of pseudorandom Gaussian distributed numbers with mean $\mu = 0$ and variance $\sigma^2 = 1$ and p is noise effect coefficient. The coefficient p amplifies the noise as needed. If the expert assumptions do not include any information about the noise, the variable p should be so that the output will be reasonable, i.e. no extreme differences between each two consecutive resampled points are achieved but on the other hand, the function $f(x)$ should not be clearly visible. In addition, the coefficient needs to be variable with the magnitude of occurrence observations, because the same noise cannot influence data with hundreds of occurrences per given time period in the same way as those with no more than ten. Therefore, p needs to be expressed rather as ratio, dependent on the average number of occurrences of given event type, multiplied by constant as follows:

$$p = r\cdot\frac{N}{M}, \quad (4)$$

where N is number of selected occurrence observations of original distribution, M is scale determined by the new distribution to be produced and r is constant to be set. Experiments performed in this study estimated the value for $r = 0.125$ to fit well the EUROCONTROL data repositories but it may be set different for other cases. The sum of all N_i may not precisely be equal to the real values of N due to rounding the results and adding the noise, but it should remain acceptably close for all cases. This also means that there should not be too much noise added, otherwise the resampling output may exceed reasonable limits.

For the particular expert assumptions introduced in this chapter, data seasonality may be modeled by sinus function:

$$N = \int_0^M k\cdot\sin\left(x\cdot\frac{2\pi}{M}-\frac{\pi}{2}-\frac{2\pi}{M}\right)dx. \quad (5)$$

The sinus uses the expression

$$x\cdot\frac{2\pi}{M}-\frac{\pi}{2}-\frac{2\pi}{M}, \quad (6)$$

to move the extreme values on the interval $\langle 0,M\rangle$ so that its maximum is achieved at the point of $7\cdot M/12$ (July data) and the minimum at $M/12$ (January data). The sinus function is shifted upwards by constant of integration so that no values are negative. Recalculating new occurrence distribution during given year will, therefore, follow the equation:

$$N_i = \left[-k\cdot\cos\left(x\cdot\frac{2\pi}{M}-\frac{\pi}{2}-\frac{2\pi}{M}\right)\right]_{i-1}^{i}, \quad i = 1,2,...,M, \quad (7)$$

where N_i is number of selected occurrence observations during month i in selected year, M is scale determined by the new distribution to be produced, k is coefficient of seasonal variation and i is successive time step of the series from new distribution.

However, problem may arise as soon as specific requirement exists for resampled data distribution. No data distribution is assured by Eq. (7) but empirical testing showed that Gaussian and various skewed distributions are randomly obtained with the sinus function and k. Safety occurrences in aviation are assumed to follow non-Gaussian distribution (Seshadri, 1998; Wang et al., 2014) which also seems to be the case in other industries, where inverse Gaussian distribution fits incidents and lognormal distribution fits less severe but more frequent non-conformances (Love et al., 2015). Unfortunately, inverse Gaussian distribution could not be obtained from Eq. (7) and there is no general transformation function by which such distribution could be obtained e.g. from Gaussian distributed random variable (Chhikara, 1988), which is frequent product of the equation. The basic solution in Eq. (2) may produce different data distribution with different $f(x)$ and k and so has the investigator first check the distribution of the output from Eq. (2) and then add white noise with appropriate distribution in order to obtain desired distribution of the resampled data. Due to the complexity, however, this may not always be possible.

To demonstrate the resampling method as applied on aviation safety occurrences (Eq. (7)), at this point there is missing only a real figure of annual occurrences of selected event type (variable N_i) and the final decision about how many points are to be obtained from the figure (variable M). In this paper, SMI severity B recorded number of occurrences for year 2011 within the EUROCONTROL region was randomly selected ($N_i = 217$ occurrences) and this figure was resampled into monthly-distributed dataset of 12 figures ($M = 12$) for each month during 2011. The results are in shown in Section 3.

2.2.2. Data simulation

As long as there are no data available and it is important to generate some, assumptions have to additionally include what is available for resampling, i.e. occurrence observation figures. Experts to provide such assumptions are preferred to be front line personnel as they can usually estimate how frequent some occurrences are. For example, an Air Traffic Control Officer (ATCO) can estimate how many times a day or a week does he or she experience Short Term Conflict Alerts (STCA), alerting him or her to some aircraft being on collision course, whether horizontally, vertically or both. Usually, ATCO can also estimate how much does this value vary during a year, providing an estimation for variability as well.

Key principles of the simulation remain the same as for data resampling, but this time the core lies with pseudorandom number generation. Concerning data simulation, the pseudorandom component will not simulate noise only, but the entire dataset. The distribution parameters are to be fitted to the expert or front line personnel assumptions on the occurrence. The basic solution for data simulation is then as follows:

$$E_i = ||\vec{e_i}|| = \sum_{j=1}^{D_i} e_{ij}, \quad \vec{e_i} \sim IG(\mu_i, \lambda_i) \wedge e_{ij} \in \mathbb{N}^0, \tag{8}$$

where E_i is sum of occurrence observations of event type E during time period i, $\vec{e_i}$ is vector of observations during time period i, D_i is number of data points during time period i and e_{ij} is j^{th} element from the vector $\vec{e_i}$. Vector elements are assumed to be natural numbers or zero and obeying inverse Gaussian distribution with mean μ_i and shape parameter λ_i (both variable with i). In this case, no real data exist which would restrict the simulation and so it can be based on truly inverse Gaussian distribution.

The vector $\vec{e_i}$ is to be generated using pseudorandom numbers as MATLAB or similar software can produce. Average value μ_i and its estimated variance can be provided by an expert, but shape parameter λ_i is difficult to obtain. It can only be reliably inferred from real data samples of similar occurrences. Because data in EUROCONTROL's repositories are not sufficient for such analysis, parameter λ_i will be replaced for the purposes of this study to produce single parameter inverse Gaussian distribution as follows:

$$\lambda_i = \mu_i^2. \tag{9}$$

This distribution allows overcoming the issue with unknown λ_i, but eventually it may not be so different from the distribution based on real data. For lower numbers of occurrence observations (μ_i less than approximately 25), the probability density function is similar in shape to how the distribution of aviation safety occurrences is described by Wang et al. (2014), whilst for larger numbers (μ_i more than 25) it is approaching normal (Gaussian) distribution. Mean μ_i greater than 25 can be prevented simply by utilising the pseudorandom element to simulate data "on daily basis" as it is the case in Eq. (8), where weekly or monthly data can be produced as a sum of daily simulation. This is possible due to additive property of the distribution according to which the sum of inverse Gaussian distributed random variables produces another inverse Gaussian distributed variable under given conditions (Chhikara, 1988). According to all EUROCONTROL's datasets, it is very unlikely, that there would be on average 25 or more observations per an occurrence a day. This way, the desired properties of inverse Gaussian distribution are preserved and can be used to simulate synthetic data. However, the noise induced by the omission of actual λ_i may be significant in some cases, and so should such a simulation be used only when necessary and only for testing of mathematical models, analytical tools etc. The desired noise is added by rounding the values to achieve natural numbers or zero but this may change the distribution. It is therefore highly advisable to perform tests of the produced statistics before the data are used.

To demonstrate the simulator, fictional assumptions (a) STCA is experienced on average 2 to 3 times a day; (b) the average occurrence rate during peak days is by 1 occurrence more a day, and vice versa, the average during trough day is by 1 occurrence less a day; will serve as the basis to synthesise new data.

STCA is a safety occurrence similar to SMI. In fact, it relates to SMI because it is supposed to alert ATCO to prevent SMI or similar situations in advance, but obviously there must be more STCA warnings than SMIs, because STCA under normal operational conditions precedes SMI and only after the conflict is unresolved by ATCO, SMI can emerge. Other assumptions are therefore the same as in the example with data resampling.

The assumptions are to be taken into account in similar way as for data resampling, i.e. by the means of mathematical functions, which quantify the assumptions. For the STCA assumptions, Eq. (8) was complemented with the following equations, using the same sinus function to model data seasonality:

$$\mu_i = k \cdot \sin\left(i \cdot \frac{2\pi}{M} - \frac{\pi}{2} - \frac{2\pi}{M}\right) + x_E, \quad i = 1,2,...,M, \tag{10}$$

$$k = \frac{\max(x_e) - \min(x_e)}{2}, \tag{11}$$

where μ_i is the distribution mean during time step i, k is distribution mean variation, M is scale determined by the new distribution to be produced and x_E is expert assumption on process intercept. Given the assumption on occurrence rate for STCA, the process intercept value (x_E) is 2.5 per day. Coefficient of seasonal variation k can be calculated as the difference between its maximum and minimum estimated value, as follows (by the means of Eq. (11)).

$$k = \frac{3.5 - 1.5}{2} = 1 \tag{12}$$

If the goal is to generate data distributed by month, D_i corresponds to number of days per each month from January to December and M is equal to 12. Likewise, many other assumptions may be included, which can set different λ_i, x_E and μ_i or even set requirement for different probability distribution of the simulated data. The simulator does not aim to provide solution for every possible scenario but rather provide key principles on how to simulate safety data by reusing the principle of data resampling from previous section.

At this point, the simulator Eqs. (8)–(11) can be used to generate synthetic data for STCA event type according to the afore-mentioned expert assumptions (a) and (b). Variable M was set to 12 as in case of data resampling, D_i included number of days of each month during average year (28 for February) and variable k was set to 1 in line with Eq. (12). The results are in shown in Section 3.

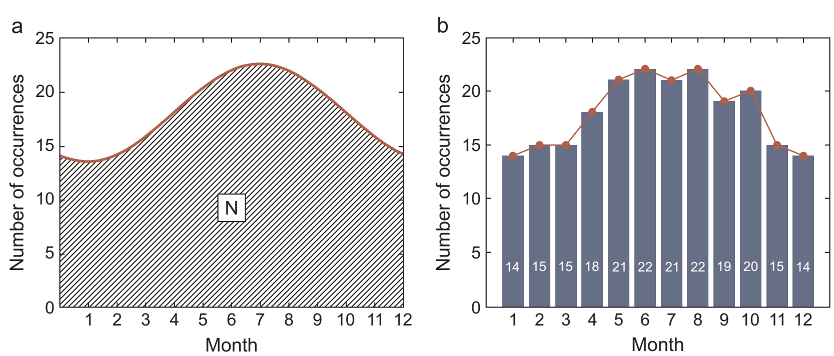

Fig. 2. Basic solution for given assumptions and SMI severity B in 2011 (a) and generated monthly-distributed data according to the basic solution for SMI severity B in 2011 (b).

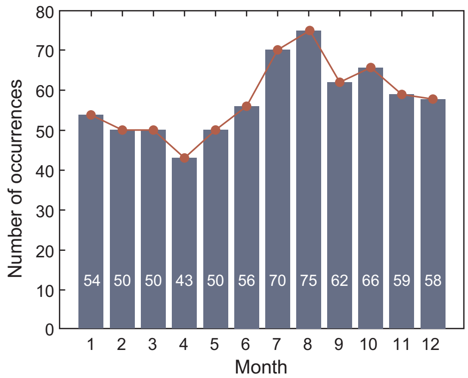

Fig. 3. Example of simulated data for STCA event type.

3. Results

The results of data resampling are depicted in Fig. 2. They are based on SMI severity B from year 2011. Fig. 2a demonstrates the sinus function behind the data resampling equations, where the area below the sinus curve and x-axis equals total number of SMI severity B observations in the year 2011. Fig. 2b depicts resampled data. Pseudorandom component (as per Eqs. (3) and (4) with $r = 0.125$) was added and so the distribution does not follow the sinus function too precisely as it is assumed to be the case during real operations. The data represent occurrence observations distributed by month of the year 2011. Data distribution remains random in this case.

The results of data simulation are on Fig. 3. The simulation is based on the fictional assumptions about STCA event type and the results are distributed by month of a fictional year. For February, 28 days are assumed in this example and the data obey inverse Gaussian distribution.

4. Discussion

The sum of all resampled occurrences on Fig. 2b is 231 which, compared to the real data of 217 occurrences in 2011, shows that the sum of the error induced by rounding and adding the noise was 6.45% thus not so significant.

Concerning data simulation, due to quite a lot of uncertainty put in the simulator (all the assumptions together), each time it runs it usually produces a notably different curve or histogram. This may not always correspond to the reality and thus shall not be preferred over data resampling, but the results make it possible to learn how to build or to trial different methodologies or advanced models where no other options exist. In any case, it is advisable to check on regular basis with experts or front line personnel how the trends evolve in order not to have the simulated data based on obsolete assumptions.

It is possible to use different or even multiple functions $f(x)$ instead of the sinus used in this study for data resampling or simulation equations. However, in such case, it is important to carefully quantify qualitative statements, which produce such need and insert them into the equations as either coefficients, constants or mathematical functions. This study does not aim to provide solutions for any possible case that may exist, but it rather outlines and exemplifies how such simulator and data resampling works, providing general solution for most common issues. On the other hand, the general nature of the proposed methods provides an option for their implementation in other transportation domains or high-risk industries.

When considering the results in terms of other research performed especially in reliability engineering, where similar problems with data unavailability appeared, the overlap with this study regards using more robust functions $f(x)$ or parameter estimation of more optimal function than sinus used in this work. Bayesian approach of integrating different data sources and expert knowledge works with probability density functions of parameters typically pertaining different variables (inputs) composing a regression model to predict future output. This study is, however, focused only on the mathematical models and their application on increasing data granularity. The core principles are also demonstrated on data simulation, but the input available in this study is very limited to allow for robust approach in producing mathematical models. If the inputs necessary to use such modelling are available, Bayesian approach and other methodologies applied to data scarcity can be used to produce more complex and precise model for generating or resampling data. Likewise, additional improvement can be achieved by robust expert elicitation, following the published frameworks suitable for particular application.

Both resampled and simulated data are suitable for applications only as entire datasets. This is because local differences between two consecutive data points may not correspond to the reality at all either due to inaccuracies in expert assumptions or due to added noise, and if only a selection of such data is used for building mathematical models, this may be completely misleading. Therefore, it is highly recommended to use entire datasets and not only their subsets.

As an example of application of the methods in this study, reconstruction of Aerospace Performance Factor (APF) according to the methodology developed by FAA (Lintner et al., 2009) will be demonstrated. Generally, the APF is one of the system-wide information, which can be produced by composing safety data into a single data point, which is intended to quantify level of system's safety performance. Concerning the data published by EUROCONTROL, the APF signal can be reconstructed for several years and in this example, it is calculated from 2008 up to 2015. According to the APF methodology, required are (a) resampled data on selected EU-wide safety occurrences into distribution by month and (b) EU-wide traffic distribution data by month in total hours flown format.

For the selected time period, data on safety occurrences from all EUROCONTROL data repositories were subjected to resampling. The real data sample comprises only 8 data points per each occurrence (distributed by year), i.e. 96 data points per each event type were achieved by the resampling process. It is to be noted here, that EUROCONTROL used for their APF calculation larger datasets concerning the safety occurrences included in the calculation (Neubauer and Lintner, 2010) whilst in this study only the occurrences provided in the public data repositories were used. The reason for omitting majority of safety occurrences used by EUROCONTROL is the complete unavailability of respective safety data. The missing data were not simulated due to that only rough assumptions could be provided. On the other hand, the most critical safety occurrences are included in the public repositories and so simulating the rest of the data could actually introduce more noise to the reconstructed signal than just omitting the data. Therefore, in this case, data resampling was preferred over data simulation. The impact of this decision can be verified through the comparison of the reconstructed signal with EUROCONTROL's output (Fig. 4), because both include year 2008.

With regard to the traffic distribution, the public repositories include annual total figures for flight hours in the EU region, but only for year 2015 the distribution by month is available. On the other hand, the same data for traffic distribution in the EU region are available using different unit, namely average daily movements, for the entire time period both as annual figures as well as figures distributed by month. The procedure to obtain distribution by month for years 2008 up to 2014 needs no resampling because the real data are there and just need to be converted into different units. Most important is to obtain the ratio between the figures as follows:

$$R_m = \frac{ADM_m}{THF_m} \tag{13}$$

where R_m is the calculated ratio, ADM is traffic in average IFR daily movement format, THF is the same figure in total flight hours format

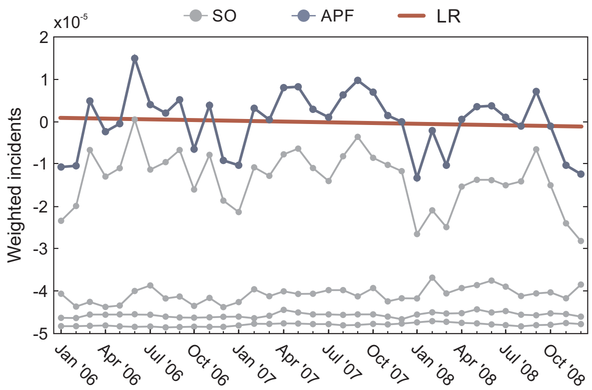

Fig. 4. APF signal based on real data from 2006 to 2008 (Lintner et al., 2009).

and m stands for respective month. Because the traffic figures in total flight hours format distributed by month are accessible for year 2015 only, the ratios R_m can be calculated using data from year 2015 only. Obtained ratios serve then as coefficients to recalculate all the years backwards using Eq. (13) to obtain monthly-distributed traffic data in total hours flown format.

At this stage, all variables are known and the APF signal can be reconstructed. Fig. 5 depicts the results. For the year 2008, reconstructed APF signal is similar to the one on Fig. 4. EUROCONTROL used relative APF figures, which are adjusted to the process mean whilst Fig. 5 demonstrates absolute APF figures, which cause shifting the scale of y-axis. Some difference can be observed, which is certainly attributable to the difference between the data behind each calculation, but comparing the outputs for the year 2008, the two signals are convincingly similar in shape and magnitude.

Last point to discuss is the new type of data on organisational factors. They are publicly available in Europe only, measured from 2012 and referring to the three EU-wide SKPIs, measured at both national and ANSP level. The data contain information on (a) Effectiveness of Safety Management; (b) Application of Just Culture and (c) Risk Analysis Tool (RAT) methodology usage.

This dataset is limited compared to the accidents and occurrences due to its novelty. It is available on the same EUROCONTROL websites together with accidents, incidents and occurrences but methodology and format of these data is obviously different from safety occurrences. To evaluate these SKPIs, artificial scores are used, represented by percentage derived from self-assessment questionnaires (see EASA). These questionnaires, however, provide certain room for bias, and so the data are not comparably accurate to the safety occurrence records. Considering this new type of safety data, no such data resampling or simulation can be used as for safety occurrences. These data are not seasonal nor do they depend on the volume of traffic etc. Their dynamicity is very low; according to the dashboards at EUROCONTROLs websites they tend to change a bit year after a year, but it is quite normal as they refer to things, which are hard to change (such as fundamentals of safety management system), and which are seasonally independent. At this point, resampling the data would more or less just follow even distribution with some linear trend during all the year thus it makes no sense to pay special attention to them. Should this change in the future and new assumptions could be drawn, then similar principles as used in the examples in this paper can be reused to build dedicated simulator for these datasets.

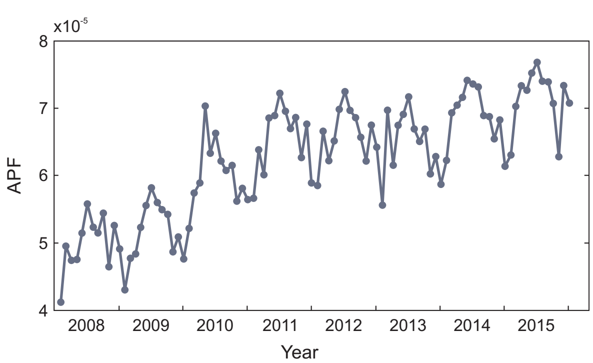

Fig. 5. APF signal based on public data repositories with applied data resampling from 2008 to 2015.

5. Conclusions

Restrictions concerning aviation safety data and their availability lead to the search for solutions, which are capable to overcome them. There are cases in which almost all safety data are accessible and just few data points need to be acquired via data resampling; in other cases there are very little or no safety data available and so they need to be simulated using expert assumptions only. The former can help to verify new methodologies or advanced modelling as they are likely to achieve comparable results with real data; the latter makes it possible to learn how to build or to trial the same methodologies or advanced models as in the former case. Both cases are usable for modern research and development activities in the domain of aviation safety but due to their general nature, they can find application in other transportation domains or high-risk industries. Because the data to be simulated or resampled in aviation are related to socio-technical system, expert assumptions are often of critical importance and are to be considered adequately.

This paper drew basic principles and solutions to the above-mentioned problems. Using basic mathematical functions, expert assumptions were transformed into sets of equations. Were real data were accessible, the equations considered them. Typical problem with such data in aviation is that it is available only annually as total figures whilst month or day distribution is desired. Introduced sets of equations were used for data resampling whilst annual total figures were obeyed. Where no data are available, the solution is based on pseudorandom number generation, such as modern computational software can generate. Mathematical functions then complement the pseudorandom number so that it produces conceivable outcome in accordance with expert assumptions.

It is clear that the synthetic data used to fill the gaps of existing limitations will never contain anything outside of what is inserted in the very equations behind the simulation. Even though they are based on expert assumptions and account for randomness, it is not possible to include all the variables, which affect the values of measured aviation safety data. The less real data and expert assumptions there are, the more inaccurate the resampled or simulated data and vice versa. It is important to note that because the aviation is a socio-technical system, it is unlikely that the system is deterministic. Therefore, there is no ultimate set of assumptions and equations, which describe the system completely and so real data should always be preferred. On the other hand, some of these limitations may be reduced by further research, applying methods from different studies dealing with data scarcity, such as Bayesian approach or Monte Carlo simulation, to refine and perfect the mathematical functions used to generate synthetic data in specific applications.

Despite the limitations, the synthesised data make it possible to implement, verify and validate advanced methodologies or analytical tools, which are highly dependent on data sample size. There are constraints stemming from the confidential nature of aviation safety data but because no aviation stakeholder is willing to share them extensively, under the risk of their misuse and with no assurance what will the benefits be, it seems unlikely that this will improve soon. On the other hand, a chance exists to improve the situation with new technologies and inventions. At this stage, these can be pre-set up and checked using simulated data and then, if proven, used to demonstrate their capabilities to aviation stakeholders, including regulatory bodies. This may eventually resolve the general unwillingness to share and work with safety data jointly and to establish the full picture of aviation safety. As soon as some technology is proven at least on partially real data, it may eventually convince aviation stakeholders to trial it.

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