Czech Technical University in Prague
Faculty of Electrical Engineering

Doctoral Thesis

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Czech Technical University in Prague
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Department of Measurement

Measurement of pilot's performance in emergency situations

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Declaration

I declare, that this work is all my own work and that I have cited all sources I have used in the bibliography.

Prague, 29.8.2018

Prohlášení

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškerou použitou literaturu.

V Praze, 29. 8. 2018

Abstract

Doctoral thesis investigates physiological signals of pilots who were subjected to a simulated engine failure on Stewart platform simulator. This experiment is unique with use of motion simulator together with emergency landing assistant and was performed with professional pilots, who can give a very relevant feedback in terms of device design and simulation.

Many of the experiments are performed on a fixed based simulators and we utilize a low cost motion simulator to test pilot's performance in simulated engine failure. In the scope of this thesis different navigational paradigms were tested, including highway in the sky and cross. The navigation paradigm evaluated as the most suitable is integrated into navigation instrument.

Measured data showed that even though the simulator is not an exact copy of aircraft interior, tested subjects exhibited physiological changes in landing and approach phase of flight, which are related to increased focus and working performance.

Keywords:

navigation, pilot performance, workload, situation awareness, emergency landing, ultralight aircraft

Abstrakt

Disertační práce se věnuje měření fyziologických signálů pilotů testovaných na pohyblivém simulátoru se Stewartovou platformou v situaci simulovaného nouzového přistání. Tento experiment je unikátní testováním profesionálních pilotů malých letadel s použitím pohyblivého simulátoru s kokpitem vybaveným přístrojem pro nouzové navedení na přistání v případě selhání motoru. Piloti zprostředkovali velmi zajímavé informace k návrhu a provedení naváděcího systému.

Mnoho experimentů se provádí na simulátoru s pevnou základnou. V tomto případě bylo ale použito necertifikovaného simulátoru s pohyblivou plošinou. V rámci práce bylo otestováno několik forem zobrazení navigace na nouzové přistání, například tunel, břevna a jiné.

Nejvhodnější navigační vizualizace je integrována do testovacího systému. Z měřených dat vyplývá, že i když se jedná o simulátor bez přesného kopírování interiéru letadla, je i tak možné navodit pilotovi stav, ve kterém jsou měřitelné fyziologické rozdíly oproti klidovému stavu, způsobené pravděpodobně zvýšeným úsilím pilotáže v náročných fázích letu.

Klíčová slova:

navigace, výkonnost pilota, zátěž, přehled, nouzové přistání, ultralehká letadla

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Abbreviations

ANOVA	Analysis of Variance
DOF	Degree of Freedom
ECG	Electrocardiogram
EEG	Electroencephalogram
EDA	Electrodermal activity
HR	Heart rate
HRV	Heart rate variability
BR	Breath rate
DFA	Detrended fluctuation analysis
EASA	European Aviation Safety Agency
MPI	Max Planck Institute
NTSB	National Transportation Safety Board

Chapter 1

Introduction

Air transport and military pilots receive extensive training preparing them thoroughly for a demanding job. The training is lengthy and costly to ensure, that pilots will be physically (especially combat pilots) and mentally fit for service. High demands require also high level of technical equipment: high fidelity flight training devices including full flight simulators with Stewart platform and top simulation programs allow pilots to prepare for any situation that might occur during the flight and train for it as much as needed. Of course this training is costly, but pilots take responsibility for the people, cargo, or for the success of a military mission. It is not surprising that great deal of attention is paid to their training. It is not the case for pilots of small aircraft.

Pilots of aircraft bellow 5700 kg of take off mass (general aviation), do not have such responsibilities and therefore they do not receive such extensive training. Most of the training happens in a classroom and then directly in the aircraft with flight instructor. These pilots take flying as a hobby, means of transportation for short distances, or they fly for pleasure. They seem to be in greater danger of accident or crash than their professional counterparts, who use to fly on daily basis. According to European Aviation Safety Agency, there were more fatal accidents and fatalities, than in commercial air transport.

This thesis focuses on pilots of small sport aircraft as well as on pilots of ultralight aircraft. Airliner pilots are not in the scope of the thesis, since they receive extensive training for dealing with emergency situations and also have available advanced simulators to prepare for such situations. In contrast to that, flying small aircraft for recreational purposes requires comparably shorter training. As a result, pilots have less time to focus on certain situation. During their training pilots most often do not use simulators and are trained directly on real aircraft flying with instructors. Part of the training is handling emergency and precautionary landings, stall, and other possible events that might occur, such as spiral spin.

All above mentioned things are rather dangerous manoeuvres. Especially spiral spin is rarely trained. Other situations receive more attention. Emergency landing is trained with instructor on board and the pilots main responsibility of this task is to decide and suggest proper place for landing. Site selection and proper approach is critical to performing a successful landing. If the place is chosen poorly, the plane might be destroyed and pilot suffer deadly injuries due to failed landing. An example can be when pilot underestimates the length of landing site. Another example might be that pilot misses the electrical conductors and the airplane hits electrical wires while landing attempt. The pilot

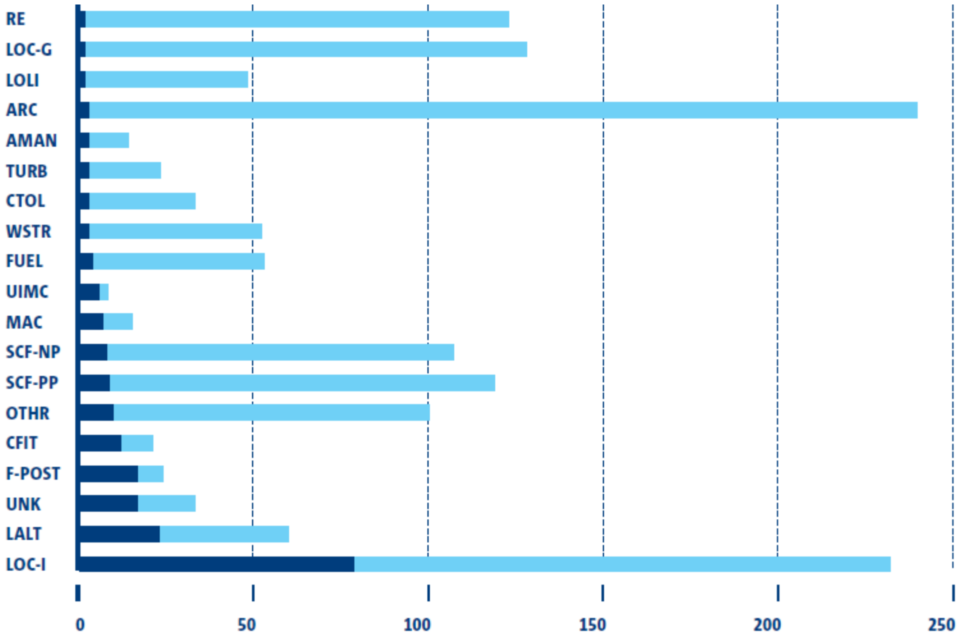

Figure 1.1: EASA Safety review table regarding the general aviation (source: EASA Annual Safety Review 2012).

may also estimate the approach in a wrong way and fails to reach the landing site entirely, forced to land in some other place, which must be selected in very limited time.

European Aviation Safety Agency issues the Annual Safety Review, which is a document with statistics of flight accidents and incidents in both commercial air transport and general aviation. Annual Safety Review 2017 shows, that there was only one fatal accident in commercial air transport regarding a cargo flight in 2016 with two fatalities. In comparison there were 46 fatal accidents with 78 fatalities [13]. This trend seems to be prevalent for past years. The Annual Safety review from 2012 [2] states that in case of general aviation bellow 2250 kg MTOM one of the main causes of fatal accidents were controlled flight into terrain (CFIT). From the same report from 2012 it can be read, that other causes were loss of control (LOC), fire post impact, low altitude operations. Category unintended flight into instrument meteorological conditions (UIMC) has the highest rate of fatalities. Similar trend can be seen from the review from 2016. Very high number of accidents can be related to the CFIT and UIMC. Loss of control in flight is according to National Transportation Safety Board (NTSB) the most critical reason of accidents in general aviation. European Aviation Safety Agency (EASA) states in the Annual Safety Review 2016, that Aircraft upset in flight is responsible for 47 % of fatal accidents. NTSB calls for extensive training of pilots of such situations and European Union is attempting to deal with the problem in similar way. To review the graph see Figure 1.1.

By controlled flight into terrain is understood a situation, where pilot approaches ground with intention of landing. It includes precautionary and emergency landings as well. The fatal accident occurs when the pilot does not manage the landing maneuver and crashes the plane killing himself and the passengers. Controlled flight into terrain can also appear in the instrument meteorological conditions, where the navigation instruments malfunction and the pilot crashes into elevated terrain. This should not happen, unless the pilot fails to assess the weather situation and flies in inappropriate meteorological conditions. This is can result into an accident labeled as unintended flight into instrumental meteorological conditions (UIMC).

Unintended flight into IMC is a situation, which should not occur very often, since the procedures before flight include the research of weather forecast at the place of departure as well as on the place of arrival and along the way. The weather forecast is major part of pre flight planning. There are areas, where the weather changes rapidly and for that reason, pilots can find themselves in a fog, a cloud or a rain, making it very hard for small aircraft to deal with the situation, if it is not equipped for IMC. Pilot tries to descend below clouds and such situation can lead to controlled flight into terrain. Pilot may also attempt a precautionary landing, but due to mishandled landing or poorly selected landing site, landing can again result in an accident.

Loss of control during flight is a problem caused by weather conditions or insufficient training. The airplane enters such flight mode, which the pilot is not able to deal with and results in a crash of the plane. The solution lies in increased training efforts focused on managing emergency situations.

Fire or smoke post impact is very hard to deal with, since it occurs on the ground, usually after an emergency landing. Another case is when engine or electrical installation goes on fire during cruise.

One way to reduce accidents would be to require pilots to take more flight hours and to extend the training. This would raise costs of flying and it does not appear so far as a viable solution. On the other hand most of the accidents seem to be related to emergency landings. It is of course not desirable to perform training of emergency landings with physical landing. And even though pilots train engine failures with instructors, the time there is very limited to get proper practice. One way to tackle these issues could be the use of virtual reality and low cost simulators to train pilots for these cases. It is clear, that theses situations are in simulated environments, so the experience will certainly be different than from a real aircraft, but if the pilots can get themselves familiar with emergency and critical situations, it might help them to tackle same situation in real world. Simulators can of course have different fidelity levels, but what is actually the level needed for pilots to gain necessary experience and confidence in handling the task? Staying calm and not to stress is often a key thing in dealing with unpredicted event during the flight.

In scope of this thesis a low cost motion flight simulator with equipment resembling glass cockpit is used. The flight display is equipped with a function which is supposed to lead pilot to a safe landing site, which is one way how emergency landing could be better handled by a pilot. Of course there are many caveats in using such navigation, such as over reliance, but we would like to address how pilots perceive their experience and how viable it would be to use similar simulators for training.

Assessing how the pilots perceive and rate their experience is a complex problem. Questionnaires have been used to assess subjective opinions, but the pilots are prone bias and the answers may not reflect accurately their mental state. This could be measured by some physiological parameters. In this study mainly ECG was used. Parameters derived from it have shown to be used to determine stress and workload. For that reason it was used also in this research.

Measured physiological parameters could allow comparison across tasks and pilots to help determine classes which will be possible to later study in more detail. In this dissertation an attempt was made to provide comparison between flights where support system actively guided pilot to target location and where it did not and the pilot had to navigate as he would normally do.

Many of new aircraft companies are taking advantage of electronic and equip planes with glass cockpit. To distinguish from other competitors, these instruments are equipped with many functions intended to aid pilots with controlling the aircraft and to maintain high situation awareness. Although it seems questionable whether these instruments really improve situation awareness, they have found their way into general aviation.

This dissertation thesis presents results of subjective rating and physiological measurements from simulated flights on low cost simulator in an attempt to evaluate what physiological effects this simulation environment has on different parameters and how this could be leveraged in testing and preparing general aviation pilots to better handle emergency situations without compromising their best performance.

Chapter 2

State of the Art

2.1 Introduction

The question arises: How to help pilots to cope with situations such as CFIT, UIMC and LOC-I? The causes of CFIT and UIMC were researched in past, but the interest in these was increasing during last years. The major institutions such as Max Planc Institute for Biological Cybernetics, NASA Langley Research Center, German Aerospace Center, Honeywell and others are working in this field along to many universities worldwide. CFIT after an engine failure is the main scope of this study. This chapter reviews approach taken by other institutes and describes the state of the art.

2.2 Research institutions

2.2.1 NASA Langley Research Center

Group around Prinzel from NASA Langley research center did some extensive work regarding Synthetic Vision Systems, mainly for commercial transportation. Their works include evaluation of 2-D and 3-D concepts as well as testing possible navigation paradigms for large aircraft's (Boeing) head-down displays. Stating that the "tunnel" guidance has the greatest potential in reducing workload and increasing situation awareness in [61], [60], [59].

Synthetic Vision Systems (SVS) were also investigated by de Haag [12] in cooperation with Langley Research Center. SVS are used to visualize the terrain on pilots screen so he can avoid elevated terrain and obstacles. The study in [12] was concerned with the malfunctions of visualization system based on radar data. The original system was enhanced by terrain database and the data were cross checked for validity.

2.2.2 Max Planck Institute for Biomedical Cybernetics

MPI is a cutting edge center with the best available technologies. CyberMotion is one of the most advanced motion simulators. It is shown on Figure 2.1. Groups seek to: (a) advance current models of human orientation and motion perception in both open and closed loop self motion conditions, (b) understanding and modeling voluntary and involuntary human manual control actions, and (c) enhance virtual environments by virtually expanding the perceived work-space.

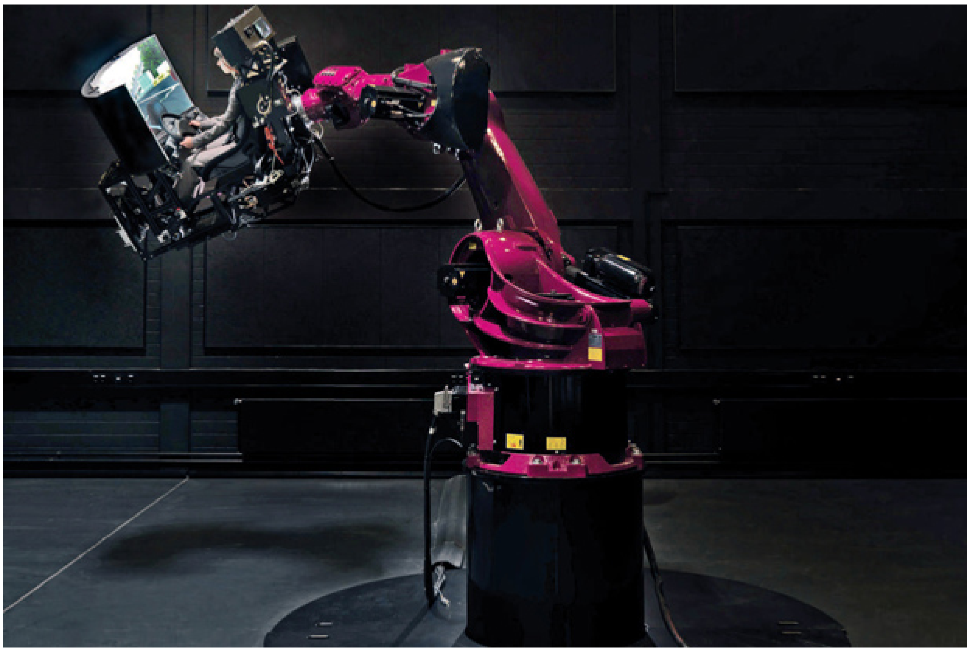

Figure 2.1: MPI CyberMotion simulator.

Groups produce many papers each year, some of it regarding personal aerial vehicles and helicopters, the most recent being [11], [52], [50], [62], [76] and [71].

2.2.3 German Aerospace Center

German Aerospace Center is well known institution with a wide range of specializations. Its focus is not only the aircraft, but also spacecraft. In terms of research regrading this study, the Institute of Flight Control, branch of Pilot Assistance produced over 200 publications in past 10 years. The publications [35] and [34] were focused on designing aid for pilots of helicopters in degraded visual environments. Pilots used head-up or head-down display with synthetic vision system displaying the obstacles such as power lines and others. Pilots rated used avatars on a subjective scale. Other publications were focused on systems preventing collision of two aircraft, trajectory design and systems for aid with approach and landing such as [56], [18], [85].

2.3 Navigation and pilot aids

Ishibashi focused on creating of SA (situation awareness) model for a glass cockpit [27] and explains, that SA is lost gradually due to large complexity of systems which are made hard to interact with, especially when performing approach and landing procedures. Loss of situation awareness lead to several accidents.

Young [84] analyses the CFIT in military missions. Despite the study from 1988 from LeBourne [38] the collision with terrain is still an issue. Young states the main reasons for terrain collision for military missions, but some can be also applied for a general aviation. Those are: (a) maneuvering at low altitudes as weather conditions deteriorate and approach operational minimums, (b) flight at low altitude with low visibility conditions, (c) takeoff and landing in mountainous terrain where approach paths are not aligned with runway. The military aircraft uses altitude activated voice warnings.

Pilot is then supposed to adjust the flight path according the GCAS system based on TFR and OW (obstacle warning). The information about obstacle and course correction is provided to the pilot via an indicator on the HUD.

Another approach was taken by Frantis in [19] and [20]. Author creates a SVS displaying virtual word similar to the one from a flight simulator, so the pilot is aware of the terrain. When entering IMC, the pilot can use the SVS to avoid terrain and let the system guide him to airport using a ”tunnel” like navigation interface. The system is also capable of navigating the pilot to reach an airfield in case of engine failure. System takes advantage of very detailed military based maps.

Experiments are mostly performed in simulators with fixed based platform. Simulations are needed to make the environment as realistic as possible to maximize outcomes from the test. Unfortunately, very realistic simulators are rather expensive, so Yavrucuk et. al. in [82] made an effort to create a virtual simulation environment using virtual reality glasses and FlightGear simulator.

Simulators are enabling technology to assess performance of pilots and systems as well like did Sarter in [64] for a multisensory interfaces and [32] for a Runway Awareness and Advisory System. There was also investigated an effect of alcohol and age on flight performance [83].

Some technologies are known for a longer period of time, Barrows et. al. tested 3D SVS for a glass cockpit in 1995 [3], but need to integrate new systems and to provide pilot with more information requires an additional research. The interfaces were investigated for guidance - Snow [70]; advisor [58], [68]; performance [9], [47], [44], [49], [51].

2.3.1 Measuring physiological data to assess workload

First physiological data of pilots were collected at the dawn of aviation in year 1917, when mr. Gemelli measured blood pressure, heart beat, and respiration frequency during flight in fighter pilots candidates [22]. In his work Gemelli observed increased heart rate during some situations. Other measurements followed with second world war when war pilots were monitored during military operations [33] (for example American pilots over Japan) or during long range exploration or scientific flights [48] (such as flight to Arctic). Most attention was focused on physiology with arrival of space exploration. The experiments related to space flight were focused mainly on physical fitness and ability to survive high accelerations. This research was not used to assess mental workload or stress, but later the recorded data were analyzed for this purposes as well [16, 26, 53].

Measurement of mental workload is a very complex task and there is no single variable reflecting load at present time. It is always a combination of multiple measured parameters which can determine what the test subjects experience. For example heart rate (HR) is one of the most often used parameters. Unfortunately interpreting the measurements is not straightforward. Autonomous nervous system consist of two branches (sympathetic and parasympathetic) and both affect the heart rate. The parasympathetic branch is responsible for digesting, relaxing and generally it lowers down the heart rate, and increases the heart rate variability. Sympathetic system increases heart rate and reduces the heart rate variability. It is interesting to bring heart rate into perspective with respiration. Respiration reflects the intake of oxygen, which is important for physically demanding activity, such as for example running. When it comes to pilots, they exert the most physical activity when doing aerobatics or when coping with high Gs. Also the heart and breath have been shown to be synchronized when at calm state. This is called the cardio-respiratory phase synchronization. The body reacts to increased level of physical activity with changing the electrodermal activity of the skin (EDA). It is taken into account in some studies as well. It is used in combination with HR, EDA reflects activity of sympathetic nervous system only. It helps to determine which system is dominant and has greater effect on HR.

Electrooculography measures electrical activation of muscles around eyes. It is used to capture blinking frequency, duration of open and closed eyes. This can be also combined with remote eye tracking to capture regions of interest. It helps to understand which kind of information pilots seeks most often. Measurement of pupil diameter can be used for mental load determination as well. It was shown that larger diameter usually reflects increased mental load.

For example [75] used heart rate, respiration, elctrooculography, and cortisol to assess the workload of pilots during simulation and real flight. Subjective data were collected using Rating Scale Mental Effort (RSME). Authors attempted to measure differences in physiology when flying a real aircraft and when using a flight simulator. The experiments were performed on a Frasca 141 simulator, which was a certified solid base fixed wing simulator. Real flights were performed on a small dual-seat Slingsby aircraft. Several general aviation pilots participated in experiments. Authors utilized the Fast Time Frequency Transforms (FTFT) to calculate HRV from HR. This method proved more useful for non-stationary parts of signal, windows longer than 40 secs. Results showed that pilots subjectively rated the simulator as more demanding. Measured physiological data did not show any significant difference between the simulator and real flights. Parameters obtained from ECG did not show statistical difference between flight and simulator. Significant difference was obtained in comparison against baseline. Respiration also did not show any significant difference between simulation and flight. Although measurement of respiration amplitude showed decrease in task against baseline during simulation. Similar effect seems to happen for blinking frequency. Frequency decreased during simulator task against the simulator baseline, where it increased against the baseline significantly during real flight. There were no significant levels of increased cortisol during simulation, but it was found for real flight.

Another paper from Wilson [79] measured heart rate as well, but tried to use also electrodermal activity and electroencephalograph. Along with EDA also an electromyograph was measured to be able to distinguish possible artifacts originating from movement. The test subjects were fighter pilot candidates. They flew experiments in a real airplane (Piper Arrow). The authors confirmed that the heart rate increased and heart rate variability decreased in take off, approach, and landing.

The current research suggests the use of ECG could give the most reliable results when assessing the pilot stress and load. Together with EDA it should provide enough information to tell how the pilots perceived the low cost simulation and what their physiological reaction to engine failure is.

2.4 Books

Several books are included in this study, because significantly contributed to experiments. In [36] the authors explain the basic principles and techniques for human related research. According to this book the database was created and first experimental tests were run. With contribution of [80] and [21] all relevant experiments were designed and performed. Books explain proper metrology. How to evaluate the data from telemetry is shown in Table 2.1. Partially it covers which biological signals are eligible for processing and how to process them. Generally it is possible to use them to evaluate mental state.

Parameter		Derivative Metric	
Altitude	Glide slope	RMSE	Autocorrelation
Airspeed	Tracking	SD	Time outside tolerance
Roll	Flaps	Max/min	Median
Control Inputs	Trim	Mean	ND
Heading	Speed brakes	Frequency analyses	Boolean
Pitch	Sideslip	Range	Correlation
Vertical Speed	Landing gear	Deviation from	Moments
VOR tracking	Acceleration	Criterion	MTE
Yaw	Position	Time on target	
Turn rate	NDB tracking	Mean absolute error	

Table 2.1: Evaluation of flight data.

The most used are the following ones:

- electrocardiogram (ECG),
- heart rate (HR),
- heart rate variability (HRV),
- blood pressure (BP),
- photoplethysmograph (PPG),
- respiration,
- pupil diameter (PD),
- electroencephalogram (EEG),
- electrooculogram (EOG),
- electromyogram (EMG),
- electrodermal activity (EDA).

Method for evaluation are often used from the field of cybernetics and artificial intelligence. Metrics were reviewed in [29]. Some examples of what can be applied are:

- support vector machines,
- Bayesian classifiers,
- Fisher's discriminant analysis,
- adaptive neural networks,
- linear discriminant analysis,
- short term furrier transform,
- quadratic discriminant analysis,
- Higuchi's fractal dimension,
- Gaussian mixtures of EEG spectrogram, and
- magnitude square coherence estimation.

These measures are not the only ones used. While these systems are rather complex and human is a part of the whole loop, it is common to use subjective evaluations as well. Most of the subjective measures are described in detail in [21]. Among the most common to use are Cooper Harper Rating, NASA Task Load Index (TLX), NIOSH fatigue test battery, rating scale mental effort (RSME), and more. Most of them are used to subjectively assess the aircraft, task difficulty, complexity, perceived stress, mental load, situation awareness. These metrics were based on the research in psychology. Mentioned tests were used in many papers, for example in [14], [25], [8], [17].

Lastly, for experiments dealing with stress, inducement of the stimuli is described in [31].

2.5 Existing support systems

The state of the art would not be complete without listings of systems, which are currently in use and that help to manage unpredictable situations leading to necessity of emergency landing. In this field the best software and hardware can be found on board of gliders, which are equipped with smartphone, tablet or pda based computers. Today, there are multiple systems helping pilots to localize the closes place for landing and providing pilot with a distance, altitude and heading of the airport. These systems are LK7000, LX8000, XSoar, Naviter SeeYou, Condor.

Such systems provide pilot with information where to fly, but do not provide an trajectory planning and most of the time do not consider wind in the calculations. Gliders compared to ultra-light aircraft are soaring from greater altitudes and therefore have more time to select a backup airfield and to get there. Pilot of ultra-light aircraft has time from 1 to 3 minutes depending on the aircraft, altitude and weather.

Another group of systems are those, which help pilot with a pre flight preparation. Part of the preparation is also to consider possible places for emergency or precautionary landing and enter them into database. One of the newest systems on the market is currently SkyLiberty. It is an iPad based application. Despite these systems might seem convenient, they suffer from overheating from Sun and pose a possible risk of loss of situation awareness in case the battery dies. The display of old types is hardly readable when in direct Sun.

Beside the software, some aircraft is equipped with a emergency parachute system. This system is possible to use from altitudes starting in 80 meters above terrain. Unfortunately, if used, the aircraft is damaged and the landing can cause damage to aircraft's body. On the other hand it can safe crew's life.

One support system is also being developed at the CTU by doctor Pěchouček. His work is focused on developing a GPS based collision avoidance system for Ultralight Aircraft. The research is conducted under the grant TA01030847 of the Technological Grant Agency of the Czech Republic.

In this chapter was covered what was researched in past years and what is being researched now-days. The support systems were presented and their weaknesses pointed out. Following chapter provides an overview of own work, which was focused on assessment of pilots and emergency navigation system.

2.6 Simulation

Cost of an aircraft flight hour is greater than cost of low end simulator. Simulators have different fidelity classes based on their interior, available systems, motion capabilities, and latency. Full flight simulators (FFS) of type D (type 7) are the most advanced simulators allowing IFR training and testing. Although full flight simulators and training devices are well established, there are attempts to use innovative technologies to further enhance training and increase fidelity. One such attempt is the dynamic seat by Sparko et.al. [72]. It might be expected to see more experiments with virtual reality headsets trying to leverage virtual reality and other ways of simulation to provide credible simulating environment. Assessing simulator credibility in terms of hardware is another interesting topic closely related to simulation performance and was analyzed by Eek in [15].

The difference of FFS to a real cockpit is very small. Flight in a FFS simulator is as demanding as a real flight in a real airplane. Unfortunately for general aviation pilots, there are no FFS, since there are too many types of aircraft with different equipment.

Therefore the interest is to create a low cost simulator which would emulate glass cockpit and motion platform with 6DOF to simulate the movement. The interior does not reflect a specific type of aircraft and uses generally accessible control parts.

2.7 Summary

Most of the work done in the area of testing the pilots aims to provide flight performance data such as control stick movement, control surface position, eye tracking, reaction time and other signals and data processed with specific metrics. These experiments are performed on various types of simulators. The main goal is to test new types of support devices for example haptic feedback, or new ways of data visualization. The author of the thesis did not find experiments investigating physiological signals on a motion based simulator as a response to emergency situation with and without decision support system.

Chapter 3

Objectives

It has been established that emergency landing is endangering pilots' life. Therefore we proposed a method to help pilots handle emergency landing and a method to assess its results. To prepare, process, evaluate, and present the results the main points are the following.

It is important to emphasize, that this thesis deals with pilots of general aviation aircraft, not with pilots of large airliners or cargo aircraft. The pilots used in this study have experience with aircraft such as Cessna 172, and ultra light aircraft.

Main goal of the work was to expose pilots to a simulated engine failure and examine measured flight and physiological data. It is of our interest to see what physiological parameters will be affected and how, and what the pilots have to say about simulating and possibly practising such situations in the simulator. The next main task was to explore viability of providing pilots with a visual aid to help them handle emergency landing and avoid crashes.

To achieve the main objective several partial tasks were determined. Completing each step allows to provide relevant and meaningful data for evaluation.

1. Evaluate pilots ability to determine risky situations in the simulator.
2. Design visual navigation aid which aims to help pilots handle emergency situation. Perform experiment with alternative navigation paradigms and determine, which seems to provide the best pilots flight performance. From previous experiments it is hypothesized, the paradigm will be highway in the sky.
3. Interview pilots to gain insight on possibilities to deal with emergency situations.
4. Examine the physiological data from flights without engine failure. The hypothesis is that the pilots should exhibit physiological changes during approach and landing, such as elevated hear beat.
5. Compare physiological data at the moment of engine failure with other segments of flight. Determine, which parameters seem affected and which do not.
6. Investigate the influence of the emergency landing navigation to pilots physiology in case of engine failure.

Chapter 4

Addressing partial tasks

4.1 Preparation of Tests

Mitigation of pilot accident rate should be delivered by the means of cockpit automation. For this goal a navigation instrument with a search, resolution, path planning, and navigation is developed. Its purpose is to guide pilots in case of engine failure to a safe landing site. The question is, how it is possible to genuinely verify that this sort of function is the most suitable one. It needs to provide the pilot with the information about where to fly, prepare a trajectory and yet the task of using the instrument must not impose additional mental load, which might the pilot later lack somewhere else. Navigation, that would require full pilot's attention and took all his mental and physiological resources would be useless. How can it then be evaluated without putting a real pilot into danger, yet test if the instrument delivers the information and at what cost?

It is necessary to assess pilot's performance. There are several ways to explore performance. The pilot's response to certain stimuli is reflected in physical actions (like moving a control stick or throttle), changes in physiology (for example elevated heart rate), and changes in emotional state. Physical activity directly affecting the subject of control, which in this case is an aircraft on approach to landing, is directly transferred to movements of the aircraft and affects the control error. Pilot observing the outcome of actions can then plan, evaluate and adjust further actions to achieve desired goal. These aspects are easily measured as flight parameters of the aircraft and can be easily processed. The amplitude and speed of the control stick's movement, distance to desired trajectory, changes in roll, pitch, and yaw. Those are all variables which are a direct result of pilots actions and can be evaluated by common techniques. Physical actions cause changes in physiology. Fast and intensive movements lead to higher physical demands and cause changes in heart rate, respiration, pupil diameters and other physiological measures. Changes in physiology may also occur as a result of emotional state, such as fear, happiness, surprise. When flying an aircraft, the physiology can also reflect states as stress or startle, which are important in the context of this study. Above mentioned measures are objective values, which provide insight on how the pilot responded and how well the task was managed. It can also provide insight into how demanding the task was.

Evaluation of the instrument's ability to guide pilot to a safe landing site depends largely on used navigational interface. It affects the way pilot performs control actions in order to follow desired trajectory. The ability and success can be evaluated easily with established measures. Guiding pilot

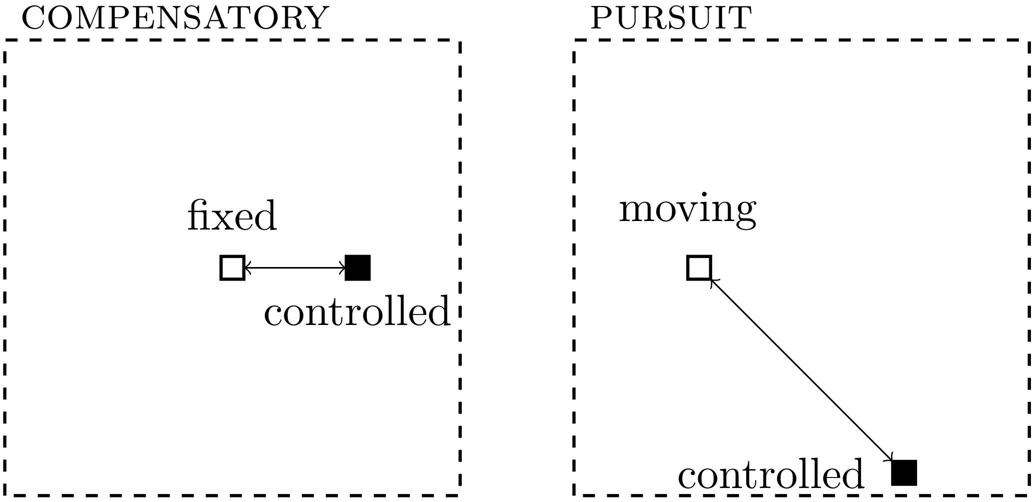

Figure 4.1: Tracking tasks modes. The goal in both tasks is to maintain the black square over the void square. The difference between the modes is based on how the black square gets to move around, In pursuit the empty square travels in a $2D$ plane or on a line and a test subject uses controls to move the black square. In case of compensatory mode, the black square is displaced from center and the test subject applies controls to counter this displacement.

to target location is a variation of tracking task [28] performed by pilot. There are two main modes in which the task can be presented. The simplest alternatives of these two modes are shown on Figure 4.1.

Factor determining the performance is a distance in plane or on the line from target (white square) to the controlled object (black square). The lower this distance is the better the performance. It is important to know that performance is affected by amplitude and frequency with which the target moves or the error displacement is generated. Developed navigation interfaces took inspiration from these modes. Evaluation of performance is then in following sections.

The aim is not to expose pilots to navigation and later evaluate the tracking performance, since this has been already done before and it tests only single task to which the pilots can attend completely. In order to provide more insight into how pilots would use the emergency navigation in real situation, it is important to introduce some variation of a secondary task. This secondary task will ensure that the pilot cannot fully attend the navigation and needs to divide focus. Since the navigation deals with pilots, it was decided to use a simulator, and actually simulate engine failure. First reason to use the simulator with moving Stewart platform is mainly to provide a secondary task to tracking the navigation. Flying it is a task the pilots need to adapt to, since the simulator is not an exact copy of a cockpit, but it provides good enough environment with simple interface in which the pilot can take off, fly, and land with certain degree of authenticity. In first round of experiment without actual engine failure the simulation serves as a pure secondary task. In a variation of this experiment with actual unexpected engine failure it is hoped to explore, whether and how will pilots to decide follow a navigation, if they decide to stay on track the whole time, and if they manage to land in the selected landing site.

The simulation with engine failure is not expected to directly induce a stress. Nevertheless, it is important to observe if there will be any measurable response to this event at all suggesting the pilot experiences stress. The way to assess stress in a most precise way would be to collect salivary samples and measure the level of cortisol, which is a measure of perceived stress. It is also possible to directly question subjects and learn how they felt based on their subjective evaluation. Unfortunately questionnaire provides only subjective data and to understand the effects of the experiment on pilot in a wider context, it is desirable to have also another measure to determine the inner state. In this study it was not feasible to measure cortisol. There are physiological measures, which might be used to indirectly determine the level of stress or emotional state. In some experiments, some physiological measures were also used to determine mental load. The most efficient in this sense seems to be measurement of pupil diameter. It was used to assess mental load in numerical tasks and learning experiments [74].

To obtain objective data about subject's emotional state it was decided to use physiological measurements. Physiological measurements are continuous and provide information in time instant. That is useful for experiments with unexpected engine failure, since it allows to focus on that very moment and investigate if this event was also reflected in the physiology. It is not clear, how pilots will respond to emergency situation with prepared setup. Equipment used in experiment allowed measurement of heart, respiration, and skin conductance. When working with physiological data it is important to realize how each organ is affected by nervous system. Heart, perspiration, and breath are controlled by autonomous nervous system (ANS). This nervous system is mostly independent from ones will. There are two branches - sympathetic and parasympathetic (sometimes called also vagal) and for illustration see the Figure 4.2. Each branch contributes to different organs in different way. There are also organs, which reflect activity of one of these branches only. For example pupil diameter mentioned earlier is controller by the parasympathetic system. Heart is affected by both branches and each produces different outcomes. Sympathetic innervation causes heart to increase heartbeat and decrease its variability. This innervation is a preparation for a fight of flight response. This system also contributes in situations involving a stressful stimuli. The parasympathetic innervation of the heart on the contrary decreases the heart beat and increases its variability. The peak activity of parasympathetic system is in situations such as digestion or relaxation. The intrinsic value for the heartbeat is approximately around 100 bpm. Unfortunately it is hard to evaluate the contribution of each system to heartbeat from ECG only. To provide more information, the skin conductance is measured. Skin activity is mainly controlled by the sympathetic system. As a result in combination with recordings of heartbeat it is easier to determine which system was more active and what the corresponding mental state is.

Skin forms a very large surface and it is constantly in contact with the environment. Some parts of the body are more suitable for measurement of conductance. Some favoured parts seem to be feet and palms, although these are not the only used. In the experiments with simulator, the feet did not appear to be a good place to measure skin activity, because the pilot needs to use rudder pedals to control the aircraft. Palms are not appropriate either, pilot has to use left hand to control the throttle and right to control yoke. In both cases measurement might directly affect pilot's ability to control the aircraft. For the purpose of experiment electrodes were placed on the left clavicle in such a way, it would be as little obstructive as possible. This appeared to be the best solution under the circumstances. It was also due to measurement of respiration, which was primarily measured by a respiration belt and temperature sensor placed under the nose to capture inhalation and exhalation. The temperature is used to complement the data from respiration belt and provides information about the temperature in cockpit.

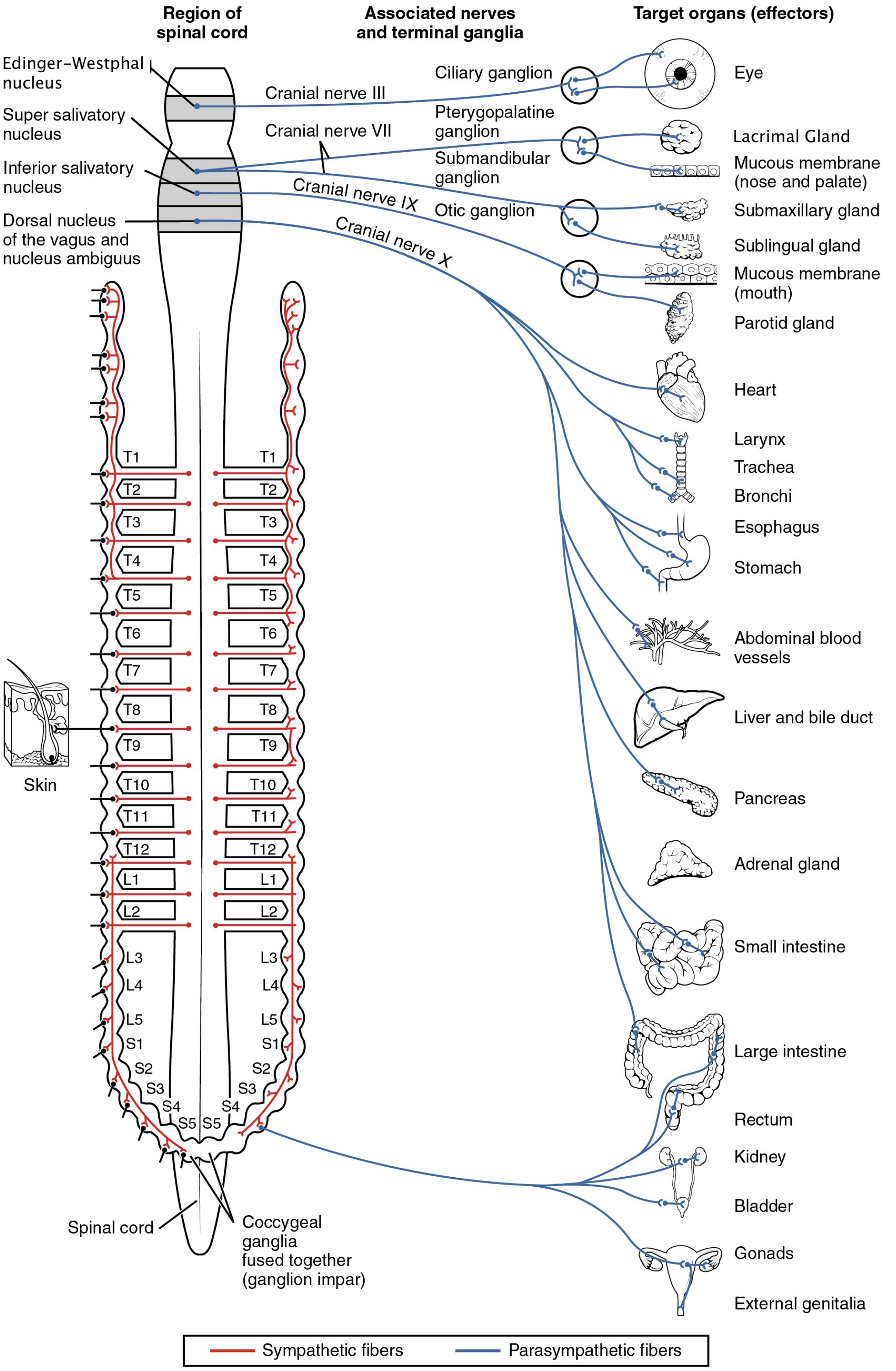

Figure 4.2: Sympathetic and parasympathetic nervous system (source: Wikipedia).

4.2 Test Subjects

Since the main goal is to provide an experiment with real pilots, it is necessary to gather test subjects. The university does not have a record of pilots who already participated in some past experiments. In experiments the authors were aware of, the students from faculty of transportation training to become pilots were asked to help.

For the purpose of this thesis, since the task was to provide insight into how emergency situation can be simulated with a motion simulator and if visual navigation aid could be used in such situation, it was concluded to recruit wider range of subjects. It is believed that more people with different levels of experience could provide more insight and information about how it would be possible to approach solving the goal of this thesis.

A simple online questionnaire was created and sent out to faculty staff and shared on social networks. The questions aimed to learn pilots experience (flight hours, available license, experience with emergency landing, involvement in education and training, age) and their possible biases towards electronic instruments and use of modern technologies in airplanes.

At the end of the recruiting process database exists with 86 pilots who volunteered to be part of the experiments and who can be divided based on several parameters. From this point on, this data base was used to select pilots and call them for testing.

To address the issue whether the motion simulator at the faculty can be used to simulating emergency situations, experiment described in Section 4.3 chapter was designed and executed.

4.3 Dangerous Situations on Simulator

To explore the abilities of the university motion simulator, which at the time was a new addition to the laboratory and its capabilities were not yet tested, a simple experiment with pilots was devised to see if pilots would be able to tell two basic emergency situations happening. The main focus of this thesis is unexpected engine failure, which can cause big problems right after take off during the climb. It is a phase where the engine works on its maximum power and therefore is also most likely to fail. Due to low speed and altitude, leaving the landing surface, it is also very dangerous situation, especially in places, where there is no concrete landing surface and only grass. The authors are familiar with several situations where an ultra light aircraft lost the engine power while taking off and the pilot decided to turn the aircraft back to the airport to land it. It resulted in a plane crash and death of the pilots. This situation is described in [6] and was presented in detail there. The experiment was based on recreating events of the accident in the simulator and seeing whether pilots will mark some moment of the flight as potentially dangerous.

Since the motion simulator was used, pilots were expected to feel how forces affecting their body change and should be able to realize that the loss of traction was caused by engine failure. Pilots did not know, what was going to happen during the flight. Two main events were expected to be marked as dangerous - the moment of engine failure and the moment when the pilot started turning the aircraft with a large roll angle in an attempt to speed up the turn. The engine failed at time of 137 seconds from take off and the dangerously large roll angle was set to time 162 seconds. The marks the pilots gave are in Table 4.1.

From this table it can be seen, that pilots were mostly able to determine, that something went wrong with the flight, some were even under the suspicion, that something might go wrong in the future and marked the event before expected time, which is not seen as a mistake, but more of a sign of precaution and was regarded positively. Interestingly some pilots failed to determine any dangerous situation. It is hypothesized, that these pilots might be prone to go down the same way as the pilot

Subject	Event - Situation 1 [s]	Event - Situation 2 [s]
s001	141,34	164,49
s002	FAIL	FAIL
s003	137,00	FAIL
s004	137,97	168,60
s005	137,86	157,06
s006	FAIL	166,83
s007	135,91	156,60
s008	FAIL	158,49
s009	134,49	165,63
s010	138,49	155,97

Table 4.1: Ability to estimate possible threat at take off on the simulator.

in the real accident.

After the pilots finished the test flight, they were asked to describe what their impression was of what was going on during the flight. Pilots correctly reported, that the first potential situation was engine failure and some also noted, that the angle of attack was becoming too large for a Cessna according to their judgment, so that was reason for markings of first situation before the expected time stamp.

After this experiment it was concluded, that despite some pilots failing to recognize dangerous situations, the motion simulator, even though it was not a certified training device, should be able to provide pilots with additional sensory input which would help them to recognize there was an engine failure in other tests. It was decided to use the motion active for experiments. From this point the development of visual aid for pilots in emergency landing was started and is described in next chapter.

4.4 Navigation to Emergency Landing Site

4.4.1 Design of Emergency Landing Navigation Assistant

Many pilots of small single engine aircraft are not well trained to cope with engine failure. They are not well familiar with gliding characteristics of their airplane and the training focuses only several hours to prepare the pilots for that. Pilots usually do not have a glider experience so they think in different ways once the plane starts gliding. These event can result in failure to approach selected landing site, failure to perform proper landing. Pilot under pressure and stress can respond very abruptly and can make maneuvers that lead to a crash. To help a pilot to deal with such situation, an emergency landing assistant is proposed. The assistant takes advantage of modern glass cockpit equipment (primary and secondary flight displays, synthetic vision system [34]) together with modern guidance systems [4,43,45]. The system activates in a state of emergency, and based on the remaining kinetic and potential energy it searches for reachable area suitable for landing, plans a trajectory, and provides the pilots with navigation to chosen target.

The detection algorithm for engine failure (emergency situation discussed in the scope of this thesis) requires only an engine revolutions sensor. Revolutions below a certain threshold during flight will activate the assistant. The selected configuration is intended to not only lead the pilot to the destination, but also prevent him from any maneuver on the edge of safety and stability. Some crashes were caused by impaired manoeuvring skills due to emergency situation. The aircraft entered spiral spin and the pilot was unable to recover.

4.4.2 Landing Site Search and Selection Module

A more sophisticated approach can be taken with a camera mounted on the aircraft, which could provide a real time images of the surface bellow aircraft. Camera images together with map database can be used for terrain segmentation, which can serve as an input to determine convenient landing site. Map data are very important source of information, because some regions such as bodies of water or forests can be processed for landing last. Combination of those two inputs should be enough to select appropriate landing site [4] and [69]. Also merging the data with additional sources could provide even more useful information. For example electrical wires with high voltage in the countryside are dangerous aspect of the country, which is hardly visible to pilot and also hard to detect. The height map layer can help an algorithm to exclude areas that are too high.

4.4.3 Path Planning Module

Flight path planning algorithms in avionics are used mainly in unmanned aircraft. Modern algorithms are usually based on genetic principles [73,81]. Some approaches that were developed tested trajectory design for emergency landings specifically in [10,45].

Published algorithms have usually one property in common – they use spline as curves for flight paths representation. Another approach uses way-points to which the pilot can be directed by the system. In house implemented navigation uses guidance along lines and arcs. The major concern regarding splines is that they would require constant attention. In terms of way-points, the concern is that the energy might be wasted by inadequate maneuvers when turning the airplane. Circles and lines appear to be a good compromise between these two options.

A very simple path planning algorithm has been implemented in the electronic emergency assistant. It plans a trajectory to the closest possible airport in reach and calculates the trajectory in a way that the pilot is lead to the runway threshold, taking the final approach into account. When the aircraft gets into an emergency situation, the maximal length of the trajectory to the ground is limited by the altitude, the airspeed and angle of descent.

To successfully glide to target location it is important for the pilot to maintain optimal airspeed. The speed polar characteristic and maximal lift-to-drag ratio can be used to calculate the recommended airspeed as it was done in [4]. According to current airspeed and altitude, minimal and maximal airspeed corresponding to lift-to-drag ratio could be approximately determined. From this interval one point is selected and the desired flight path length should be moved closer to the path length at this point. Another variable should respect the angular turning length – a bigger radius and smaller heading difference are preferred due to safety reasons. Too large bank angle and low airspeed may result in spiral spin.

In experiments done in the scope of this thesis was used in house developed simulation of an electronic flight instrument system (EFIS) with programmed function of emergency navigation landing assistant. Ideally such system would be able to locate most suitable landing place based on aircraft location, speed, altitude and direction. Development of software EFIS is discussed in papers by Levora and Paces in [40], and [54]. The task of selection the landing site and approach trajectory generation is elaborated in papers from Levora in [41] and [42]. In the experiments conducted in this study, the pilot flew over a well know and predefined location in the simulation and for this reason there was no actual search for the landing site. The path generation was dynamic and allowed the trajectory to be planned according to current aircraft condition. Planned trajectory was then presented to the pilot. The navigation in airplanes used for instrument landing system (ILS) used two lines perpendicular to each other. Another approach used a so called pathway, goal posts, or highway in the sky. The first steps were in a direction to determine which navigation paradigm would be suitable to navigation to landing site.

4.4.4 Navigation Interface

Generated trajectory is a sequence of straight lines and arcs, thus the navigation problem could be divided into two parts – navigation along lines and arcs. Line segments are implemented by defining their end points. Arcs are redundantly defined by start point, end point, direction, and center.

Several different navigation algorithms were implemented as well as four different visualizations (navigation paradigms). First algorithm displays static shapes depending on the style - tunnel, pavers, and more. Such kind of algorithm has more of information value to the pilot telling it where the flight path is recommended. Tunnel shows geometrical shapes such as rings or squares along a desired flight path through which an aircraft should fly. Pavers are visualized as a paving surface placed on the desired flight path. Both the tunnel and pavers are shown at a short distance in front of the airplane and they move themselves along the flight path with the airplane [78]. The navigation implemented for the purposes of this thesis uses a rectangular shapes which the pilots is expected to fly through. There are always several rectangles to show desired path of the trajectory, see Figure 4.3. The trajectory in this sense is static and the pilots can displace the aircraft away from the trajectory.

Second navigation algorithm provides pilot with commands on where to fly and it is similar to representation of instrument landing system. The navigation module prepares advice to the pilot on where to fly and conveys this information through display. The implemented algorithm calculates a so called meeting point that is defined as the intersection of the desired flight path and a circle with the radius of a distance in which the airplane exceeds the certain period. The intersection point in the direction of flight is chosen for navigation. The function of navigational command calculation should determine the distance of the aircraft position from the meeting point in both vertical and horizontal directions. Both distances are then displayed on the screen like vector commands. The vector is placed into the screen center and only the end point is plotted. In the vector end point, two crossing line segments are displayed. The cross consists of a horizontal (parallel to artificial horizon) line and a line perpendicular to the horizontal one.

For initial experiments there were three possible representations of this information. Two representations formed a cross which either rotated with the artificial horizon or did not. These visualizations are in Figure 4.4 and Figure 4.5 respectively. The third represented an endpoint of a vector towards the desired point on the flight trajectory, see Figure 4.6.

The navigation operates as a state machine running along the whole flight path. The state of the machine contains current flight path segment – line segment or arc. When the meet point reaches the end of the current section, the state of the state machine transfers to following one. While there is no

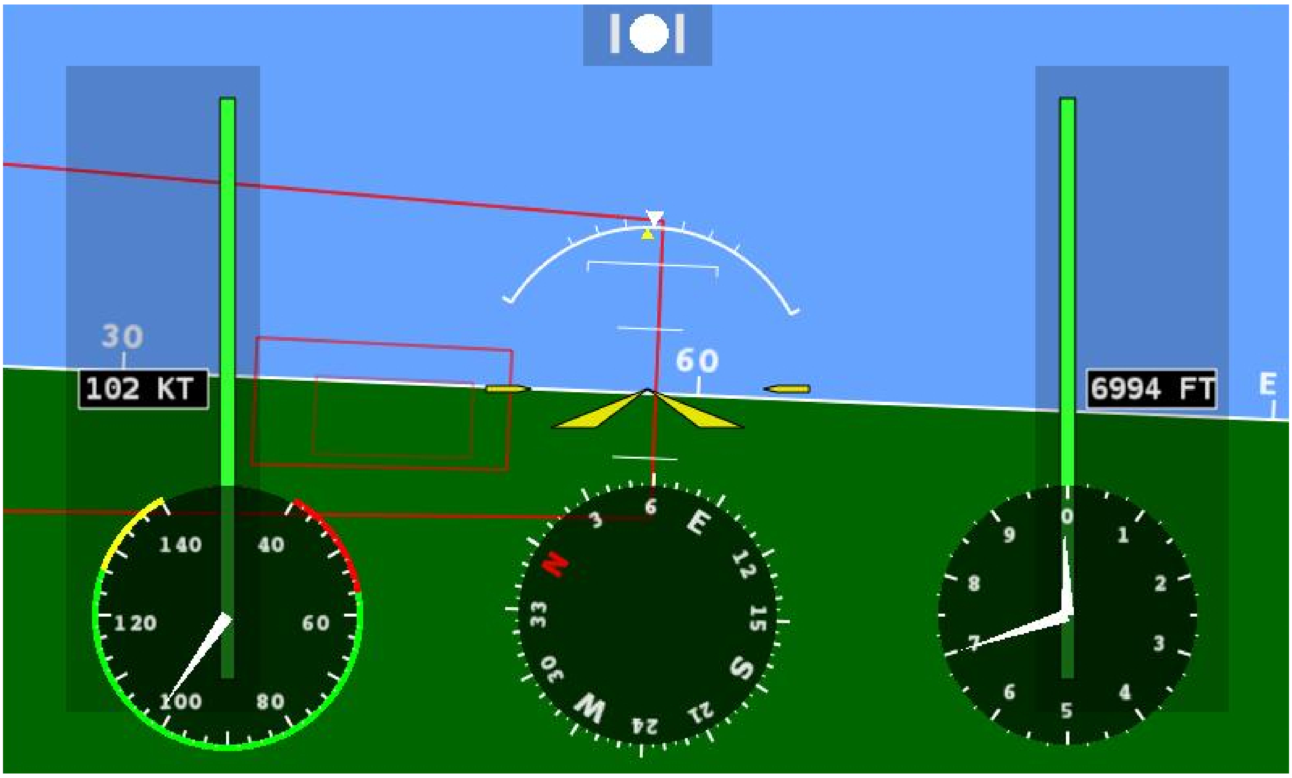

Figure 4.3: Implementation of tunnel used for testing in this thesis.

Figure 4.4: Implementation of cross used for testing in this thesis.

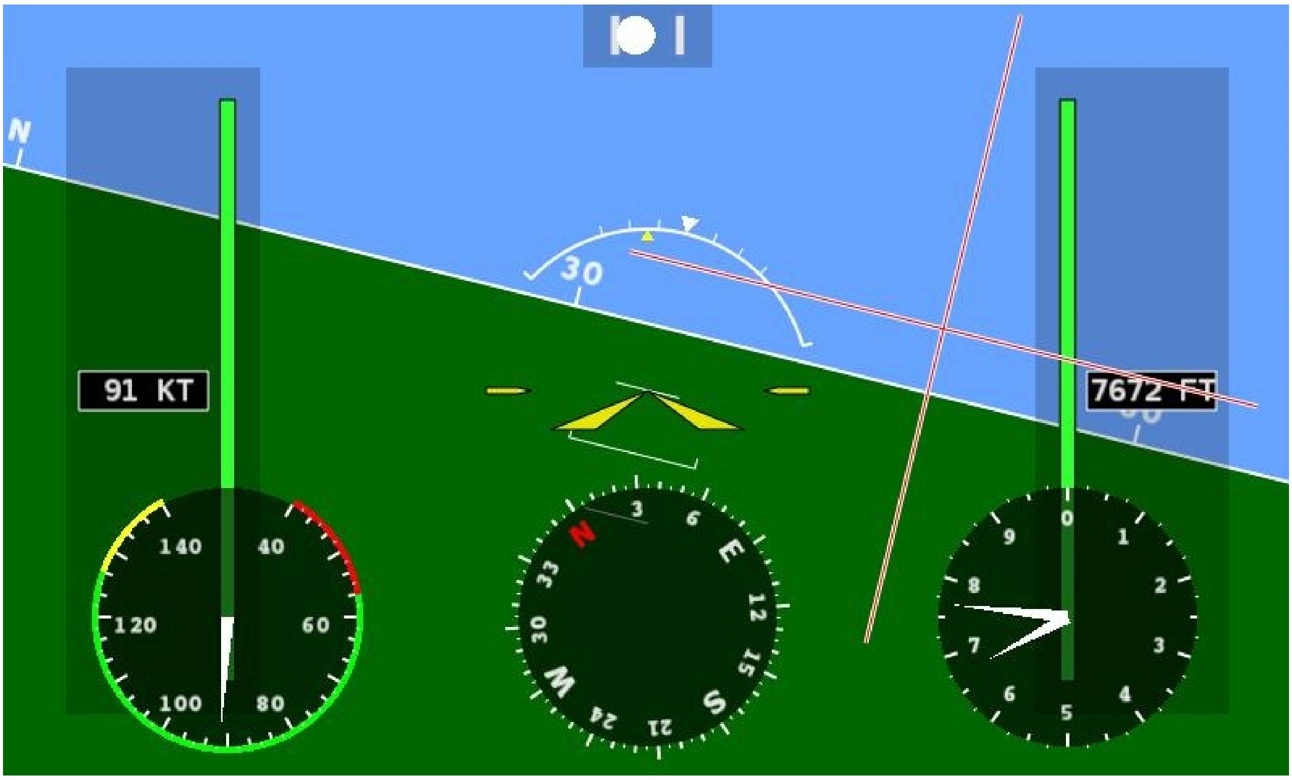

Figure 4.5: Implementation of non rotated cross used for testing in this thesis.

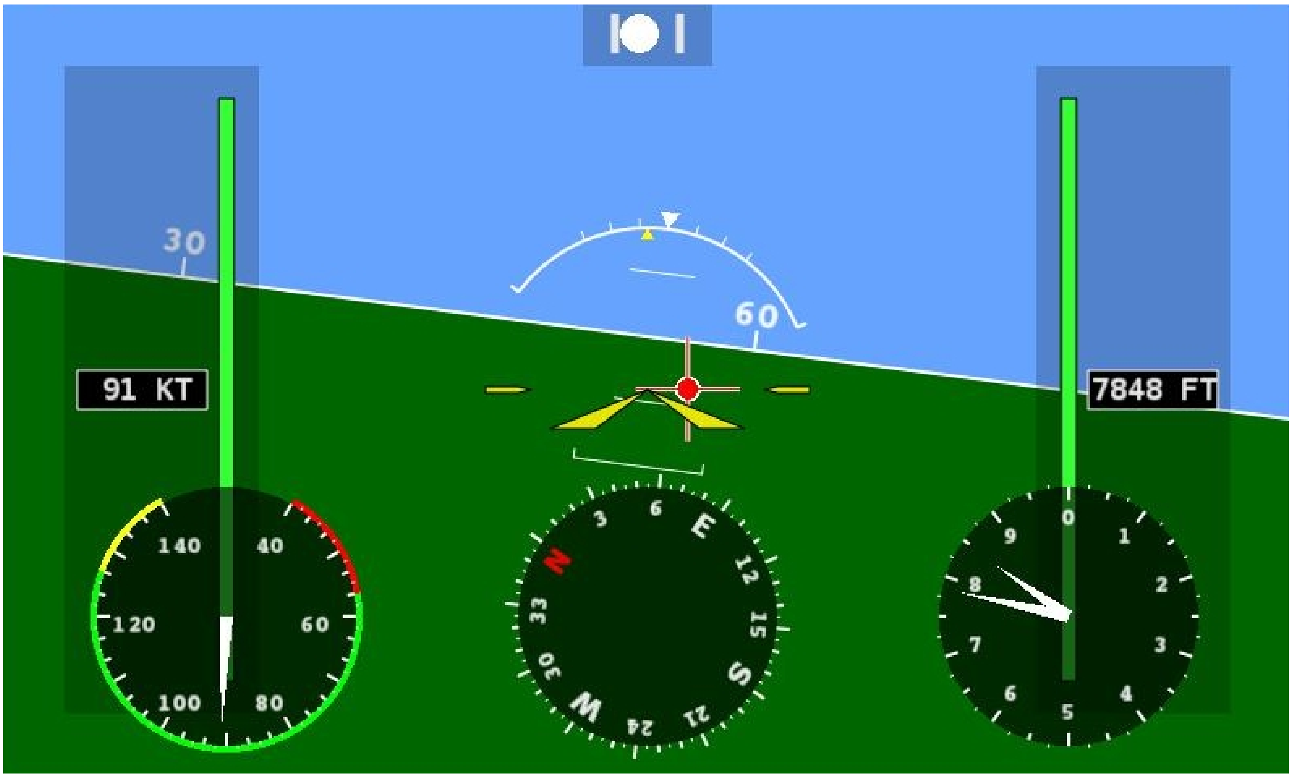

Figure 4.6: Implementation of direction vector is presented as a point on screen.

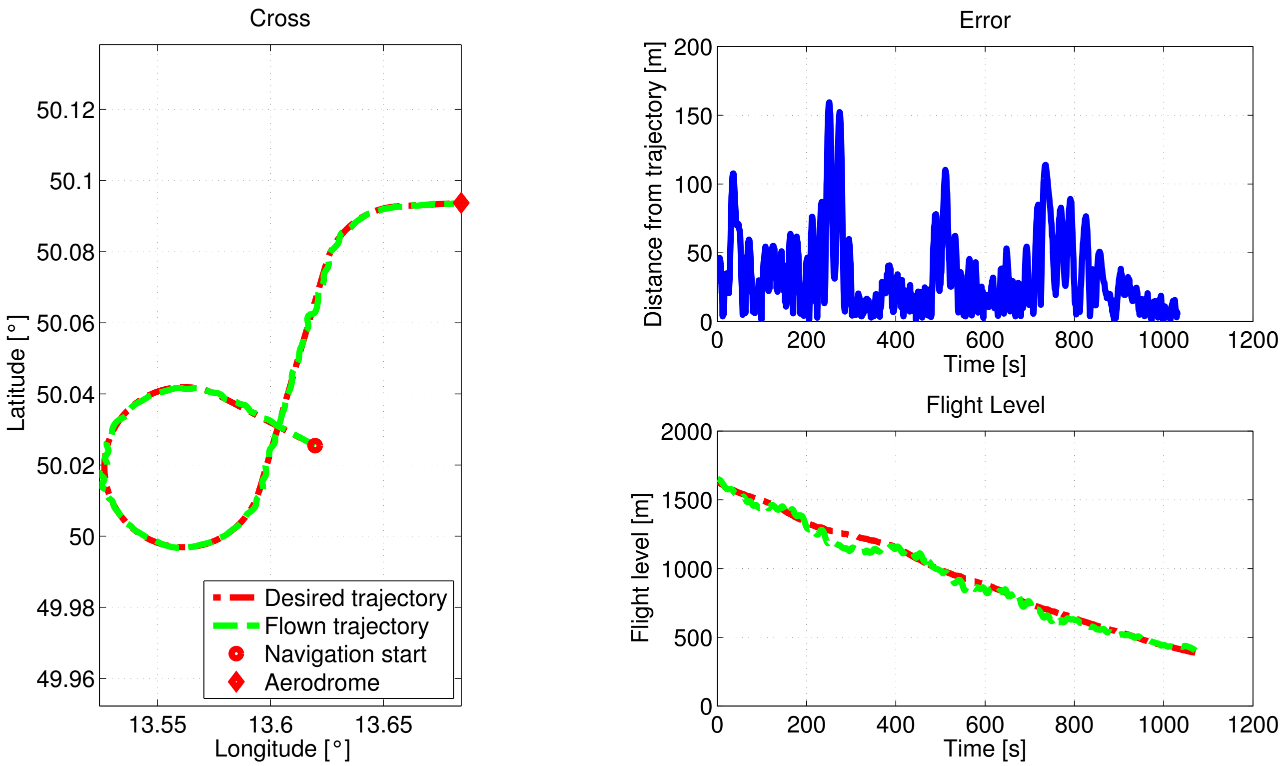

Figure 4.7: Example trajectory to nearest airfield. This trajectory was generated to test subject's tracking performance and there was no engine failure. Navigation used in this example is cross.

meet point – ideally only when the aircraft is too distant from the flight path – the whole trajectory is recalculated and navigation starts from a new position. To evaluate the tracking performance of the pilot, and navigation paradigm, the trajectory was constructed in such a way that the pilot would fly an left turning arc, right turning arc and straight segment. The navigation constructed testing path as it can be seen in the Figure 4.7 and in Figure 4.8. It is obvious that the generated trajectory in this case is the same and only the navigation paradigm is different. From the picture is also seen the RMSE error from the trajectory, which in Figure 4.7 case is on average larger than for the Figure 4.8.

Two navigation paradigms were taken into account. The pathway in the sky and the perpendicular lines forming a cross which shows the intended direction of flight. After the implementation was finished, usability tests were conducted to determine the plausibility of navigational paradigm.

4.4.5 Usability Testing

There were four navigation paradigms used for testing. Two rounds of usability tests were done, first with naive subjects to select two paradigms for second round with professional pilots. Professional pilots held license for a small sport aircraft or for other aircraft (gliders, Cessna, cargo, and so on). Pilots with license for large airliners were excluded.

The first group was tested with simulation program without the motion simulator and with EFIS navigation. Tests with second sample were performed with the motion simulator. Test subjects were certified pilots and pilot trainees already holding pilot license, but with lower total flgiht hours.

The firs group were 4 subjects who were tested with a computer flight simulator interconnected with EFIS simulator. During the simulation there was no engine failure, since the purpose of the test

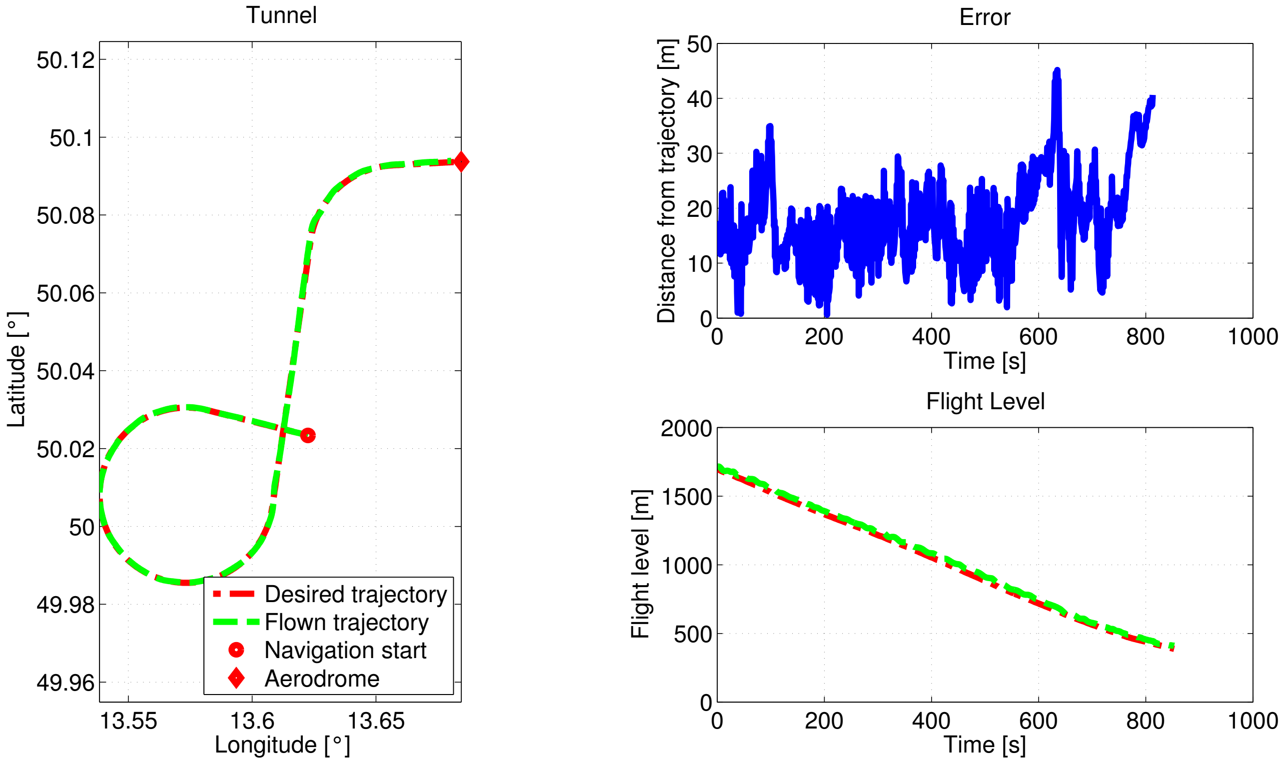

Figure 4.8: Example trajectory with navigation using tunnel as visual aid.

was to evaluate different kinds of navigation form. Subjects were given a task to follow the navigation paradigm as well as possible. The navigation lead the test subject for a landing. The experiment started with the plane already airborne and was stopped when the airplane reached the runway. After each run the navigation was changes and also parameters of the navigation algorithm were altered. Subject was interviewed immediately after each test.

The second group included 5 pilots of which three pilots had flying experience of less than 100 hours and held the professional pilot license (PPL), one pilot had between 101-400 flight hours and had license for ultra-light aircraft, last pilot with over 3640 flight hours held an air traffic pilot license (ATPL). Age of pilots was between 21 and 30.

At the beginning of each session subjects were briefed about the structure and purpose of tests. Afterwards the pilot was seated inside the simulator and went through an initial flight, which aimed to familiarize pilot with behaviour and control of the simulator. When the pilot felt confident enough with the simulator, tests began. Series of four test flights was conducted in random order. Each testing one navigation paradigm. Pilots had to attempt to follow the trajectory as precisely as possible with the use of navigation.

After each flight, pilots were given NASA TLX (task load index) questionnaire to evaluate the flight. The questionnaire rates the different aspects of task on a scale from 1 to 20. The lesser the rating is the better. It focuses on six different aspects: mental demand, physical demand, temporal, performance, effort, frustration. Results are summarized in Table 4.2.

After the last test flight, pilots filled in a final questionnaire where they expressed on a scale from 1 to 20 points how satisfactory each navigation was. Rating of 1 means unsatisfactory and 20 means very satisfactory. Obtained data are consulted in following section.

4.4.6 Results of Navigation Usability Testing

Based on pilots rating the four navigation interfaces, it was decided to use only two paradigms for conducting larger experiments, which would be more time consuming and there would not be time enough to perform the tests with all navigation paradigms. Chosen paradigms were a highway in the sky (tunnel), and non rotated cross. Cross and Tunnel were navigation tools the pilots were most happy with.

Interface	M	Ph	T	Pe	E	F
Cross Rotated	32	35	39	28	52	30
Cross not Rotated	37	30	32	18	45	31
Point	31	48	47	29	53	36
Tunnel	27	23	26	14	38	24

Table 4.2: Evaluation of the flight director using NASA TLX. The columns are mental demand (M), physical demand (Ph), temporal (T), performance (Pe), effort (E), frustration (F).

Subjective results were one of the means used to analyze possible navigation. Second method used focused on more objective data based on measures derived from tracking task performance.

Some pilots, despite the test with the navigation stated that they would not like to use this function in a real aircraft. Reasons they stated are summarized in Section 4.5. Here in Table 4.3 is shown how successfully were pilots able to reach the target landing site in the emergency situation. It can be seen that most pilots preferred to use the highway in the sky, but there are also some who went with cross as well (total of four pilots).

4.4.7 Trajectory Metrics

The flight director was intended to lead the pilot from certain point on the map to the emergency landing site, which would suggest the shortest possible route, but for testing purposes the scenario was different. Pilots started with the aircraft flying and the navigation guided the pilot to a nearby airport. Generated trajectory was digit eight shape like. That allowed to evaluate tracking of the trajectory in a clockwise and counter clockwise turns as well as in straight line. The trajectory was constantly descending and the final part was an approach for landing.

Basic statistical measures were used to evaluate tracking performance. Mean and standard deviation is applied to flight path error divided into segments based on path curvature. A mean of the flight path error is a measure of pilot's ability to fly along a guidance line (flight path graphical projection). The flight path error standard deviation is important to determine how fast in advance the navigational algorithm should refresh the command markers to give to the pilot enough time to react. The flight path error is determined as Euler distance between aircraft's position and desired path. For a straight line segment, the error is calculated according to 4.1.

$$\Delta_{line} = \frac{|P - L_1| \times |P - L_2|}{|L_1 - L_2|} \tag{4.1}$$

The Δ_{line} is orthogonal distance of point P to a line defined by two point L_1 and L_2. Error from arc is calculated based on 4.2.

Subject	Using tablet	EFIS	EMG	FH[h]	Time[s]	ARDM	Interface
01	N/A	Y	N	101-400	F	F	None
02	N	N	N	0-100	F	F	None
03	N	N	Y	401-600	F	F	None
04	N/A	N	Y	101-400	F	F	None
05	N/A	N	N	0-100	F	F	None
06	Y	Y	N	101-400	F	F	None
07	N	N	N	0-100	F	F	None
08	N	Y	N	0-100	405	F	Cross
09	Y	Y	N	101-400	150	F	HITS
10	Y	N	N	101-400	45	F	HITS
11	N	N	Y	101-400	156	F	HITS
12	Y	N	Y	800	86	F	HITS
13	N	Y	N	101-400	293	F	HITS
14	Y	N	Y	401-600	0	S	Cross
15	Y	N	N	101-400	Never	S	HITS
16	Y	N	Y	0-100	Never	S	HITS
17	N	N	Y	101-400	173	F	HITS
18	N	Y	N	0-100	112	S	HITS
19	Y	N	Y	0-100	Never	S	Cross
20	N	N	N	101-400	163	F	Cross

Table 4.3: Trajectory tracking with engine failure and navigation assistant. Table shows what navigation interface pilots wished to use in case of emergency. ARDM tells whether pilots succeeded in reaching the target landing site determined for them by the navigation (S–success, F–failure). EMG is stating if the pilots had previous experience with emergency landing (Y–yes, N–no). Column time shows the time instant when the pilot guided trajectory, or it shows F (never followed, navigation was not used) or never (trajectory was followed to the airport.). Column EFIS shows whether the pilot uses EFIS in the aircraft. Similarly in column tablet is seen if pilots uses tablet or smart phone for navigation.

$$\Delta_{arc} = r - |P - A_C| \tag{4.2}$$

Where Δ_{arc} is a distance of point P from a line formed by an arc with a center at point A_C and radius r.

Tracking performance was related to parameters dealing with command display. After testing different settings for pilots, the navigation was settled to use the combination of time and gain which suggested the lowest tracking error, as seen in Table 4.4.

To evaluate trajectory tracking task, following measures were used: (1) root mean square error (RMSE), (2) percentage of samples out of flight envelope, (3) number of deviations (ND), (4) mean time to exceed envelope (MTE).

Data in Table 4.5, Table 4.6, Table 4.8, and Table 4.7 are referenced to a flight envelope created by a cylinder around the flight path with radius $50m$. If the error is less than $50m$ the aircraft is considered to be inside the envelope. The RMSE was computed using 4.3.

$$RMSE = \sqrt{E((\hat{\Theta} - \Theta)^2)} \tag{4.3}$$

The $\hat{\Theta}$ is the actual position of the aircraft and the Θ is desired position. The results are shown

Time [s]	P [-]	$\overline{\Delta}_{arc}$[m]	σ_{arc}[m]	$\overline{\Delta}_{line}$[m]	σ_{line}[m]
5,00	0,20	9,98	8,98	7,27	4,61
7,50	0,20	21,63	5,49	10,50	7,38
8,75	0,20	20,54	12,58	9,68	8,89
10,00	0,20	46,37	9,19	10,25	9,39
5,00	0,50	9,40	3,95	3,11	3,77
7,50	0,50	25,72	5,82	14,82	5,11
8,75	0,50	35,61	6,93	11,15	8,11
10,00	0,50	49,40	3,32	10,51	10,43
10,00	0,10	35,43	16,77	17,04	7,89

Table 4.4: Determining the time parameter.

Interface	Mean[m]	Sigma[m]
Tunnel	61.28	5.49
Poin	105.12	50.31
Cross Rotated	86.60	31.29
Cross not Rotated	111.77	54.14

Table 4.5: RMSE evaluation of subjects flight.

in Table 4.5. Small RMSE us considered as a good performance. Another measure of performance is a percentage of flight out of the envelope as in Table 4.6. The smaller percentage the better.

Interface	Subject1	Subject2	Subject3	Subject4
Tunnel	50.20	45.08	57.92	57.55
Point	62.13	70.42	81.77	92.50
Cross rotated	64.77	52.36	68.14	86.58
Cross n/R	79.63	70.40	80.36	99.04

Table 4.6: Percentage of aircraft out from flight envelope from the whole flight.

Data in Table 4.6 we calculated from 4.4.

$$OE = \frac{N_O}{N} \cdot 100\% \tag{4.4}$$

Where N_O is a number of samples outside the flight envelope and the N is a total number of samples.

Number of deviations reflects how often the pilot left and returned to flight envelope. Data in Table 4.7 need to be read together with data in Table 4.5, Table 4.8, and it Table 4.6. Low number can mean both good and bad flight performance. For example the Subject 4 has 8 deviations, but spends most of the flight out from the envelope. Data in Table 4.8 represent the mean time it takes to pilot to leave the envelope. If the subject does not leave flight envelope, the MTE should approach infinity. In case the MTE is a small number, pilot is likely struggling to maintain the aircraft in the flight envelope.

Interface	Subject1	Subject2	Subject3	Subject4
Tunnel	58	61	82	84
Point	82	113	58	8
Cross rotated	83	28	87	37
Cross n/R	50	44	54	4

Table 4.7: Number of deviations.

Interface	Subject1	Subject2	Subject3	Subject4
Tunnel	4.97	4.38	2.87	2.83
Point	2.54	1.47	1.74	3.69
Cross rotated	2.32	8.23	2.11	1.80
Cross n/R	2.35	3.34	1.66	0.35

Table 4.8: Mean time to exceed tolerance

4.5 Feedback to Navigation Instrument from Subjects

Interviews with pilots after each flight provided insight into how pilots use the device and how they think about it. The points they made can be summarized as follows:

- Watching the screen can lead to decreased situation awareness.
- Tunnel shows trajectory in advance, which have been accepted very positively.
- The point is too small to be used for navigation purposes. Hard to find on the screen.
- Cross and point flight director considered are stressful, because it does not show the trajectory.
- Show the whole trajectory in advance.
- Larger tunnel squares.
- Useful show desired heading and miles to reach the location instead of using flight director.
- Using EFIS (electronic flight instrument system) in small aircraft is undesirable.
- Time to impact in case of engine failure estimated to minutes, which provides pilot with no time to interact with the device.

Pilots were also asked, whether they would like to use the navigation in their plane. Some of them would not like it. The reason they gave was a trust issue. They were not sure, where exactly was the navigation leading them and had to cross check the view from the window with the navigation screen. They noted, that in case of head up display, where they could see the area directly would be nice, but since the small aircraft are not getting HUDs any time soon, they would rather avoid using such navigation.

It suggests that pilots who would be over relying on such system, could possible get themselves in more trouble. As the it shows in Table 4.3 some pilots decided to leave the trajectory once they were certain (or at least they thought so) where it leads them and then tried to fly and reach the target area on their own. Some have decided to land where they thought would be a good spot to regardless of navigation.

Another important point was that the navigation algorithm must necessarily use wind to plan the trajectory and must directly communicate to pilot what the target location is. The trajectory then is nice feature, but not as important as the landing site. Especially, as pilots said, there is only few second left after the engine goes out in some cases, so the pilots does not have much time to make complex decisions and analyze complex data on a computer screen.

All together the pilots seemed keen to use the device under the condition it would communicate better the target location and it would consider wind.

4.6 Physiological Data

4.6.1 Introduction

After navigation paradigm was established, the next stage of experiments started. Recruiting pilots for experiment with a moving platform simulator was started. The goal was to prepare for experiments where human physiology would be measured and evaluated. The goal was to see how the subjects physiology would react during normal simulation flight and flight with engine failure.

Experiment was focused on obtaining physiological data from pilots on simulator with a moving platform. Physiological data were collected for the purpose of analyzing to what extent can low cost simulator elicit physiological response. In case the response will be noticeable and significant, the next step is to involve unexpected engine failure and compare measured results with those where there was no emergency situation. The last goal is to see whether the physiology exhibits additional changes when there is a navigation instrument during emergency situation. Informed consent was obtained from all individual participants prior the experiments.

The experiment consisted of two parts: a) The first, presented pilots with different navigation configuration and let pilots perform a test flight, where they had a chance to get used to the environment and behavior of the simulator. After a test flight, pilots performed two flights, each with a different navigation paradigm and with the engine still running. These flights were important to prepare pilots for the following part and to understand their flight performance during normal conditions. b) The second, pilots were given information that they will perform three flights, where they will start already airborne and fly a short navigation flight to airport in the vicinity and land there. Pilots were given instructions and a map to prepare the flight. When the data was loading the pilots were asked which navigation paradigm they would prefer if they should encounter engine failure. Then the experiment started, and based on random distribution, engine failure was generated in two out of three flights. During one flight the pilot did not have the emergency landing assistant available and had to land on his own. The phases are divided into four parts: 1 - before failure, phase 2 - engine failure, phase 3 - soaring to the airport, phase 4 - approach and landing.

After the last flight pilots were presented with a simple questionnaire where they rated each segment of flight according to perceived level of stress. Ratings of the subjective questionnaires related to flight segment were from one to four with the following meaning: 1 – Most stressed; 4 – least stressed. Pilots were asked to rate on a Likert scale from 1 (not stressed at all) to 20 (extremely stressed) how stressful each flight was. In addition they rated on the same scale, how stressed they think they would be in a real situation.

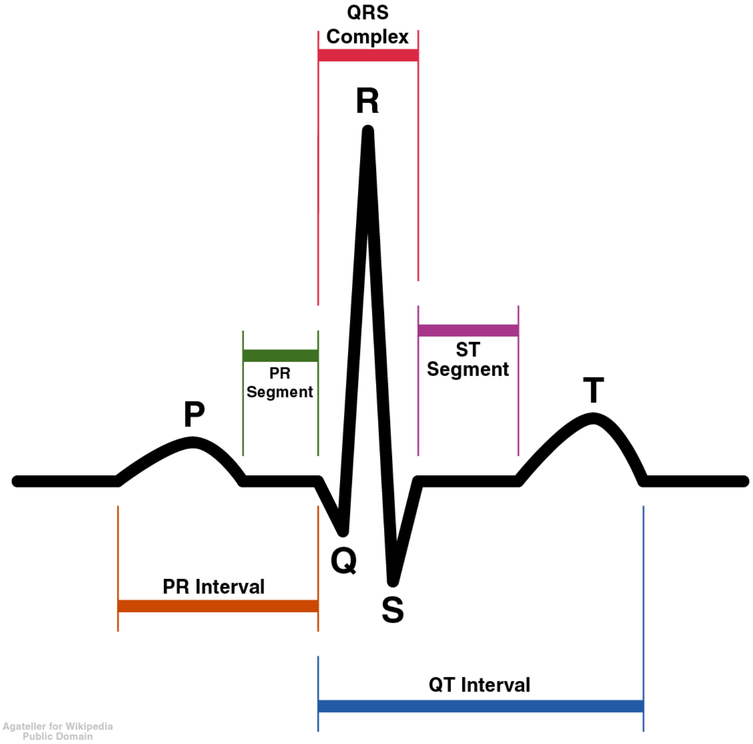

Figure 4.9: Cardiac rhythm with described parts of the wave, QRS complex is a part encapsulating the points Q,R, and S. Source: Wikipedia

Together with subjective data, pilots wore harness with electrodes to measure their physiological response. The most often and discussed measures in previous research are electrocardiogram (ECG), electroencephalogram (EEG), electrooculogram (EOG), electromyogram (EMG), electrodermal activity (EDA), blood pressure (BP), photoplethysmography (PPG), pupil diameter (PD), heart rate (HR), heart rate variability (HRV), skin temperature, and respiration belt [24, 37, 39, 46, 55, 63, 77].

For the purposes of experiment, data collected were ECG, EDA and respiration. Other means were not available at the moment of measurement. To record the data it was necessary to connect pilots with a logging device. The EEG was not measured, because the environmental conditions were too harsh and would not allow for safe data collection. Data were collected with BIOPAC, sampling frequency was 500Hz.

ECG data were processed by a Pan-Tompkinson algorithm to detect the QRS complex and to extract the inter-beat-intervals (in the scope of this thesis RR intervals). The processing was done by a bachelor degree student and is described in detail in [1] as well as processing of respiration and electrodermal activity. The algorithm was altered due to many falsely detected R peaks and not detected R peaks (lead to significant changes in HR) according to Hooman Sedghamiz as in [67]. Typical QRS complex is on Figure 4.9. The target of the algorithm is to detect the R peak and return its location in signal. The time between two R peaks is fundamental for further analysis. Similarly the peaks and valleys were detected for respiration.

In former experiments, verified methods to induce stress were used. Among the most common methods were public speaking, public arithmetic task, stroop color word test, cold pressor test, computer work and games [31].

This experiment hopes to induce stress by unexpected engine failure. The pilot then must then perform an emergency landing. This event happens without the pilot being told beforehand. The data could also show some significant changes during the introduction of the simulator to the pilots. It might be that the test subject is simply nervous and this might be reflected in the physiological data as well.

The department is equipped with a 6DOF enclosed hydraulic simulator. Simulator was used for all experiments – it represented a virtual environment in which the pilots flew and fulfilled their tasks. The pilot had one display available with a Fresnel lens before him, where he could observe the environment. The other display, situated underneath the main, served as a electronic flight information system (EFIS) providing the pilot with all necessary information. Controls involved in the experiment were joystick, throttle, rudder pedals, and trim.

The software used for simulation was FlightGear 2.4. It is an open source program that is easy to modify and work with. The navigation assistant developed at the department was implemented as a separate program and run on another machine than the computer with simulation software. The landing assistant was used for all simulations to provide either emergency guidance or flight variables to the pilot. The goals were firstly to evaluate how a pilot interacts with the proposed navigation, and secondly to be able to evaluate their interaction and stress based on a simulated flight. From previous tests it was decided that the navigation will be provided by tunnel and cross on the EFIS screen.

4.6.2 Scenarios

Test subjects were given 10 minutes to practice with the simulator. During this time they were given simple tasks such as to descend to a certain flight level or to change heading and maintain it. The subjects were not required to takeoff with the aircraft, because the program started with the plane already flying at $4000ft$ altitude. Once the subjects reported they were ready, the experiment proceeded to the next phase.

After warm up, pilots were given a task to follow the predetermined path that was presented to them on an EFIS screen in the form of a navigation metaphor: The test introduced two – cross and tunnel. Both flights were run with the engine on. The aircraft started flying at the same location and at the same altitude every time, and predefined moment after the start, the navigation instrument activated. The pilot was supposed to follow the predetermined path from the starting point of the flight to the landing site as closely as he could. The trajectory was eight like loop with descending tendency. Each flight took approximately 10 minutes. After landing subjects reported first impressions and filled in prepared questionnaires. The instruments were tested in random order. The two flights were done, the pilots were asked to fill in the overall assessment of flight interfaces and were interviewed. Among other questions, pilots were asked which interface (paradigm) would they prefer (if any at all) in case of emergency. The navigation of their preference was then prepared for following phase of the experiment.

Pilots were presented with an ICAO map of the Czech Republic and were given a task to prepare a navigation flight. They were instructed that this flight would be used for comparison with the two flights they had already flown. There were three flights ready and in two of them the engine would fail and the pilot would have to perform an emergency landing. This kind of information was not shared with pilot. In the case of an engine failure in one case the pilot had the navigation assistant available and in other he had to land on his own. Of course even when the navigation was available, the pilot might decide not to follow or could give up following at any time.

4.6.3 Sample

Pilots willing to get involved in the experiment were selected from the database described in Section 4.2. Resulting test sample consisted of 20 pilots aged from 21 to 48, with average of 30 years. The average number of flight hours was 200. The maximum amount of flight hours was 800. Some subjects had flown less than 100 flight hours. Some subjects reported that they had previous experience with emergency landing. Most of the pilots had a professional pilot license, but there were also some who had a glider license as well. These pilots were extremely useful when stating the drawbacks of our emergency landing assistant. In the selected pilots, some claimed to have previous experience with Garmin G-1000 or with other EFIS. Some pilots reported that they used the application in their tablets to serve the purpose of an EFIS. Some applications are known to be able to emulate an artificial horizon. Some pilots use even smart phones in order to emulate an EFIS.

4.6.4 Exploratory data analysis

The data were checked to remove any outliers and artifacts, so the analysis would be performed on clean data. ECG data posed a challenge, since the detection algorithm used to detect the QRS complex in EGC did not cope well with saturated signal. This was a case for data recorded during real flight. Additional challenge was removal of artifacts caused by movement of the simulator and pilot inside the cockpit. Movement of the pilot and the cabin cause oscillations in the signal which were hard to filter out and remove. Therefore the signal was manually checked to remove these errors. Faulty files were excluded from analysis.

After collecting the clean data from all measurements the first analysis of data was provided by simple calculation of mean, median, and standard deviation. Data were divided to several groups based on conditions during the experiment to see, how to analyze the data further. The groups were distinguished according to the presence of navigation instrument and engine failure. There were altogether four cases. Since one of the objectives was to investigate if the navigation will have effect to pilots' physiology, the flights were separated to ones with cross and failure during the tracking task and their mean and max values were compared. Its can be seen from Figure 4.10 that means do not seem to differ. Only maximal values seem to be different and it will require further investigation of in which phase of flight the heart rate peaks.

To explore whether and how the data are affected by the main variables of the experiment (navigation, engine failure), mean and standard deviation was calculated to get initial information about possible grouping and data distribution. First the data were plotted in terms of each variable, mean against the max value. In case of ECG, the heart rate was used for initial processing. In case of respiratory data was considered inter breath interval and peak value difference. Inter breath interval is used to calculate respiratory rate (breathing frequency). Peak value parameters is a difference between maximum and minimum of one breathing cycle. It is important to note, that graphs on the left side have more data points. It is because of the setup of experiment, where the navigation tracking task was performed by each pilot for each navigation paradigm. With engine failure there was only one flight with navigation. Therefore lesser amount of data points.

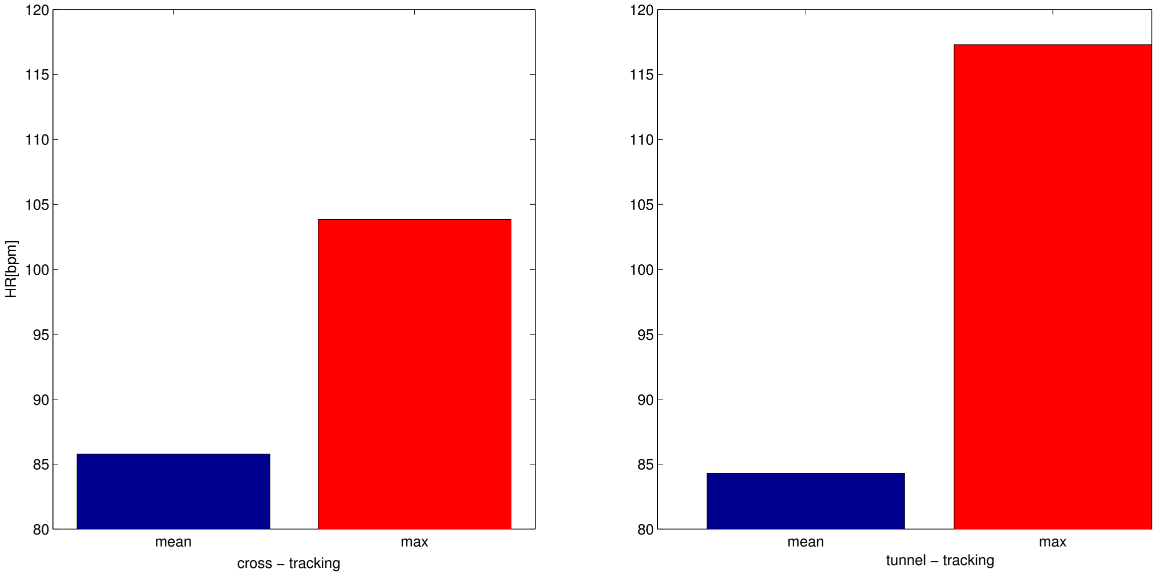

Figure 4.10: Mean HR of subjects during tracking task for both cases (cross on the left, tunnel on the right). Both the mean and max values shown here are averaged across all test subjects.

The heart rate shown in Figure 4.11 groups around an approximate line going from lower left to upper right corner. This is the same case for flights with engine failure and without it. The average number of beats per minute for a normal healthy person not doing any demanding physical activity is between 65 bpm to 75 bpm and varies slightly around these values. Therefore some of the mean values of HR might seem a bit elevated and the average increase in HR from the mean is about 10 bpm. The data do not seem to be affected by the navigation or the engine failure.

Respiration data on Figure 4.12 and Figure 4.13 do not group in same way as the HR does. The data is more spread out. Average breathing frequency of a normal, healthy adult person is in range from 12 to 18 breaths per minute. This of course changes with conducted activity. For example during sports, the rate may increase up to 70 breaths per minute. When looking on Figure 4.12 it is noticeable, that for cases with engine failure the maximum respiratory rate does not exceed 80 cycles per minute, and that for tracking task the maximum is quite high about 100 breaths per minute.

The peak valley parameter shown in Figure 4.13 has most values concentrated in the lower left corner for all the cases. Some instances of maximal values spread out to values of 13, especially for the tracking task without the engine failure. The difference between the four investigated cases seems marginal here.

The measurement of EDA was very hard to analyze, since in the cockpit was a high temperature. At times even more than 30°C. It was because of the weather and the hydraulic engine placed under the enclosed cockpit. The skin conductance response detection was very unreliable, because the pilots perspired due to high temperatures.

From this initial analysis is concluded, that using basic statistical measures will not be enough to establish whether the navigation and engine failure in a simulator somehow affect the pilots. The data will be further investigated with additional measures. The flights will be separated into several segments to explore them independently. The data will be also compared to a real flight in the following chapters.

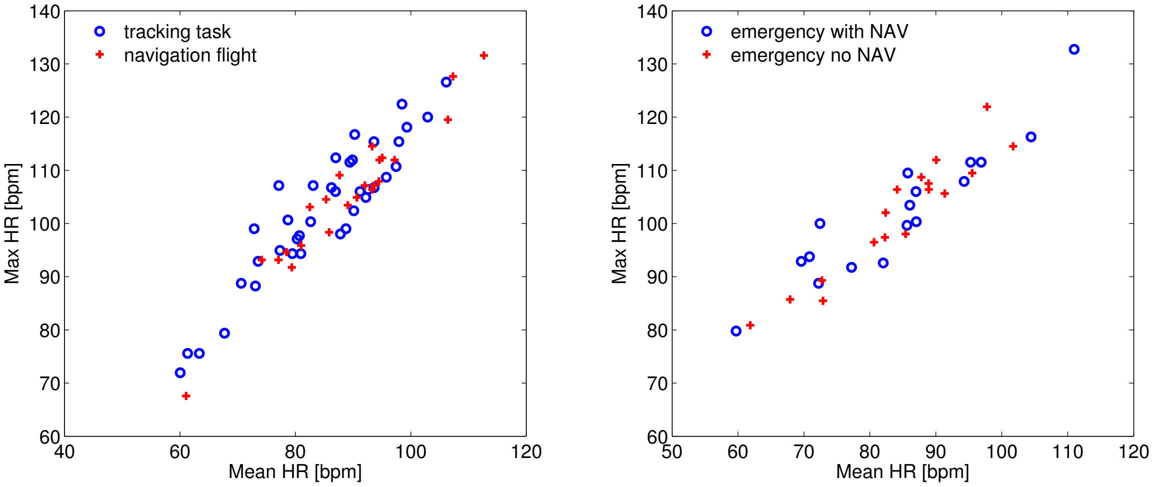

Figure 4.11: Comparison of heart rates in flights without engine failure–left, and with it–right. In flights without engine failure are compared cases where the pilot followed a navigation to a landing site for navigation evaluation, and the training flight (with + marker), where the pilot flew a simple trajectory to get acquainted with the simulator. The flights on the right show the case with engine failure divided into category where the navigation assistant was available and where it was not.

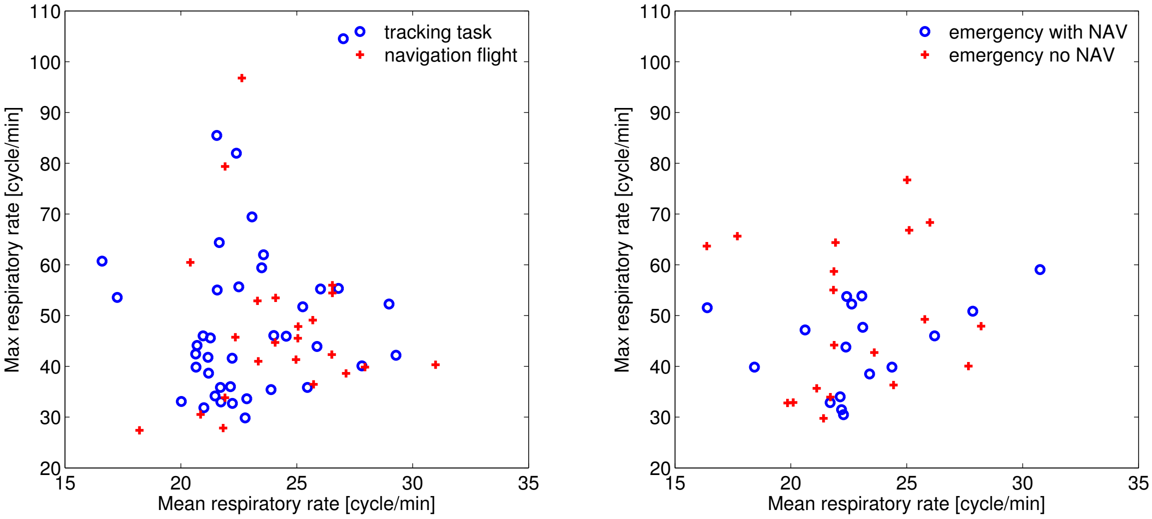

Figure 4.12: Comparison of respiratory rates in flights without engine failure–left, and with it–right. In flights without engine failure are compared cases where the pilot followed a navigation to a landing site for navigation evaluation, and the training flight (with + marker), where the pilot flew a simple trajectory to get acquainted with the simulator. The flights on the right show the case with engine failure divided into category where the navigation assistant was available and where it was not.

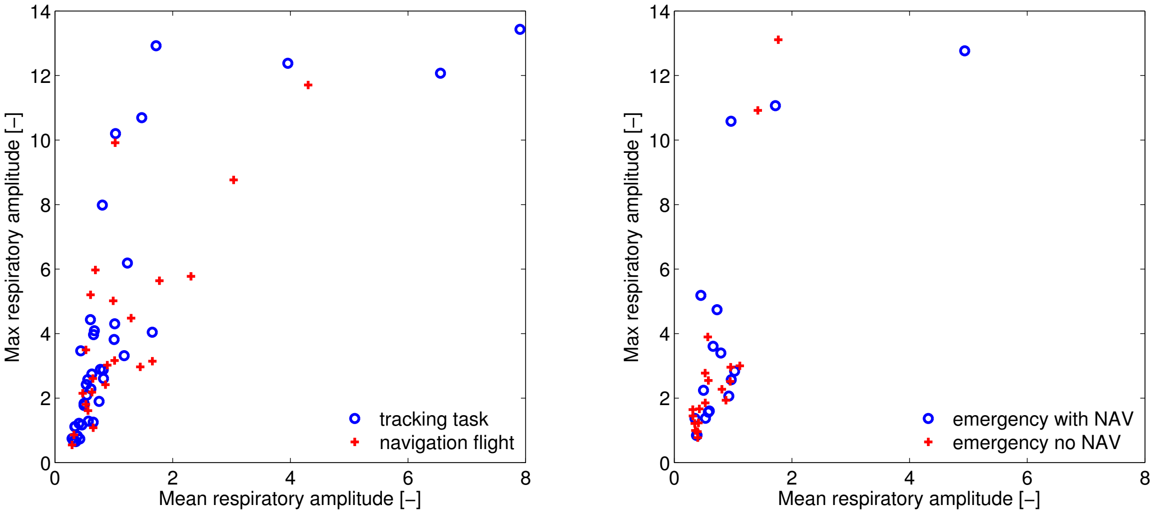

Figure 4.13: Comparison of respiratory amplitudes in flights without engine failure–left, and with it–right. In flights without engine failure are compared cases where the pilot followed a navigation to a landing site for navigation evaluation, and the training flight (with + marker), where the pilot flew a simple trajectory to get acquainted with the simulator. The flights on the right show the case with engine failure divided into category where the navigation assistant was available and where it was not.

4.6.5 Engine Failure

Influence of external stimuli in form of in flight engine failure to physiological state was examined. Measurements are reflecting situation awareness and workload [66]. It is assumed, that experiencing engine failure causes mental and physical load. Pilot has to maintain airplane airborne for as long as possible, select most convenient landing site, plan approach and perform landing. The hypothesis is that if this is the case the effects of focus and attention should be present in physiological data. It is expected to observe a decrease in heart rate variability. All these tasks are well managed by a well trained air transport pilots, so it is questionable how these experienced pilots will interact with a low cost simulator. However, the pilots of ultra light aircraft who do not get many flight hours and do not train so extensively could exhibit more readable changes in their physiology.

The flights without engine failure were cross compared with flights where the engine failure happened. It is important to note, that since the flight without engine failure did not have same segments as the one with engine failure, it was divided into four equal parts. These segments allowed to observe how parameters developed with time and it was possible to relate these flights to ones with engine failure. Presented results were also presented in a conference paper of authors [7]. From all used parameters only four were found significant: standard deviation of RR intervals (SDNN), average power in frequency spectrum band 0 to 0.5 Hz (RF1), average power in frequency spectrum band 1 to 1.5 Hz (RF3), average breathing frequency (ABF). Each Figure is showing comparison of flight without engine failure denoted as flight 1, and the flight with engine failure as flight 2.

SDNN has significantly different means with respect to phase $p = 0.018$, to flight $p = 0.0175$ and with phase against flight interaction $p = 0.0433$ which is near to evaluated level of significance.

RF1 with interaction phase against flight of $p = 0.018$ is also below the desired $\alpha = 0.05$. The significant differences are noted to be in the phase 4 of flight with engine failure and in the phase 1 of the free flight. Unfortunately the absolute value of the power level of RF1 is too low to be considered important for the assessment of actual effect of the stimuli.

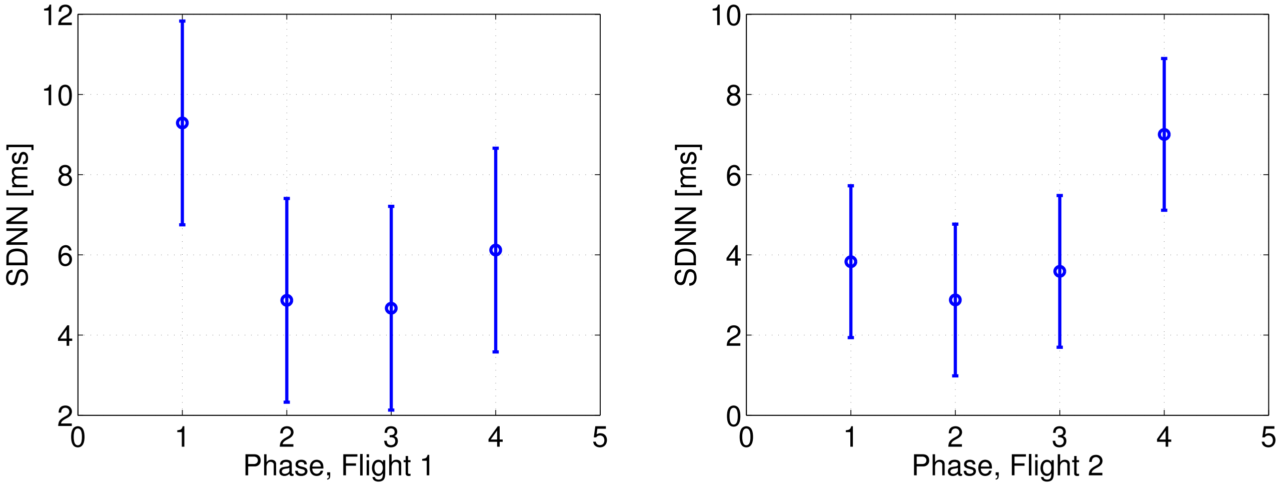

Figure 4.14: Results of ANOVA with additional multiple comparison tests margins for standard deviation of two consecutive RR intervals. Flight with engine failure is on the left and flight without engine failure is on the right. Flight 1 is divided into four same length segments. Flight 2 is segmented based on engine failure with 1– before engine failure, 2–engine failure, 3–glide, and 4–approach and landing.

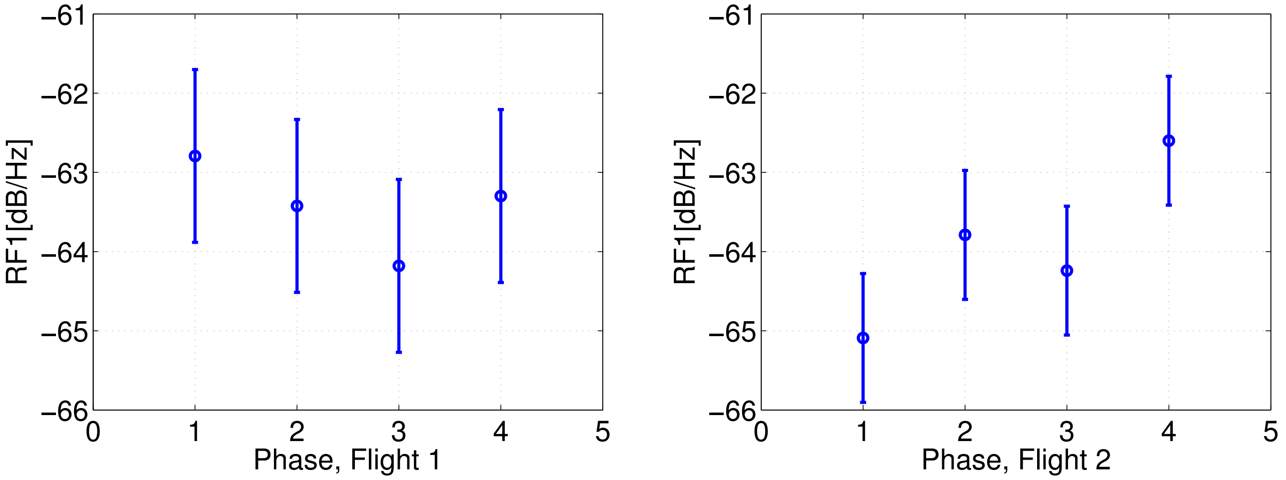

Figure 4.15: Results of ANOVA with additional multiple comparison tests margins for average power in frequency spectrum band 0 to 0,5 Hz. Flight with engine failure is on the left and flight without engine failure is on the right. Flight 1 is divided into four same length segments. Flight 2 is segmented based on engine failure with 1– before engine failure, 2–engine failure, 3–glide, and 4–approach and landing.

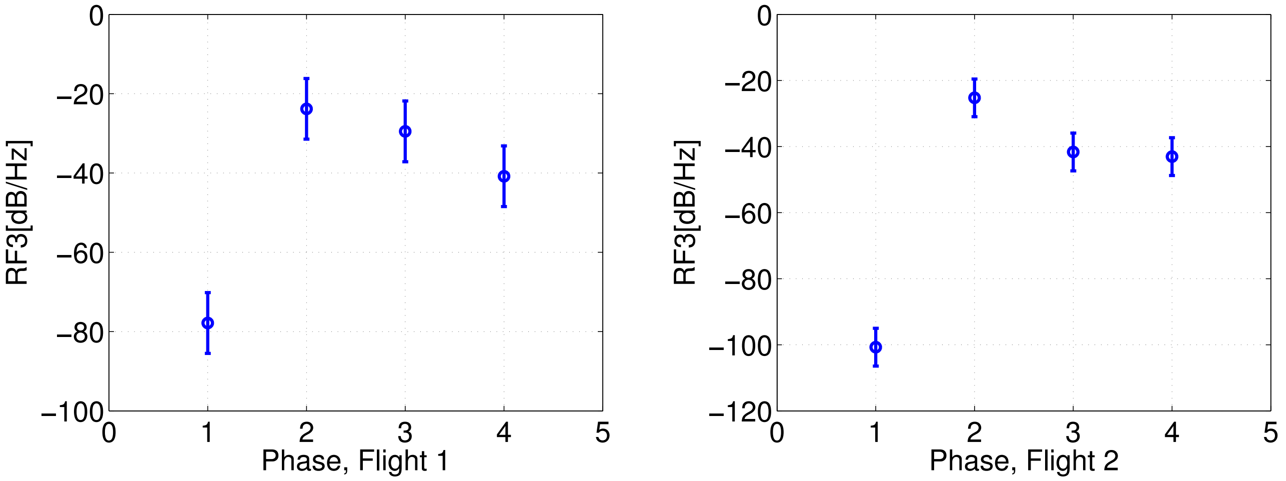

Figure 4.16: Results of ANOVA with additional multiple comparison tests margins for average power in frequency spectrum band 1 to 1,5 Hz. Flight with engine failure is on the left and flight without engine failure is on the right. Flight 1 is divided into four same length segments. Flight 2 is segmented based on engine failure with 1– before engine failure, 2–engine failure, 3–glide, and 4–approach and landing.

With parameter RF3 the phase against flight interaction results in $p = 0.0056$. The phase and flight significance is $p < 0.001$. It appears as the phase 1 where the flight starts is the calm region and after the pilots takes over the plane and must focus on its control, the power increases with the effort to control the plane.

Average breathing frequency is significantly different in the fourth phase of failure flight ($p = 0.0011$) and in the second and fourth phase of training flight. It is not significant in flights and interaction.

The expectation was to observe more apparent changes in signals, which were used successfully to evaluate stress and workload in previous experiment according to [7]. The only significant parameter derived from ECG was SDNN in Figure 4.14. It exhibited large deviation at the beginning of the first flight which seems to be related to unfamiliarity with the simulator and environment. Once the pilots get familiar with simulator the deviation decreases. In case of second flight the increase happens during the fourth phase, which is related to approach and landing. In this phase it would be expected to observe elevated heartbeat and increased breathing frequency. Unfortunately no significant changes in heart rate variability were measured.

Average breathing frequency did change its level during both flights as seen on Figure 4.17. During the first flight the ABF remained elevated after the first segment around 26 breaths per minute. It would suggest increased effort and workload to maintain the trajectory. It could also be caused by getting used to new environment. The second flight started with breath lower, at around 21 breaths per minute and afterwards gradually elevated to 27 breaths per minute.

Average power in frequency spectrum in band from $1Hz$ to $1.5Hz$ on Figure 4.16 shows similar trend.

As Figure 4.15 suggests, the RF1 parameter is excluded, since the absolute change is considered too small, though significant. On the other hand RF3 exhibited

It seems that approach and landing impose more workload to pilot, but at the moment of failure there does not seem to be directly visible change in physiology. There is a significant change between the first and following phases showing, that pilot needs to concentrate and put effort into flying even

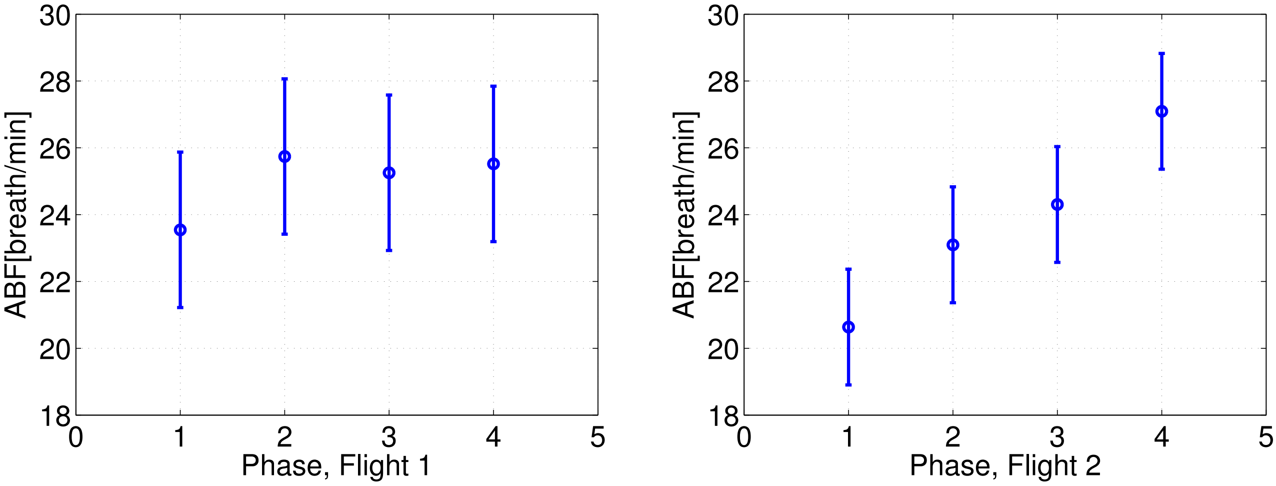

Figure 4.17: Results of ANOVA with additional multiple comparison tests margins for average breathing frequency. Flight with engine failure is on the left and flight without engine failure is on the right. Flight 1 is divided into four same length segments. Flight 2 is segmented based on engine failure with 1– before engine failure, 2–engine failure, 3–glide, and 4–approach and landing.

low cost simulator, which is expected. The approach and landing appear to have more stimulating effect on pilot than engine failure. The approach and landing most likely requires pilot to focus on where to land the airplane and how to manage the landing properly in emergency situation. Some pilots for example did not manage to land in nearby airfield, but were forced to land to terrain. This will be considered for further evaluation of the data.

This data showed that there is a measurable change in physiology for approach and landing. Engine failure does not seem to take effect. The next experiment tries to use engine failure data, divide it into four segments and compare the segments where the navigation assistant was present with the segments where it was not. The aim is to observe how will the data be affected. The navigation might make it easier for pilot to align with the landing site. As a result, the mental workload might decrease. Localization of the landing site might be also easier as well as maintaining proper trajectory to approach the airfield. On the other hand it might force pilots to lose sight of the surrounding and focus more attention to the glass cockpit navigation scree, which may decrease workload, but is not desirable, because the pilots needs to keep awareness of the real terrain and possible obstacles in a landing site.

4.6.6 Expected results

Following sections describe attempt to analyze the effects of the navigation assistant on pilots physiology. Presented data were also reported in a paper [5] and some parts were presented in a master's thesis [1].

Two sets of data composed of flights with navigation after engine failure, and flights without navigation after engine failure are obtained from experiment. Each record in a set is divided into four phases based on events occurring. Sets are compared against each other and processed with analysis of variance applied to before mentioned parameters.

Changes expected in the physiology are: events of increased EDA along with decreased heart rate at the moment of engine failure, changed respiration rate during the engine failure phase and possibly during approach and landing phase in all recorded sets. Decreased heart rate variability during approach and landing. Comparison of the set with navigation against the set without navigation should demonstrate if there is any significant difference in parameters. It was expected that pilots would be likely to choose HITS (highway in the sky/tunnel) than cross for navigation purposes.

Subjective rating of stress is expected to mark the engine failure phase as the most stressful and the fist phase of flight (cruise) as least.

4.6.7 Results

Subjective Data

Subjects rated perceived level of stress for simulations without navigation assistant and with it. Each subject also assessed level of stress in each of four segments of flight with engine failure. Subjective ratings were compared with physiological data to estimate whether there are any detectable events in biological signals that might suggest stress or metal load.

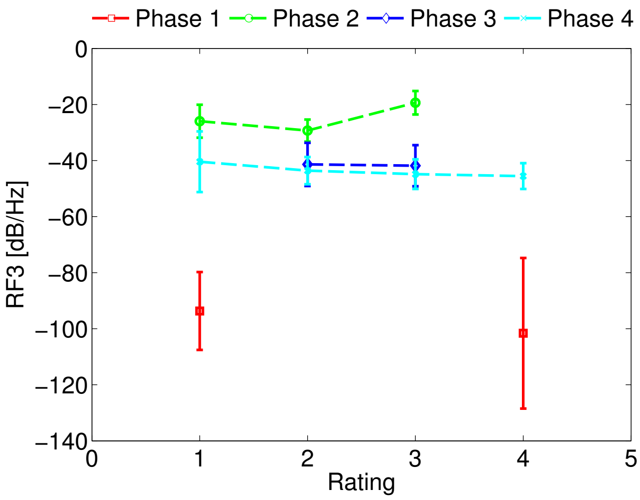

Figure 4.18: Standard deviation and mean of RF3 against pilots perceived stress rating (1 – most perceived stress, 4 – least perceived stress) across all flight phases (1 – before engine failure, 2 – engine failure, 3 – glide, 4 – approach and landing).

Figure 4.18 shows, that none of the pilots rated phase before failure (phase 1) as 2nd or 3rd most stressful. On the other hand the gliding phase (phase 2) was rated only with score 2 and 3. The moment of engine failure was never rated by pilots as the least stressful. Phase before engine failure was rated with scores 1 and 4. The subjects were divided between those who considered the first phase as most stressful or as the least stressful. It could be also due to the nature of the experiment. Subjects might suspect it is expected from them to chose the landing part as the most stressful. Physiological data show RF3 parameter of the first phase to be 30dB/Hz lower than other phases. This is also confirmed by statistical data analysis.

Multiple analysis of variance with 2 × 4 design for the two groups of flights (flight with navigation and without it) and for four phases of flight (before engine failure, during engine failure, glide without engine, approach and landing) is used to determine which variables have significant effect on the mean. To determine statistical significance of differences between individual conditions such as rating, phase or flight, multiple comparison tests were used based on Student's t-test with Bonferroni correction.

Statistically significant results were observable for parameters RF4, RF3, and ABF. Results of MANOVA show that only rating had significant effect on the parameter's mean. The flight type does not appear to have and effect. Rating affects the RF3 mean with $p = 1.033e - 13$, ABF with $p = 0.005$, and RF4 with $p = 0.0154$. The multiple comparison test show that the mean of rating 4 (least stressful) of RF3 parameter is significantly different on level $\alpha = 0.05$. On the same level of significance is statistically different mean of rating 4 of ABF parameters and mean of rating 2 of RF4 parameter. Although as can be seen from Figure 4.19 C, the scale of RF4 parameter is very small.

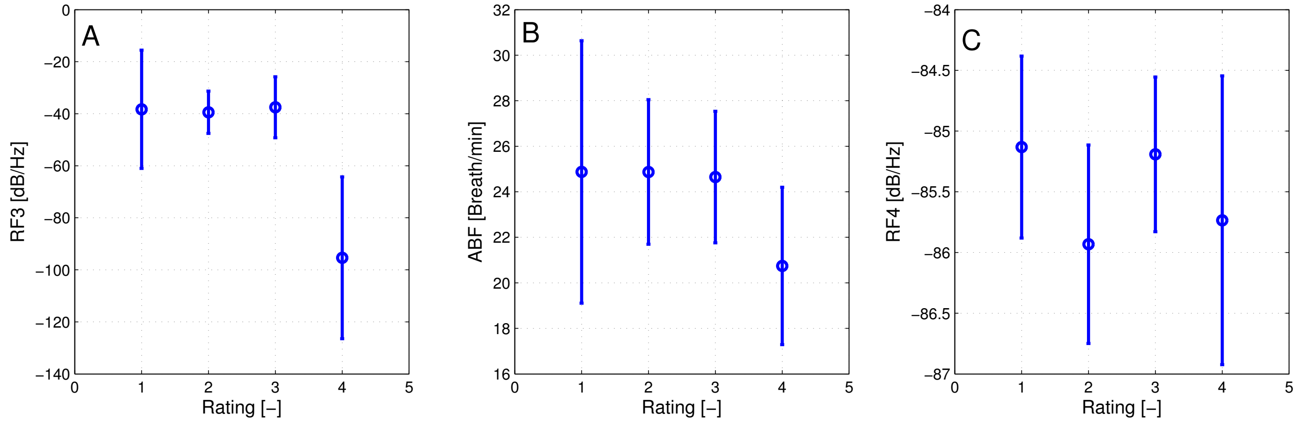

Figure 4.19: Mean and standard deviation of RF3, ABF, and RF4 parameters with respect to rating (1 – most perceived stress, 4 – least perceived stress).

When the flight was finished, the pilots were asked to compare whether they were more stressed with the navigation or without. The result is that seven pilots reported that the navigation made them stressed and therefore they decided not to follow it. They also complained that it was not clear where the navigation led them and could not localize the landing place themselves. Some pilots decided to drop the navigation once the airfield was in reach and could see it. They did not follow the path for landing and claimed, that it would be enough if they just knew the direction in which the airport is, the airport's heading, the distance, and the aircraft potential altitude on the moment of arrival. They also noted that they would not trust the system if it would not consider wind.

Physiological Data

Physiological data measured during experiment were analyzed with ANOVA except of a Figure 4.20. Figure 4.20 shows on raw data how parameter changed with respect to flight type. There can be seen no significant difference between the two flights. Phases 2 and 3 were of greatest interest, because in case that navigation would have some influence on physiology, it would be most likely seen here as a drop or increase of mean value between the flights.

Figure 4.21 A and Figure 4.21 B are not significantly different in terms of flight with navigation and without it. On the other hand, there is a significant difference between flight phases with $p = 9.6 \times 10^{-5}$. After providing multiple comparison test, the phase 1 (before engine failure) is significantly different to all other phases in the level of 0.05. The mean value for first phase is $RF_1 = -100.74 dB/Hz$ and for second phase $RF_1 = -25.24 dB/Hz$. Second, third and fourth phase means are not significantly different.

The presented time and frequency based parameters represent only linear and periodic properties

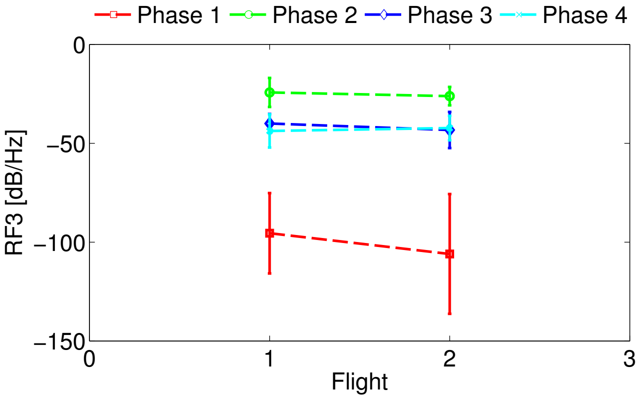

Figure 4.20: Flight type (1 – navigation included, 2 – navigation excluded) against flight phase (1 – before engine failure, 2 – engine failure, 3 – glide, 4 – approach and landing).

of the signal. To investigate nonlinear behaviour of recorded HRV data entropy measures and DFA (detrended fluctuation analysis) was employed. Entropy measures are suitable for evaluation of short time ECG data samples (less than 30 minutes), which was the case of flight experiments. Each experiment took 10 minutes at maximum.

Entropy measures are used in number of variations with different properties. Generally repeated and periodic signals (periodic repetition of the same pattern) should indicate a low entropy. Aperiodic dynamics should be reflected by high entropy. Problem may occur with short samples. If there is a pattern which is too large (needs many samples) and the number of samples collected is too little the pattern will not be detected. There are some extreme cases where the entropy without correction tends to be zero even for white noise and can lead to possible erroneous detection of determinism. Therefore selection of proper entropy measure is important. Several measures were employed - corrected conditional entropy, sample entropy, approximate entropy. Unfortunately there were not significant data recognized in most of those parameters. Entropy was calculated for each stage of flight separately to provide a comparison.

From employed entropy measures, which were applied to HRV and respiration frequency are showed in Figure 4.22 results of approximate entropy parameter. This was from all calculated entropy measures the only statistically significant. Based on multiple ANOVA the rating and phase has significant effect on the mean. The flight type again does not appear to have effect on the group mean. From multiple comparison tests it appears the variability related to phase suggests that phase 2 and 4 are both significantly different from phases 1 and 3 on the level of 0.05. Phase 1 and 3 are also significantly different on the same level of significance. HRV related to ratings shows, that the 1,2, and 3 ratings have significantly different means from rating 4. This can be seen on Figure 4.22, A, and C.

Approximate entropy of respiration analyzed with multiple ANOVA shows that phase groups do not have the same mean with $p = 4.36 \times 10^{-7}$, and rating groups also do not have the same mean with $p = 0.0022$. From additional multiple comparison tests is seen that in appraisal the rating 4 has mean statistically different from the rest of ratings and the ratings 1 to 3 do not have significantly different mean. Phase groups 2 and 4 have significantly different mean from phase 1 and 3.

Average breathing frequency exhibits similar significant trend between phases with $p = 2.2 \cdot 10^{-5}$ and no significant change in terms of flight as seen on Figure 4.21, C and Figure 4.21, D. The means of first (before engine failure) and last phase (approach and landing) are significantly different.

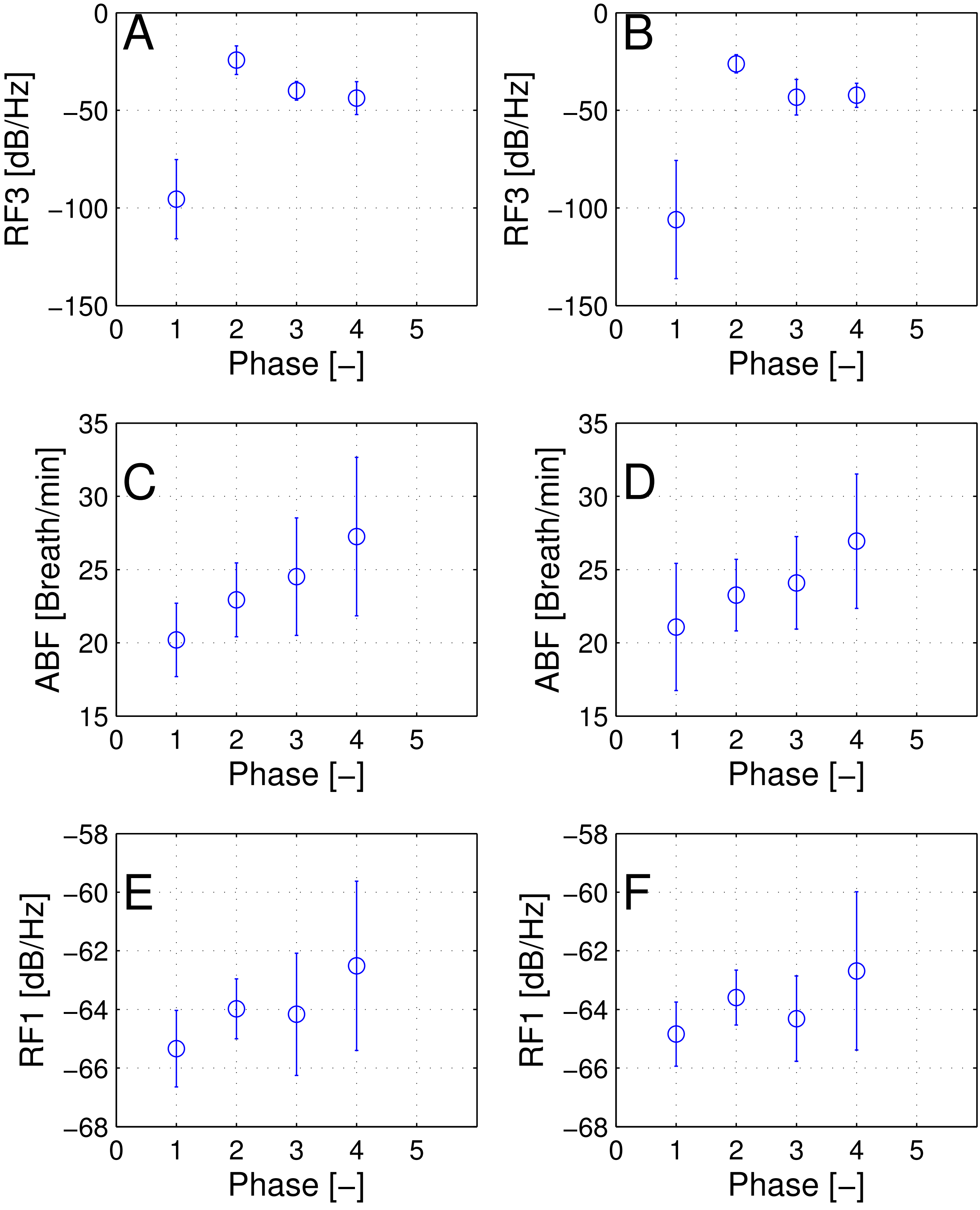

Figure 4.21: Means and standard deviations of statistically significant parameters against flight phase (1 – before engine failure, 2 – engine failure, 3 – glide, 4 – approach and landing). The left column with figure A, C, and E is for flights with navigation enabled, the figures B, D, and F are for flights without navigation support.

Parameter RF1 is significantly different only in the phase of approach and landing with $p = 0.001$. Result from ANOVA are summarized in Table 4.9 listing significant parameters only. From all

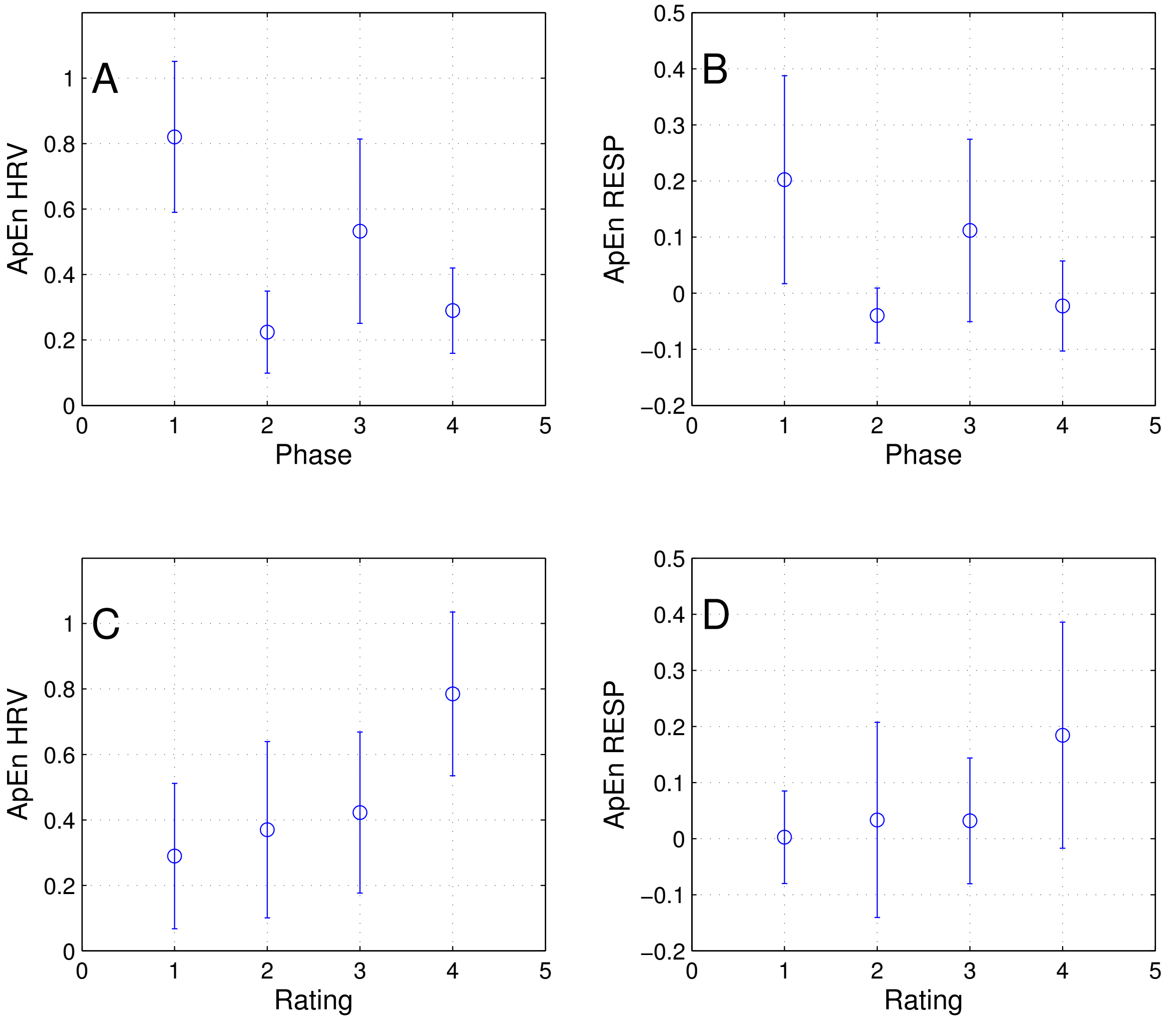

Figure 4.22: Means and standard deviations of approximate entropy of heart rate variability and breath frequency plotted against flight phase (1 – before engine failure, 2 – engine failure, 3 – glide, 4 – approach and landing) and subjective rating (1 – most perceived stress, 4 – least perceived stress).

used parameters were observed only four to be significant.

	Dimension		
Parameter	Rating	Phase	Flight
RF1	n.s.	p<0,05	n.s.
RF3	p<0,05	p<0,05	n.s.
RF4	p<0,05	n.s.	n.s.
ABF	p<0,05	p<0,05	n.s.

Table 4.9: ANOVA analysis on the level of significance 0,05; n.s. – not significant

Detrended fluctuation analysis (DFA) is a quantification of fractal scaling properties over time expressed with scaling coefficient α. The algorithm based on [57] and implementation was used from [23]. This kind of analysis helps to reveal long term correlations in the time series and determines self-affinity of a signal. The resulting coefficient determines, whether the signal is

- $\alpha \leq 0.5$: anti-correlated,
- $\alpha \simeq 0.5$: uncorrelated, white noise,

- $\alpha > 0.5$: correlated,
- $\alpha \simeq 1$: 1/f-noise, pink noise,
- $\alpha > 1$: non-stationary, unbounded,
- $\alpha \simeq 3/2$: Brownian noise.

To do the analysis, the time series $y(k)$ k=1,...,N of RR intervals of length N is first integrated and divided into equal non-overlapping segments of length n. In each segment local trend $y_n(k)$ is calculated by using least squares method and is subtracted from the $y(k)$. Afterwards the fluctuation values are calculated from 4.5 and the scaling coefficient is determined as a slope of a log-log plot of $F(n)$ against n.

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_n(k)]^2} \tag{4.5}$$

The fluctuation analysis was provided for all the groups together as well as for separate groups to provide comparison and insight into how scaling changes with task. Figure 4.23 shows the means of scaling coefficients for each group separately. The mean and standard deviation was obtained by calculating the scaling coefficient for each test first, and then calculating the mean and deviation. The results do not seem to support the idea, that groups might yield different results for separate groups. To investigate more how the scaling develops with number of beats, the analysis shown on Figure 4.24. This method was adopted from [65], where the coefficient α provided insight into correlations during sleep and wake state of young and elderly.

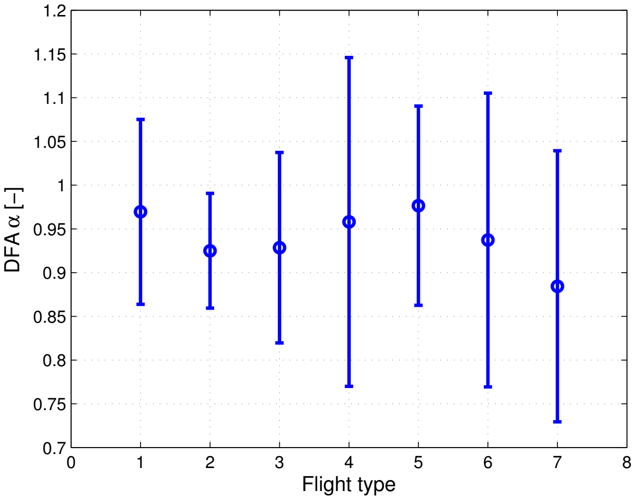

Figure 4.23: Means and standard deviations of fluctuation fluctuation analysis of heart rate against flight type (1–flight with navigation instrument using cross, no engine failure, 2–flight with navigation instrument using cross, engine failure happened at the beginning of the flight, 3–navigation with tunnel visualization and without engine failure, 4–navigation using tunnel, engine failure occurred shortly after start,5–training flight without any engine failure, 6–navigation flight without engine failure, 7–navigation flight without emergency landing support, engine failure present).

The group fluctuation function on Figure 4.24 has $\alpha_2 = 0.8564$. It can be seen, that the function seems to change its slope around 10 cycles. When analyzed separately, the slope from the beginning to $n = 10$ is $\alpha_1 = 1.3478$. Change in slope was observed by Karasik et al. in [30]. They examined people under rest and exercise conditions, measured the heartbeat and calculated slope of fluctuation function. Their experiment showed, that people doing exercise have different exponents than during rest period. They found significant differences between the rest and exercise period. The coefficient during the exercise was negative.

The coefficient resulting from flight measurement is close to coefficient reported by Schmitt in [65] for the wake time of both elderly and adult test subjects. There does not seem to be a particular difference with respect to performing experiments on a simulator and normal state. In Figure 4.25 is shown, how the fluctuation function changes with respect to different character of the task. For completeness, comparison of both main navigation instruments under the emergency and normal conditions in sections A and B. Only the cross under failure exhibited seemingly greater differences from other functions, but this was mainly caused by smaller amount of data points, since pilots were allowed to choose the navigation based on their experience. Simply there were more pilots favoring the tunnel navigation. The comparison in section C of Figure 4.25 shows aggregated failures and tracking tasks. There is almost no difference between those tracking functions. In the last section D is completed comparison of all failures, even the unexpected failure without any navigation.

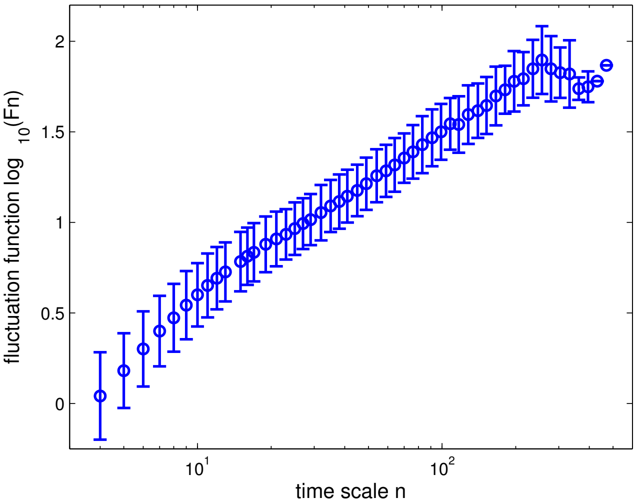

Figure 4.24: Group averages of fluctuation function with standard deviation. At the end of the graph can be seen that deviation is very low. The reason is not having enough data points and it accounts for the last three data points in the graph.

4.6.8 Physiological Data from Real Flight

To provide a comparison of how measured data from simulator relate to a real flight situations a real flight was conducted with a pilot connected to an ECG recording device. The additional devices for respiration and EDA were not possible to use. Main problem was excessive power requirements. Only one pilot was recorded, so it is not possible to perform any statistics. The purpose of the flight was to explore the feasibility of additional measurement in the future to bring simulated experiments into context of real flight. Another interest in this experiment was to see if there is measurable change in heart beat between certain types of situations. It is supposed, that if there are, it is quite likely to record them with even one measurement experiment. The experiment can and certainly should be

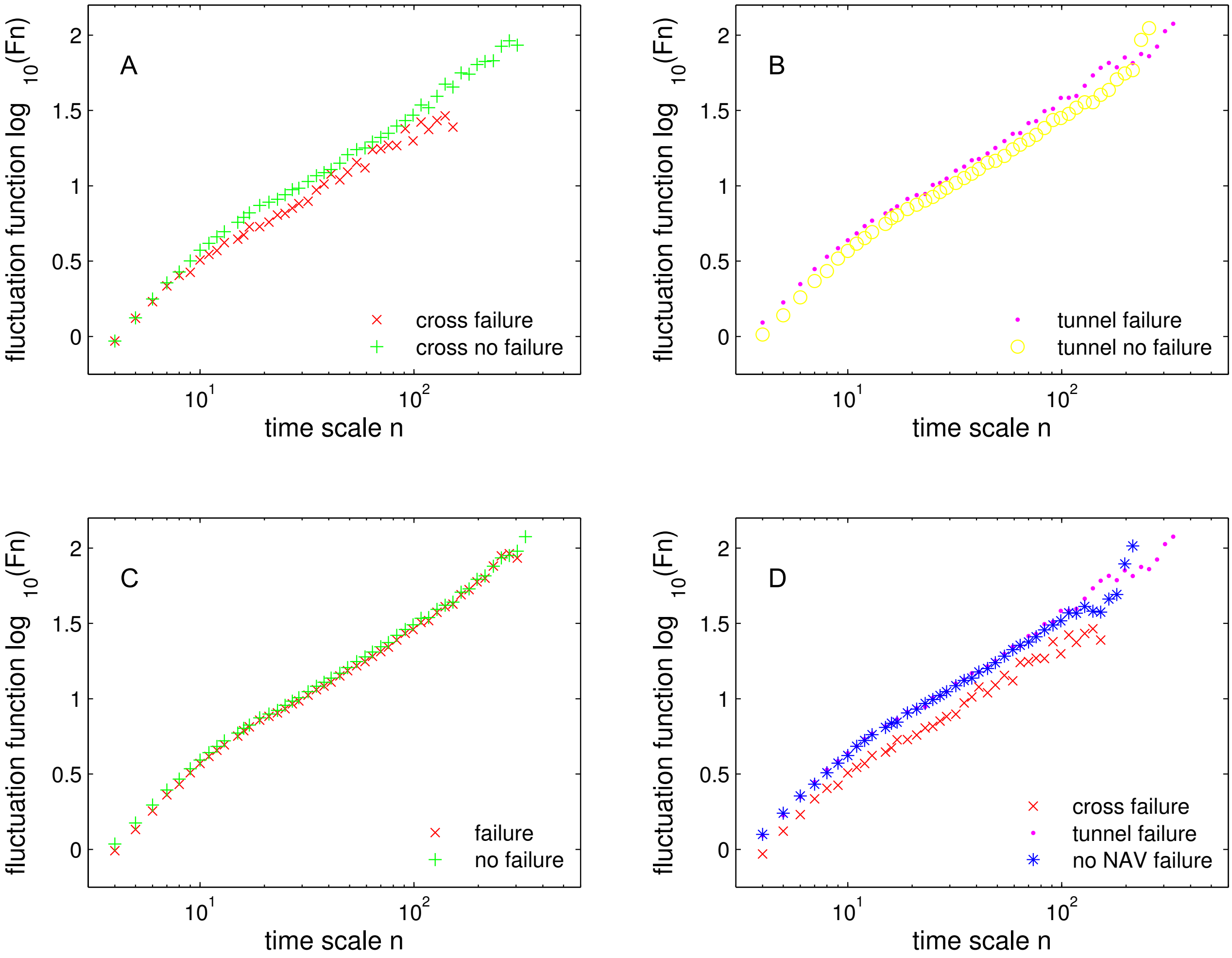

Figure 4.25: Fluctuation function for cases considered worth comparison. The graph A shows comparison of F_n averages of flights with navigation cross, both with failure and without. Graph B shows same comparison, but for navigation with tunnel. In C are all failures combined (with navigation) and plotted together with F_n of flights without failure. The last picture D shows F_n for all flights, where simulated failure occurred.

repeated with more test subjects in the future.

Cessna 172 was selected for the experiment. The same aircraft model was used in simulation. Two test sessions were provided, both with the same pilot in the same day, first in the morning and second in the afternoon.

The morning session focused on performing basic training operations, such as take off and landing. The pilot performed several approaches and immediate take offs. During this session several attempted training emergency landings were done. The case of emergency landing works in such a way, that pilot reduces the throttle to minimum to simulate engine failure and then proceeds as would in real emergency situation. Pilot chooses emergency landing site and performs approach. Shortly before touch down, the throttle is increased to maximum, so that the aircraft would not touch the ground.The aircraft flies over the possible landing site in low altitude and continues by gaining the altitude. Last trained situation was stall recovery. Pilot gradually slows down the aircraft to approach stall velocity and then slightly pulls up to increase the angle of attack. When the flow separation occurs, the aircraft starts falling.

The afternoon session was performed with a flight instructor. Having a flight instructor on board was the main difference between the two sessions. The instructor gave orders to verify pilot's skills. Even though it was not a formal examination it is believed, that this is a very stressful context. Measured signal might give an insight on how the ECG and HR changes and to what extent. The weather during the afternoon was more turbulent than in the morning, but the weather conditions remained good for flying. There were no strong winds, very good visibility, and no clouds.

There ware three breaks. One before the start of the morning session to setup the measurement and obtain the baseline. Second between the sessions, and last after the end of the second session to get a measurement of heart rate baseline again. Each flight took one hour. The relaxation period between the flights took 3 hours. The heart rate from both flights and the break between is compared in Table 4.10 and in Figure 4.26. The mean HR is highest during the session 2 in the afternoon. Mean values during the relaxation seem to be similar as those during the morning session. When compared to data from simulator experiment on Figure 4.10 it seems that mean values from relaxation session and session 1 correspond simulator mean HR in both emergency, and tracking task. Even though the first session on real flight seems a little higher with 88 bpm, this might not be important since more test subjects would be needed to establish what the appropriate level is.

	Measure		
	Median[bpm]	Mean[bpm]	Std. Deviation[bpm]
Session 1	87.77	88.54	6.33
Relaxation	84.40	84.36	8.05
Session 2	99.10	98.62	7.42

Table 4.10: Heart beats during different sessions.

The mean HR in the session 2 reaching 98 ± 7.42 bpm is higher than any mean values during the simulation flight (taking into account all executed flights) and also is higher than the morning session. It possibly could be due to the presence of the instructor, the turbulent weather in the afternoon, or other cause. This needs to be investigated further to draw proper conclusion. Nevertheless the first flight session was in terms of mean HR no different than simulator flights. When looked at in a detail, heart rate exhibited peaks reaching up to 96 bpm. Simulated flight was segmented to four stages based on the engine failure, glide (flight), approach and landing. Such kind of segmentation was not possible in this case, therefore during flight each situation was marked and its beginning and end was logged into a file for future reference. Situations extracted from the log are plotted in Figure 4.27 and Figure 4.28.

Real flights were divided into segments, where a maneuver which related to training was performed. The comparison of morning and afternoon sessions are in Figure 4.27 and Figure 4.28. Figures show the flight in its full length and the events displayed reflect the length of the event in seconds exactly as recorded.

During the second session there were no attempts to perform approach ended with runway flyover, but there were attempted emergency landings. The emergency landings are the most of interest. The navigation instrument experimented with in this thesis should provide pilot with additional means to handle this situation. Contrary to the expectations, it appears, as if in real flight the emergency landing (of course trained only) did not relate to increase in heart rate, since in both flights the rate varies significantly. The overall highest heart rate seems to be at the beginning of the flight, at time of

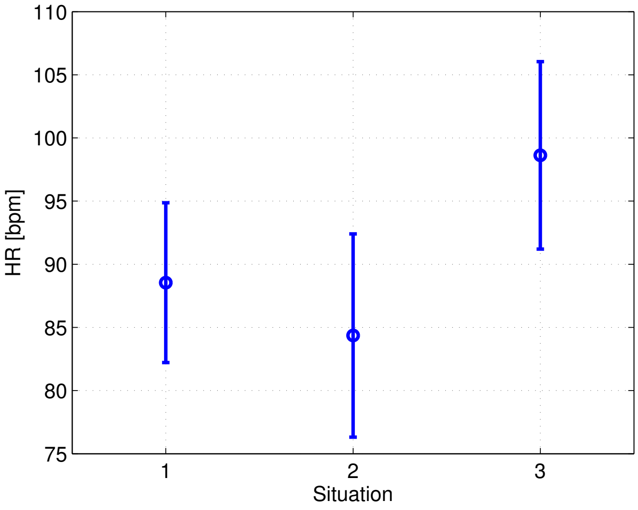

Figure 4.26: Mean of the heartbeat during different stages from flight on real aircraft. The stages are ordered chronologically (1–morning measurement session, 2–time between the two sessions, and 3–the afternoon flight with the instructor).

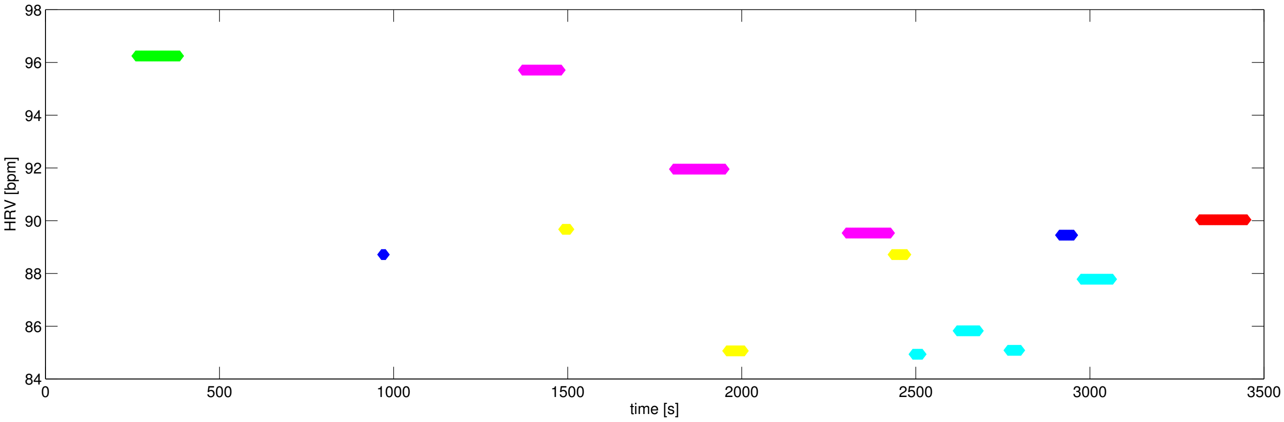

Figure 4.27: Segmentation of session 1 (morning) shows each segment as a line proportional to its duration in seconds. The key is green–take off, blue–stall recovery, purple–approach finished with the runway flyover, yellow–gaining altitude after approach, cyan–emergency landing, red–final approach and landing.

take off and shortly after. It has been observed in the simulation, that some pilots exhibited increased average heart rate at the beginning of the study and it steadily decreased towards the end of the experiment. Two tested subjects exhibited this.

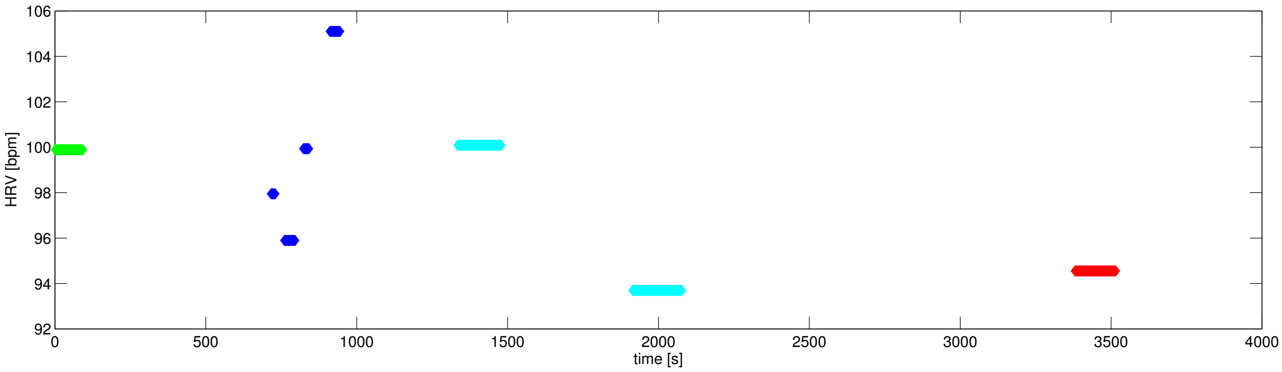

Figure 4.28: Segmentation of session 2 (afternoon) shows each segment as a line proportional to its duration in seconds. The key is green–take off, blue–stall recovery, cyan–emergency landing, red–final approach and landing.

Chapter 5

Conclusion

5.1 Summary of Tasks

The main goal was achieved and the physiological data from an experiment with engine failure were collected and analyzed with respect to presence of emergency navigation assistant.

First task regarding the motion simulator and pilot's ability to determine possibly dangerous situations in the simulation was carried out and is addressed in Section 4.3. It confirmed that pilots were able to recognize engine failure. Based on this experiment it was decided to use the simulator in motion mode, since it can provide more input to pilots.

The second objective of the thesis – to determine appropriate navigation paradigm – was addressed in Section 4.4. The result is adopting navigation using tunnel in the sky and cross. The pilots had best flight performance with respect to deviation from the trajectory with tunnel. Second best was navigation with a cross. The tunnel helped pilots to use the full potential of a glass cockpit display. Tunnel created 3D impression of a pathway which allowed pilots to navigate better around the trajectory and it helped them to understand the directions in which to fly. Tunnel did not force pilots to do sudden abrupt movements, which might occur in using the cross, when the pilot deviated from the trajectory to much. Cross was able to induce oscillations around the trajectory. It is true that the performance of pilots is also affected by the parameters calculating the meeting point the aircraft is directed to, but altering the parameters did not surpass average tracking performance of tunnel.

Third objective summarizing the information given by pilots regarding the navigation instrument was achieved and pilots reported important points for improvement of the device. This is addressed in Section 4.5. Interviews with pilots resulted in several notes related to emergency landing in general and to a navigation instrument. A very relevant proposition to improve the navigation was to consider wind in the path planning. Another point focused on detection of landing surface material to avoid swamps and other areas which might be soaked with water and might make the landing go wrong. Another important point regarded the trustworthiness of the navigation. The community is very conservative one and the pilots with many flight hours are reluctant to adopt new instruments. They claim that the instrument might malfunction and that this kind of device might cause harm and might actually impose new load to pilot.

Last three objectives are addressed together in Section 4.6. Those objectives were closely related and the results are reported in respective subsections.

Fourth objective and the main contribution of this thesis to the best of author's knowledge is that from 19 parameters extracted from ECG, and respiration signals five were determined as statistically significant. Those parameters are ABF, RF1, RF2, RF3, and RF4. The hypothesis, that pilots should exhibit physiological changes during simulated flight was confirmed. Mentioned parameters are mostly sensitive at the last stage of flight. Approach and landing is demanding and most likely cause of the changes.

The fifth objective to assess the physiological parameters based on phases of flight was addressed in 4.6.6. The main observation is that pilots reported perceived stress different from expected measured physiological data. The first three most stressful ratings yield similar means, but the rating least stressed is significantly different. The same case happens for RF3. It suggests that pilots might experience some sort of discomfort or stress in case of ratings 1 to 3, but for rating 4 they did not feel stressed. Rating 2 in Figure 4.19, C has significantly lower power than other three ratings, suggesting, that despite the subjects claiming to feel stressed, they were not. Figure 4.19,C in the context of Figure 4.20 and Figure 4.21, E and F has very small means and therefore is not considered relevant to the evaluation despite its statistically significant results.

The sixth objective was addressed by separating the data from flights with engine failure and flights without. The flights with engine failure were then further divided into two groups. The emergency landing navigation was available in the first group. Second group did not have the navigation available. By examining the parameters it was found, that the parameters on the whole sample show similar levels. Therefore it is concluded that in the scope of this experiment the presence of navigation instrument did not cause any significant changes in physiology. It suggests that pilots experienced the same mental load and emotional state in both cases. It is assumed that the presence of the device may affect the awareness of the pilot, but the pilot still needs to allocate focus and attention to actually fly the aircraft and therefore there is a demand for mental load in both cases.

5.2 Future work

The future work might focus on improving the navigation instrument and navigation environment. The simulation software could be updated to provide more detailed map data. The pilots could be also tested with EEG, which was not measured yet. Measurement of EDA should be repeated in the future with better setup to provide information about the number of detected responses in different situations.

It would be interesting to compare the data measured in the simulation with a real data from real aircraft and cross compare the measurements with a larger group of pilots. The single measurement provided in the scope of this thesis is not enough to provide information about how pilots handle real flight. The context might be at the center of the experiment in the real aircraft, since from the flight in this thesis it seemed, that weather conditions or the presence of the flight instructor may have an effect on the flight. This could also be experimented with during the simulation. In two seated simulator the test subjects could be joined by an instructor. Creating a examination like context could provide more significant physiological response.

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Thesis related publications

Articles in peer-reviewed journals

[A.1] O. Bruna, T. Levora, and J. Holub, “Assessment of ECG and respiration recordings from simulated emergency landings of ultra light aircraft,” Sci. Rep., vol. 8, no. 1, 2018.

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[A.2] O. Bruna, T. Levora, and J. Holub, “Stress measurement and inducement in experiments with low cost flight simulator for testing of general aviation pilots,” in Communications in Computer and Information Science, 2017, vol. 713, pp. 218–223.

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