ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Fakulta stavební

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Využití optických metod v procesu tvorby 3D dokumentace stávajících objektů

Use of optical methods in the process of creating 3D documentation of existing objects

DISERTAČNÍ PRÁCE

Ing. Martin Dědič

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Školitel: doc. Ing. Dalibor Vytlačil, CSc.
Školitel specialista Ing. Jiří Kaiser, Ph.D.

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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta stavební
Thákurova 7, 166 29 Praha 6

PROHLÁŠENÍ

Jméno doktoranda: Ing. Martin Dědič

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ABSTRAKT

Tato disertační práce zkoumá využití optických metod v procesu tvorby 3D dokumentace stávajících objektů. První část se zaměřuje na aplikaci metod 3D triangulace a Structure from Motion (SfM) k rekonstrukci objektů, zatímco druhá část se zabývá vlivem textury povrchu na kvalitu výsledného 3D modelu. V rámci výzkumu byly analyzovány různé povrchy materiálů a jejich vliv na hustotu bodového mračna získaného optickými metodami 3D skenování. Výsledky potvrzují, že textura povrchu má významný dopad na hustotu bodového mračna a různé úpravy povrchu mohou optimalizovat proces akvizice dat pro tvorbu digitálních modelů. Tyto poznatky mají důležité praktické důsledky pro oblast 3D skenování a digitálního modelování.

Klíčová slova: Optické metody, Structure from Motion (SfM), Bodové mračno, 3D skenování, Digitální model

ABSTRACT

This dissertation explores the use of optical methods in the process of creating 3D documentation of existing objects. The first part focuses on the application of 3D triangulation and Structure from Motion (SfM) methods to object reconstruction, while the second part examines the effect of surface texture on the quality of the resulting 3D model. Different material surfaces and their influence on the density of the point cloud obtained by optical 3D scanning methods were analyzed. The results confirm that the surface texture has a significant impact on the point cloud density and different surface treatments can optimize the data acquisition process for the creation of digital models. These findings have important practical implications for the field of 3D scanning and digital modeling.

Keywords: Optical methods, Structure from Motion (SfM), Point cloud, 3D scanning, Digital model

PODĚKOVÁNÍ

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SEZNAM ZKRATEK

3D	Three-Dimensional
2D	Two-Dimensional
CCD	Charge-Coupled Device
SfM	Structure from Motion
SIFT	Scale-Invariant Fearute Transform
RGB	Red, Green, Blue
PMVS	Patch-based Multi-view Stereo
GSD	Ground Sample Distance
UAV	Unmanned Aerial Vehicle

OBSAH

1 ÚVOD

Disertační práce je zpracována jako komentovaný soubor publikovaných článků ukazující kontinuální rozvoj využití optických metod v procesu tvorby 3D dokumentace stávajících objektů.

Aktuálně jsou 3D skenovací technologie standardně využívány pro transformaci fyzických objektů do digitálního formátu. Tyto skenovací technologie mohou být kategorizovány podle typu interakce s analyzovaným objektem na dotykové a bezdotykové. Dotykové metody jsou definovány využitím kontaktních sond, které jsou součástí souřadnicových měřicích systémů. Bezdotykové techniky jsou rozčleněny do dvou primárních skupin: metody založené na odrazu světla a metody založené na transmisi záření skrze objekt. U systémů využívajících odražené světlo se rozlišuje mezi aktivními a pasivními skenery. Rozdíl mezi těmito typy je určen metodou osvětlení skenované scény, přičemž aktivní skenery jsou vybaveny externím zdrojem světla pro osvětlení objektu, zatímco u pasivních skenerů je využíváno existující nebo přirozené osvětlení (Harding, 2013).

Tato disertační práce je zaměřena na využití bezdotykových aktivních optických technologií, které nacházejí rozsáhlé uplatnění v mnoha odvětvích včetně průmyslových i mimoprůmyslových oblastí. Tyto technologie jsou využívány v procesech kontroly kvality, reverzním inženýrství, zdravotnictví, ochraně kulturního dědictví, a také v oblastech jako je herní a filmový průmysl.

Oproti kontaktním metodám umožňují optické metody zachytit větší plochu povrchu během stanoveného časového intervalu a nepotřebují přímý kontakt s měřícím zařízením. Nicméně aplikace těchto metod může být ovlivněna řadou faktorů, které mohou negativně ovlivnit přesnost měření. Mezi tyto faktory patří nastavení procesních parametrů skeneru, okolní osvětlení, drsnost nebo textura povrchu a specificky pro tuto studii, charakteristika odrazivosti skenovaného povrchu (Bellocchio, 2013).

Je zjištěno, že povrchy s vysokým leskem, průhledností a průsvitností představují výzvy pro standardní skenovací metody, což může vést k získání bodového mračna s nízkou hustotou, a tedy k nepřesným nebo nedostatečným výsledkům. Tyto problémy lze mitigovat příslušnými úpravami povrchů skenovaných materiálů (A1).

2 SOUČASNÝ STAV ŘEŠENÉ PROBLEMATIKY

Pro zachycení geometrických tvarů a povrchových textur fyzických objektů a jejich transformaci do digitálního formátu se využívají 3D skenery. Tato zařízení operují na principu akvizice jednotlivých bodů na povrchu objektu, z nichž se generuje velké množství těchto bodů, známé jako bodová mračna. Z těchto bodových mračen se následně extrapoluje prostorový počítačový model pomocí vhodně konfigurované polygonové sítě. Pro získání dat o bodech se využívají různé technologie včetně kamer, rentgenových přístrojů, magnetických mikrotomografů, laserů a dalších. Na základě použité technologie se dále specifikují metody skenování, jako jsou rentgenové, ultrazvukové, laserové, optické a mechanické 3D skenovací techniky (Sansoni et al., 2009).

V disertační práci bylo využito metod optických, a to 3D triangulace (A2, A3) a metody Structure from Motion (A4, A5), která je speciální metodou fotogrammetrie rekonstruující realitu z 2D obrazu. Metoda Structure from Motion je relativně mladou metodou, která má obrovský potenciál jak v geodézii, stavebnictví, tak i v dalších oborech jako zdravotnictví, archeologie, ochrana památek apod. (Wei et al., 2013).

2.1 Aktivní 3D triangulace

Optická triangulace představuje bezdotykovou techniku měření vzdálenosti, která spadá do kategorie triangulačních metod. Tato kategorie zahrnuje také pasivní triangulační techniky, systémy využívající teodolity, metody fokusační a techniky založené na analýze stínů. Specifickým rysem aktivní triangulace je využití emitovaného zdroje energie, typicky ve formě viditelného světla nebo elektromagnetického záření, což umožňuje přesné určování polohy objektů ve sledovaném prostoru.

Aktivní triangulace se opírá o principy fotogrammetrie, kde je zkoumaný objekt osvětlen zdrojem světla, zatímco jeho povrch je simultánně snímán pomocí CCD snímače (Charge-Coupled Device). Trojúhelník pro triangulaci se formuje mezi zdrojem světla, CCD snímačem a osvětleným bodem na povrchu objektu. Spoje mezi světelným zdrojem a snímačem, označované jako triangulační báze, slouží jako základní linie pro měření a lokalizaci bodů na objektu (Besl et al., 1992).

V rámci metodiky aktivní triangulace je úhel tvořený světelným zdrojem a triangulační bází konstantní. Naopak úhel na straně snímače je variabilní a závisí na pozici bodu osvětleného CCD snímačem. Na základě velikosti tohoto úhlu, znalosti délky triangulační báze, a specifikací kamery a objektivu je možné určit z-souřadnici objektu. Tento postup umožňuje přesné lokalizování bodů v trojrozměrném prostoru.

V závislosti na druhu použitého zdroje záření se aktivní triangulace rozlišuje na tři druhy. Nejjednodušší způsob použitého zdroje záření je světelný bod, kdy se jedná o jednorozměrnou triangulaci (1D triangulace). Druhým druhem použitého zdroje záření je světelný pruh, který je označován jako dvourozměrná triangulace (2D triangulace). Trojrozměrná triangulace (3D triangulace) je třetím a nejsložitějším zdrojem použitého záření, u kterého je použito strukturovaného světelného svazku (Beraldin et al., 2001).

V metodě 3D triangulace je na povrch objektu promítán pečlivě vytvořený světelný vzor, jehož hlavním cílem je shromáždění informací o z-souřadnici. Tento vzor, často označovaný jako mřížka, obsahuje různé identifikační prvky nebo kódy, které usnadňují pozdější identifikaci a kategorizaci jednotlivých segmentů mřížky. Promítnutí světelného vzoru na objekt vede k jeho deformaci způsobené nerovnostmi a variacemi na povrchu objektu. Tato deformace poskytuje zásadní informace pro určení z-souřadnice objektu v trojrozměrném prostoru (Harding, 2013).

Přesnost detekce závisí na přesnosti snímané kamery a hustotě a kontrastu promítané mřížky, která může mít podobu proužků, čtverců, kosočtverců až velmi složitých tvarů. Výběr mřížky je zásadní pro co nejvyšší jednoznačnost, aby bylo možné v každém bodě přesně určit aktuální lokaci.

V kapitole 4 jsou uvedeny publikace popisující využití 3D triangulace v procesu tvorby 3D dokumentace stávajících objektů, které byly prezentovány vědecké komunitě v rámci konferenčního sborníku.

2.2 Digitální fotogrammetrie

Fotogrammetrie je disciplína, která získává informace o objektech na základě analýzy přesných obrazových dat získaných fotografickým záznamem. Od padesátých let 20. století došlo k signifikantní automatizaci vyhodnocovacích procesů v této oblasti s prvním zavedením elektronických korelátorů. Původní aplikace digitálního obrazování se zaměřila na analýzu družicových snímků pro dálkový průzkum Země, kde vypuštění družice ERTS-1, později přejmenované na LANDSAT 1, představovalo klíčový mezník. V osmdesátých letech dvacátého století s dalším rozvojem kvality digitálního obrazu a metod jeho analýzy, došlo k rozvoji digitální fotogrammetrie, často označované jako softcopy fotogrammetrie.

Digitální obraz, jaký známe, je obrazová informace transformovaná do digitální formy a existuje jako primární digitální obraz získaný digitální kamerou (například s CCD senzory) nebo jako sekundární digitální obraz, což je digitalizovaná fotografie. V případě primárního digitálního obrazu senzory snímacího zařízení přímo registrují radiometrické veličiny na jednotlivých pixelových ploškách a ty jsou transformovány na digitální signály. CCD prvky, což jsou mikroelektronické křemíkové čipy, slouží k převodu elektromagnetického záření na paměťový signál, což umožňuje detailní analýzu získaných obrazových dat.

Jedním z klíčových parametrů, který ovlivňuje kvalitu výsledného modelu, je kvalita snímacího zařízení, konkrétně kamera. V současnosti jsou běžně používány digitální zrcadlovky a drony vybavené menšími CCD čipy s integrovanými objektivy. Rozlišení těchto zařízení je specifikováno v megapixelech, přičemž platí, že vyšší rozlišení CCD čipu přináší vyšší kvalitu obrazu. Pro zrcadlové kamery je esenciální výběr vhodného objektivu, typicky normálního objektivu, teleobjektivu nebo objektivu typu rybí oko. Pro účely fotogrammetrie jsou preferovány normální objektivy s pevným ohniskem, které minimalizují radiální distorzi oproti objektivům typu rybí oko. Hlavní nevýhodou normálních objektivů je jejich omezená schopnost pokrýt rozsáhlejší území, což je oblast, kde se objektivy typu rybí oko ukazují jako výhodnější, přestože mají tendenci k větší distorzi obrazu (Luhmann et al., 2016).

Pro 3D zpracování slouží vícesnímková fotogrammetrie, u které jsou vyžadovány nejméně dva vzájemně se překrývající snímky. K vyhodnocení se používá stereoskopický vjem umožňující vytvoření prostorového modelu předmětu měření a tato metoda je nazývána stereofotogrammetrií. V případě konvergace (sbíhání) os záběrů snímku se tedy jedná se o vícesnímkové prostorové protínání. Konvergentní množinu orientovaných snímků lze vyhodnotit pouze bodově, pokud lze bod identifikovat minimálně na dvou snímcích a technologicky se jedná o průsekovou fotogrammetrii.

Fotogrammetrická technika označovaná jako **Structure from Motion** (SfM), podle Westoby et al. (2012), umožňuje derivaci trojrozměrných souřadnic z dvojrozměrných snímků získaných za použití pohybujícího se nosiče. Pro správnou funkčnost této metody není vyžadováno, aby osy záběru byly konvergentní nebo paralelní, avšak je nezbytné, aby se snímky překrývaly. SfM efektivně kombinuje principy průsekové fotogrammetrie a stereofotogrammetrie. Významnou předností této metody je, že pro úspěšnou aplikaci není třeba předem znát přesné polohy, z kterých byly snímky pořízeny. Metoda není finančně náročná a umožňuje získávat 3D data ve vysokém rozlišení (např. smartphonem). Oproti stereofotogtammetrii je Stucture from

Motion vyhodnocení ve všech parametrech přesnější, což je způsobeno počtem neomezených snímků vstupujících do výpočtů. Negativní stránkou metody jsou vysoké výpočetní nároky (časová náročnost výpočtů), které stoupají úměrně s velikostí objektu a počtem snímků (Nyimbili et al., 2016).

Metoda zahrnuje akvizici mnoha obrázků objektu z rozličných úhlů, které mají překryvné segmenty, a jsou postupně nahrány do specializovaného softwarového nástroje, například Agisoft Metashape, PIX4D, Reality Capture, Bundler nebo VisualSFM. Pro identifikaci distinktivních bodů v obrazech se využívá technika SIFT (Scale Invariant Feature Transform). Tato technika identifikuje takzvané klíčové body na základě lokalizace extrémních hodnot v obraze, typicky na hranách nebo vyvýšeninách objektu. Dále dochází k filtraci nestabilních bodů, které neposkytují adekvátní kontrast ve srovnání s okolním prostředím nebo jsou jiným způsobem nejednoznačné, což zajišťuje vyšší přesnost a spolehlivost při rekonstrukci 3D modelu (A4, A5).

U bodů, které nebyly během předchozích fází eliminovány, jsou následně definovány deskriptory, které unikátně specifikují charakteristiku každého bodu na snímku. Na základě těchto specifikací jsou pak vyhledávány odpovídající body na dalších snímcích. Aby byl bod zařazen do následujících fází zpracování, je nutné, aby byl identifikován minimálně ve třech různých snímcích. Z kompilace takto identifikovaných bodů jsou poté vypočítány polohy projekčních center kamer a orientace snímků v prostoru, což je nezbytné pro správnou rekonstrukci 3D modelu (Yang et al., 2019).

Následně jsou získány informace o epipolární geometrii všech snímků. Pro všechny snímky najednou je provedena rekonstrukce struktury (structure) v obraze a pohybu (motion) kamery. K rekonstrukci se využívá sekvenčního postupu, kdy se počítá structure a motion mezi dvěma snímky, poté pro celou množinu snímků. Výsledkem algoritmu je řídké mračno a relativní poloha všech kamer.

V následujícím stupni procesu dochází k aplikaci svazkového vyrovnání, kde jsou simultánně korigovány souřadnice bodů, polohy a orientace kamer. Pro analýzu a transformaci dat mezi snímanými a modelovými souřadnicemi charakteristických bodů se používá přímá i inverzní korelace. V důsledku přítomnosti nelineárních prvků v těchto vztazích se provádí úprava pomocí Taylorova rozvoje. Po implementaci těchto úprav je možné sestavit husté bodové mračno. Pro odvození trojrozměrných souřadnic z hustého mračna se vyžaduje další algoritmický krok, konkrétně využití algoritmu PMVS (Patch-based Multi-view Stereo), který operuje s malými obdélníkovými ploškami těsně obklopujícími pozorovaný objekt. Tyto plošky jsou postupně rozšiřovány do okolí a v závěrečné fázi algoritmus filtruje nesprávné propojení (Yang et al., 2019).

2.3 Vlivy působící na kvalitu výsledného modelu

Pro procesy 3D skenování představují významnou výzvu povrchy, které jsou charakteristické svou lesklou, průhlednou, průsvitnou nebo absorpční povahou. Tyto povrchy komplikují akvizici dat, jelikož mohou ovlivnit správné zachycení a interpretaci světelných signálů, které jsou klíčové pro efektivní generování bodových mračen (A1). Optické aktivní metody pracují s odrazem emitovaného osvětlení od měřeného povrchu a z toho důvodu je správný odraz pro tyto skenery zásadní (Wang et al., 2014). Mezi vlivy ovlivňující kvalitu výsledného modelu jsou řazeny kvalita snímače, vzdálenost stanoviska snímkování od objektivu, osvětlení a atmosférické podmínky a v neposlední řadě textura povrchu zájmového objektu.

Kvalita snímače

Jedním ze zásadních parametrů je kvalita snímače (kamery), kdy se v současnosti nejčastěji využívají digitální zrcadlovky nebo u dronů menší CCD čipy s vestavěnými objektivy. Ovšem ani ten nejdražší objektiv se neobejde bez určitých optických vad, které způsobují různé odchylky skutečného zobrazení od toho ideálního, tzv. aberace. Příkladem je barevná vada čoček, kdy je světlo složeno z různých vlnových délek, a tak probíhá rozklad barevných složek světla různě v různých vlnových délkách. Možným řešením je složení optické soustavy objektivu z několika různých druhů skel s různým indexem lomu.

Stanovení nejistoty měření je náročnější, neboť každý skenovací systém je vybaven jinou optikou a při skenování panují jiné podmínky. Obecně neexistují přesně stanovené specifikace nejistoty měření a výrobci 3D skenerů ověřují přesnost zařízení sami ve speciálních podmínkách a vyvíjejí své vlastní standardy. Ke kontrole skenerů se vytvářejí normy uvádějící postup kontroly, kterých ale v současnosti není mnoho a nejsou pro výrobce závazné. Jedním z příkladů je německá norma VDI/VDE 2634, která určuje kalibrační etalon (Rzucidlo et al., 2017).

Vzdálenost stanoviska snímkování od objektivu

Vzdálenost mezi pozicí snímkování a cílovým objektem představuje klíčový faktor v procesu získávání obrazových dat. Obecně platí, že s rostoucí vzdáleností od objektu se snižuje zastoupení objektu na snímku, což vede k redukci rozlišovací schopnosti. V kontextu snímkování s využitím bezpilotních letounů (UAV – Unmanned Aerial Vehicle) je rozlišení snímků specifikováno pomocí parametru Ground Sample Distance (GSD), který vyjadřuje reálnou vzdálenost na zemi, jež odpovídá velikosti jednoho pixelu na snímači kamery. Hodnota GSD je určena na základě ohniskové vzdálenosti objektivu kamery, výšky letu a velikosti pixelu na snímači (Zhang et al, 2018).

Osvětlení a atmosférické podmínky

Atmosférické faktory hrají klíčovou roli při terénním snímkování, zatímco adekvátnost osvětlení je kritická pro snímkování v laboratorních podmínkách. Intenzita osvětlení se mění v závislosti na denním čase a sezóně. Během letních měsíců dochází k vyššímu příjmu slunečního záření ve srovnání se zimními měsíci, kdy je slunce umístěno níže nad obzorem a celková míra osvětlení je nižší. Kvalita snímků je dále ovlivněna atmosférickými jevy, které mění rozptyl světla, jeho intenzitu a mohou způsobit výskyt stínů, větru a srážek.

Konečná kvalita snímků je závislá na směru a úhlu dopadajícího světla. Neexistuje jednoznačná odpověď na otázku ideálních podmínek pro pořizování snímků, ale pro účely fotogrammetrie se doporučuje snímkovat v době, kdy sluneční světlo směřuje ve stejném směru jako je zamýšlený směr snímkování, což přispívá k optimální vizualizaci snímaného objektu (Rzucidlo et al., 2017) (A1).

Textura povrchu zájmového objektu

Další parametr ovlivňující kvalitu výsledného modelu je samotná textura objektu. SfM při generování spoléhá na různorodost scény, v níž může charakterizovat jedinečné body k vytvoření dané scény.

Ideální objekt pro 3D skenování je málo členitý, nemající mnoho drobných detailů, matný s výraznou strukturou, a zároveň nemá jednolité plochy. Je neprůhledný a bez částí, které by se samovolně pohybovaly. Z hlediska materiálu má ideální objekt blíže k plastu, kovu a keramice než ke sklu. Všeobecně znesnadňují skenování i rotačně symetrické objekty (A1).

Skleněné objekty je vhodné nastříkat práškovou křídou ve spreji. Objekty se nastříkáním stanou neprůhlednými a nelesknou se (Rzucidlo et al., 2017).

3 VÝZKUMNÉ OTÁZKY A HYPOTÉZY

Disertační práce má dva hlavní cíle. Prvním cílem je popsat a objasnit využití optických metod v procesu tvorby 3D dokumentace stávajících objektů. Druhý cíl se zaměřuje na popis textury povrchu zájmového objektu a jeho vlivu působící na kvalitu výsledného modelu. K tomuto účelu byly vytvořeny výzkumné otázky. První výzkumná otázka byla definována na základě dvou konferenčních příspěvků (A2, A3), které pojednávají o využití 3D triangulace v procesu tvorby 3D dokumentace stávajících objektů. Druhá výzkumná otázka byla definována na základě konferenčního příspěvku (A4), který pojednává o 3D triangulaci v procesu tvorby 3D dokumentace stávajících objektů. Třetí výzkumná otázka byla definována na základě konferenčního příspěvku (A5), který pojednává o tvorbě digitálního modelu za užití pozemní a letecké digitální fotogrammetrie historicky významné stavby kapličky. Čtvrtá výzkumná otázka byla definována na základě příspěvku (A1) v impaktovaném časopise, který pojednává o vlivu materiálu na hustotu bodového mračna, která se řadí mezi nejvýznamnější faktory pro kvalitu bodových mračen.

Výzkumné otázky byly stanoveny následovně:

1. Jaký je vliv použití různých metod zpracování dat a kombinace více skenů na přesnost a efektivitu tvorby digitálních modelů složitých forem, jako jsou sochy, reliéfy a složité tvary, pomocí optických 3D skenerů?
2. Jak mohou fotogrammetrické metody a softwarové nástroje přispět k efektivní tvorbě a analýze digitálních modelů lineárních konstrukcí, jako jsou umělá říční koryta, s důrazem na přesnost, úplnost a simulaci proudění vody pro účely stavebního plánování a analýzy?
3. Jaký je vliv kombinace pozemní a letecké digitální fotogrammetrie na přesnost a detailnost digitálních modelů historicky významných budov?
4. Jaký je dopad různých textur povrchu zájmového objektu na hustotu bodového mračna při 3D skenování pomocí optických metod a jak

mohou různé úpravy povrchu optimalizovat proces akvizice dat pro tvorbu digitálních modelů.

K takto stanoveným výzkumným otázkám byly stanoveny následující hypotézy.

Výzkumná otázka 1:

I. Použití kombinace automatických metod zpracování dat a aplikace více skenů vede ke zvýšení přesnosti a efektivity tvorby digitálních modelů složitých forem, jako jsou sochy, reliéfy a složité tvary, pomocí optických 3D skenerů.

Výzkumná otázka 2:

II. Použití fotogrammetrických metod a vhodných softwarových nástrojů umožní vytvoření digitálních modelů lineárních konstrukcí s dostatečnou přesností a úplností, což umožní simulaci a analýzu proudění vody v umělých říčních korytech pro účely stavebního plánování a analýzy.

Výzkumná otázka 3:

III. Kombinace pozemní a letecké digitální fotogrammetrie vytváří digitální modely historicky významných budov s vyšší přesností a detailností než použití pouze jedné metody, což přispívá k lepšímu pochopení stavebních a historických charakteristik těchto objektů.

Výzkumná otázka 4:

IV. Hustota bodového mračna získaného optickými metodami 3D skenování bude významně ovlivněna texturou povrchu zkoumaného objektu. Dále předpokládáme, že různé úpravy povrchu, jako jsou aplikace povrchových látek nebo mechanické úpravy, budou mít signifikantní dopad na hustotu bodového mračna a umožní optimalizaci procesu akvizice dat pro tvorbu digitálních modelů.

4 SEZNAM PUBLIKACÍ

Disertační práce byla zpracována jako komentovaná série publikací v impaktovaném časopise a konferenčních sbornících.

A1) Kaiser, J.; Dědič, M., Influence of Material on the Density of a Point Cloud Created Using a Structured-Light 3D Scanner. Appl. Sci. 2024, 14, 1476. http://doi.org/10.3390/app14041476

A2) Dědič, M., 3D scanning and analysis of acquired data of historically and culturally significant objects referring to the work of Adalbert Stifter. MATEC Web. Conf. 2019, 279, 01014. http://doi.org/10.1051/matecconf/201927901014

A3) Dědič, M., Utilization of Modern Optical Methods for Creation of Digital Model of Human, 2020 IOP Conf. Ser.: Mater. Sci. Eng. 960 032016. http://doi.org/10.1088/1757-899X/960/3/032016

A4) Dědič, M., Digital Model of an Existing Building a Wild Riverbed in Tokyo, 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1066 012017. http://doi.org/10.1088/1757-899X/1066/1/012017

A5) Dědič, M., Acquisition and analysis of data of a historically significant building using digital photogrammetry. AIP Conf. Proc. 27 September 2023; 2928 (1): 180001. http://doi.org/10.1063/5.0170452

Následující publikace nebyly zařazeny do výsledků disertační práce, ale podporují vědeckou činnost autora.

B1) Kraus, M., Kaňkovský, A., Dědič, M., Navara, T., Research and development of innovative building data ware house (BDW) line to ensure quality and process control in construction and maintenance, SGEM 2023, Albena, Bulgaria, vol. 23. http://doi.org/10.5593/sgem2023/6.1/s27.50

B2) Dědič, M., Kaňkovský, A., Construction-technical survey chapel in Dolní Nivy. *AIP Conf. Proc.* 27 September 2023; 2928 (1): 070002. https://doi.org/10.1063/5.0170453

B3) Kaňkovský, A.,Dědič, M., Construction-Technical Survey of a Historical Building in Loket. 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1066 012004. http://doi.org/10.1088/1757-899X/1066/1/012004

B4) Kaňkovský, A., Dědič, M., A Solutions of Wheelchair Accessibility in Existing Building – Apartment Building in Kraslice. 2020 IOP Conf. Ser.: Mater. Sci. Eng. 960 042089. http://doi.org/10.1088/1757-899X/960/4/042089

B5) Šál, J., Dědič, M., Application of Modeling Processes and 3D Print on Casting Molds for Concrete Furniture. 2020 IOP Conf. Ser.: Mater. Sci. Eng. 728 012014. http://doi.org/10.1088/1757-899X/728/1/012014

B6) Prušková, K., Dědič, M., Kaiser, J., P ossibilities of Using Modern Technologies and Creation of the Current Project Documentation Leading to the Optimal Management of the Building for Sustainable Development, 2019 IOP Conf. Ser.: Earth Environ. Sci. 290 012058. http://doi.org/10.1088/1755-1315/290/1/012058

B7) Dědič, M., Evaluation of the processes of creating a project documentation of an existing building using a 3D scanner, SGEM 2019, Albena, Bulgaria, vol. 19, Issue 2.2, pp 127-132, 2019.

5 VERIFIKACE STANOVENÝCH HYPOTÉZ

5.1 Verifikace hypotézy I

Hypotéza I: Použití kombinace automatických metod zpracování dat a aplikace více skenů vede ke zvýšení přesnosti a efektivity tvorby digitálních modelů lidských postav pomocí optických 3D skenerů.

Publikace A2

3D scanning and analysis of acquired data of historically and culturally significant objects referring to the work of Adalbert Stifter

Dědič, M. 3D scanning and analysis of acquired data of historically and culturally significant objects referring to the work of Adalbert Stifter. MATEC Web. Conf. 2019, 279, 01014.

V rámci prezentovaného konferenčního článku je zkoumáno využití 3D skenování se strukturovaným světlem pro dokumentaci historických a kulturně významných artefaktů spojených s dílem česko-rakouského literáta Adalberta Stiftera, umístěných v Jižních Čechách. V důsledku rozsahu jednotlivých objektů bylo nezbytné provádět skenování segmentově pro každý objekt zvlášť. Integrace těchto segmentů a odstranění šumu následně umožnily generování přesných digitálních modelů. Tyto modely představují značný potenciál pro implementaci ve virtuálních prohlídkách, které poskytují rozsáhlou prezentaci historických a kulturních míst. V konečné fázi byly modely upraveny pro potřeby 3D tisku a následně vyrobeny pomocí 3D tiskáren.

Pro skenování byl použit 3D lehký ruční skener Artec Eva Lite, pomocí kterého byly vytvořeny vysoce kvalitní a přesné skeny bez barev a textur. Tento cenově dostupnější model (oproti Artec Eva) je vhodný zejména pro objekty s tvarově rozmanitým povrchem, podle kterého je skener orientován. Funguje na principu trigonometrické triangulace. To v praxi znamená, že skener promítá na snímaný objekt světelný vzor skládající se z pravidelných tvarů. Snímací senzor je pak orientován podél okrajů těchto tvarů, aby odvodil tvar objektu. Surový model tvoří bodové mračno. Vhodným objektem pro skenování tímto skenerem je např. lidské tělo, a proto je jej možno využít při skenování soch nebo archeologických či uměleckých děl. Méně vhodnými objekty pro skenování jsou objekty, které nemají dostatečně rozmanitý tvar nebo mají rovné (či texturované) povrchy, protože by došlo při skenování k jejich zkreslení. Z tohoto důvodu byly kamenné bloky modelovány ručně, neboť povrch skenovaného objektu byl příliš rovnoměrný a rovný, a proto bylo možné kontrolní bod zaměnit za jiný.

Publikace je Přílohou č. 1.

Publikace A3

Utilization of Modern Optical Methods for Creation of Digital Model of Human

Dědič, M., Utilization of Modern Optical Methods for Creation of Digital Model of Human, 2020 IOP Conf. Ser.: Mater. Sci. Eng. 960 032016

Konferenční příspěvek popisuje metodiku tvorby digitálního modelu člověka pomocí 3D skeneru se strukturovaným světlem. Tato metodika se skládá z několika hlavních fází, jako je příprava skenu na pohyb člověka, skenování v co nejkratším čase a zpracování dat získaných skenováním. Samotné zpracování dat je rozděleno do dalších dílčích fází, které popisují jednotlivé kroky nutné k vytvoření digitálního modelu. Příspěvek popisuje překážky, které je třeba při 3D skenování odstranit nebo minimalizovat, aby nedošlo k narušení integrity modelu a vytvoření digitálního modelu.

Pro skenování živých tvorů, v tomto případě člověka, je velmi důležitá rekognoskace, rozdělení snímaného objektu na části a vhodný výběr překryvů. Cílem všech těchto akcí je zajistit, aby skutečné skenování proběhlo v co nejkratším čase. U překrývajících se skenů je nejlepší plochou pro celkový digitální model oblast trupu. Oblast trupu se nejsnáze skenuje – nejsou zde žádné vyčnívající části a skener pracuje v jednotné vzdálenosti. Každé jednotlivé skenování tedy začíná v této oblasti těla, a poté se skenuje dále od ní. Během procesu skenování lze sledovat zachycené body na displeji. Při používání optického 3D skeneru se často objevují problémy se skenováním vlasů kvůli jejich jemnosti. Proto se doporučuje zvolit účes, který vlasy udrží kompaktní a sníží tak jejich pohyblivost. Dalším problematickým elementem jsou oči, které, i přestože skener nepředstavuje riziko pro zrak, by měly být během skenování obličeje uzavřeny, aby se předešlo možným chybám v zachycení. Nakonec lesklé kovové objekty, jako jsou náušnice, piercingy nebo přezky, mohou způsobovat odrazy, které narušují kvalitu skenu, a je proto vhodné je před skenováním odstranit.

Během skenování nelze detekovat pohyb snímané osoby. Tyto pohyby nelze odhalit, dokud nejsou data zpracována. Pro eliminaci odchylek způsobených pohybem byl zvolen reverzní postup úpravy dat. Klasický přístup spočívá ve spojení jednotlivých skenů do jednoho mračna bodů před čištěním, vyhlazováním a modelováním mračna bodů. V tomto případě byly nejprve jednotlivé skeny upraveny a až poté jeden po druhém spojen.

Publikace je Přílohou č. 2.

Na základě provedeného výzkumu prezentovaného v obou publikacích je možné předpokládat, že použití kombinace metod automatického zpracování dat a aplikace více skenů má pozitivní vliv na přesnost a efektivitu tvorby digitálních modelů lidských postav pomocí optických 3D skenerů. První publikace naznačuje, že i přes automatizaci zpracování dat jsou ruční úpravy nezbytné ke korekci chyb, které se vyskytnou během skenování. Druhá publikace dále potvrzuje, že ruční úpravy jsou nevyhnutelné a zdůrazňuje, že výsledný model může být kombinací více skenů, aby se minimalizovaly chyby způsobené pohybem skenované osoby. Na základě tohoto výzkumu lze tedy předpokládat, že kombinace automatických funkcí softwaru pro zpracování dat a použití více skenů povede ke zlepšení přesnosti a efektivity tvorby digitálních modelů složitých forem, jako jsou sochy, reliéfy a složité tvary pomocí optických 3D skenerů. Hypotéza I byla potvrzena.

5.2 Verifikace hypotézy II

Hypotéza II: Použití fotogrammetrických metod a vhodných softwarových nástrojů umožní vytvoření digitálních modelů lineárních konstrukcí s dostatečnou přesností a úplností, což umožní simulaci a analýzu proudění vody v umělých říčních korytech pro účely stavebního plánování a analýzy.

Publikace A4

Digital Model of an Existing Building a Wild Riverbed in Tokyo

Dědič, M., Digital Model of an Existing Building a Wild Riverbed in Tokyo, 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1066 012017.

Konferenční článek představuje aplikaci fotogrammetrických metod pro tzv. obrazové modelování a vykreslování. Pro reálné využití digitálního modelu umělého koryta pro divokou řeku v Tokiu byla použita metoda digitální fotogrammetrie. Tato technologie byla aplikována pomocí dvou softwarových programů. Byla vyhodnocena jejich kompatibilita a navržena opatření, která by měla v budoucnu zvýšit efektivitu při tvorbě digitálních modelů stávajících budov. Je zde popsán proces tvorby modelu v obou softwarech samostatně a vyhodnoceno jejich použití pro daný typ objektu. V tomto příspěvku jsou popsány jednotlivé procesy od výběru fotografií přes čištění a vyhlazování mračna bodů až po finální digitální model. Dále je zde uvedeno praktické využití vytvořeného digitálního modelu. Na obrázcích je zobrazená řešená struktura, postup spojování jednotlivých fotografií a výsledný model pro celkovou představu o aplikaci této metody. V části výsledků a diskuzí je popsáno vyhodnocení softwaru a také návrhy opatření pro jejich využití zejména pro vodní stavby liniového charakteru obsahující opakující se prvky, jako jsou vodní překážky.

Pro vytvoření digitálního modelu bylo celkově pořízeno 1800 fotografií. Charakter stavby – umělé koryto pro závodění na divoké řece – neumožňoval automatické spojení všech částí, protože se jedná o liniovou stavbu s neustále se opakujícími vodními překážkami. Nebylo možné rozlišit, která překážka se nachází v které části koryta. Snímky tedy byly rozděleny do skupin podle jednotlivých částí umělého koryta divoké řeky na 3 části (startovní část, střední část, cílová část). V cílové části se nacházela vodní plocha, která byla vyhodnocena jako potenciálně problematická z hlediska vysoké odrazivosti povrchu. Po rozdělení a smazání nepotřebných a nekvalitních snímků jich zbylo 1200 sloužících k vytvoření digitálního modelu. Před spojením jednotlivých částí bylo nutné vyčistit mračna bodů od bodového šumu, a to pomocí automatické funkce a ručního čištění. Dále byly jednotlivé části vyhlazeny, aby bylo jejich spojení co nejjednodušší. Před pořízením vstupních dat nebylo využito vlícovacích bodů, a proto nebylo možné jednotlivé vygenerované části digitálního modelu spojit automaticky do jednoho celku. Bylo tedy použito ruční spojení pomocí zvolených bodů, které se vždy nacházely v obou spojovaných částech.

Publikace je Přílohou č. 3.

Hypotéza II byla potvrzena. Hypotéza vychází z předpokladu, že fotogrammetrické metody spolu s adekvátními softwarovými nástroji jsou schopny vytvořit digitální modely existujících staveb s dostatečnou přesností a úplností pro inženýrské účely. Tato hypotéza je podložena zkušenostmi a výsledky prezentovanými v publikaci, která popisuje použití těchto metod pro vytvoření digitálního modelu umělého říčního koryta pro účely plánování a analýzy konstrukce. Digitální modely vytvořené touto metodou jsou použitelné pro simulaci proudění vody a analýzu umělých vodních překážek, což znamená, že mohou sloužit jako užitečný nástroj pro inženýrské a stavební účely.

Tato hypotéza, podpořená zkušenostmi a výsledky prezentovanými v publikaci, zpochybňuje tradiční metody vytváření digitálních modelů staveb pro inženýrské účely a navrhuje alternativní přístup využívající fotogrammetrické metody. Základem této hypotézy je přesvědčení, že kombinace fotogrammetrických technik a specializovaného softwaru poskytuje dostačující přesnost a úplnost pro tvorbu digitálních modelů, které jsou užitečné pro inženýrské aplikace. Důležitým bodem je také zdůraznění možnosti využití těchto modelů pro simulace proudění vody a analýzu vodních překážek, což přináší další potenciál pro praktické inženýrské a stavební aplikace. Hypotéza II byla potvrzena.

5.3 Verifikace hypotézy III

Hypotéza III: Kombinace pozemní a letecké digitální fotogrammetrie vytváří digitální modely historicky významných budov s vyšší přesností a detailností než použití pouze jedné metody, což přispívá k lepšímu pochopení stavebních a historických charakteristik těchto objektů.

Publikace A5

Acquisition and analysis of data of a historically significant building using digital photogrammetry

Dědič, M. Acquisition and analysis of data of a historically significant building using digital photogrammetry. AIP Conf. Proc. 27 September 2023; 2928 (1): 180001.

Konferenční příspěvek popisuje projekt, během kterého byl proveden sběr dat kulturně a historicky významné stavby kaple na Horních Nivách pomocí letecké a pozemní digitální fotogrammetrie. Získaná data byla následně analyzována pro potřeby tvorby digitálního modelu. Data byla generována z jednotlivých fotografií jako mračno bodů. S ohledem na parametry objektu byla data snímána částečně ze země pomocí fotoaparátu a částečně ze vzduchu pomocí kamery umístěné na dronu. Spojením modelu exteriéru a interiéru a odstraněním nežádoucích bodů (šumů) vznikl digitální model.

Vytvořený model sloužil jako podklad pro zpracování stavebně technického a stavebně historického průzkumu.

V popsaném procesu pozemní a letecké digitální fotogrammetrie zaměřené na historicky významnou stavbu jsou popsána rekognoskace, sběr a analýza dat včetně vytvoření digitálního modelu stavby. Jednotlivé etapy jsou podrobně popsány, aby bylo možné proces opakovat, a tím ověřit. Digitální fotogrammetrie je nedílnou součástí tvorby digitálních modelů ve stavebnictví a díky rozšiřování schopností dronů se stále více uplatňuje zejména v liniových stavbách. Digitalizace historické budovy s důrazem na hodnotné prvky je jedním z nejnáročnějších procesů. Digitální fotogrammetrie umožňuje uživateli více se zaměřit na určité části budovy a tím zvýšit hustotu mračna bodů. Do budoucna se jeví jako optimální kombinace digitální fotogrammetrie pro cenné stavební prvky a 3D skeneru pro hlavní prostory budovy.

Je třeba zmínit, že i když software generuje model ze snímků poloautomaticky, hlavní část práce – sběr dat – zůstává ruční prací. V budoucnu je možné pro snímky interiérů použít 3D skener, jako je například Leica BLK360, a ručně skenovat nebo fotit pouze historicky cenné části. Exteriér lze fotit automaticky zadáním souřadnic jednotlivých snímků do dronu, to však v tomto případě nebylo možné kvůli blízké poloze vysokých stromů. Tento projekt demonstroval tezi, že nejdůležitější součástí tvorby virtuálního modelu pomocí digitální fotogrammetrie je prvotní rekognoskace. V případě, že jsou známy základní parametry stavby, umístění osazovacích bodů, postup snímků, jejich umístění, úhel sklonu k rovině stavby. Ohniskovou vzdálenost a světelné podmínky lze v interiéru ovlivnit a změnit na požadované hodnoty. U exteriéru budovy lze vyhodnotit okolí budovy a zvolit správnou metodu snímání, výškové úrovně a úhel snímání. Pro bezpečnost letu dronu je nutné znát předpověď počasí a vyhodnotit nejvhodnější denní dobu z hlediska světelných podmínek.

Publikace je Přílohou č. 4.

Na základě výzkumu a analýzy digitálních modelů historicky významných budov pomocí kombinace pozemní a letecké digitální fotogrammetrie bylo zjištěno, že tato metoda skutečně umožňuje vytvářet digitální modely s vyšší přesností a detailností než použití pouze jedné metody. Tato kombinace přispívá k lepšímu pochopení stavebních a historických charakteristik těchto objektů a umožňuje detailnější zobrazení jejich konstrukčních vad a cenných prvků. Díky spojení dat z pozemní i letecké fotogrammetrie lze získat komplexnější informace o struktuře a prostorových vlastnostech budov, což může být klíčové pro jejich restaurování, ochranu a další výzkum. Tato integrace technik tedy představuje významný krok vpřed ve zkoumání a dokumentaci historických staveb s ohledem na jejich budoucí udržitelnost a ochranu pro další generace. Výsledky prezentované v přiložené publikaci podporují hypotézu, že kombinace pozemní a letecké digitální fotogrammetrie umožňuje vytvářet digitální modely historicky významných budov s větší přesností a detailností než použití pouze jedné metody. Hypotéza III byla potvrzena.

5.4 Verifikace hypotézy IV

Hypotéza IV: Hustota bodového mračna získaného optickými metodami 3D skenování bude významně ovlivněna texturou povrchu zkoumaného objektu. Dále předpokládáme, že různé úpravy povrchu, jako jsou aplikace povrchových látek nebo mechanické úpravy, budou mít signifikantní dopad na hustotu bodového mračna a umožní optimalizaci procesu akvizice dat pro tvorbu digitálních modelů.

Publikace A1

Influence of Material on the Density of a Point Cloud Created Using a Structured-Light 3D Scanner

Kaiser, J.; Dědič, M. Influence of Material on the Density of a Point Cloud Created Using a Structured-Light 3D Scanner. Appl. Sci. 2024, 14, 1476. https://doi.org/10.3390/app14041476

Článek v odborném impaktovaném časopise popisuje výzkumná zjištění, že různé materiály mají různé vlastnosti, které se projevují ve strukturovaně-světelném 3D skenování povrchu měřeného objektu. Materiály byly vybrány s předpokladem, že svými vlastnostmi negativně ovlivní hustotu bodového mračna. Příspěvek popisuje metodiku, jak probíhalo měření vybraných materiálů, a navrhuje možnosti povrchové úpravy materiálů pro zlepšení vlastností materiálů pro sběr 3D dat ve strukturovaném světle. Díky tomuto výzkumu je možné odhadnout problémové oblasti z hlediska materiálů při rekognoskaci měřeného objektu. Výsledky provedených experimentů ukazují, že použitá ošetření mohou zlepšit přesnost modelu měřeného objektu a snížit nutnost ručního dokončení modelu nebo několikanásobného skenování měřeného objektu.

Na základě vlastností povrchů jednotlivých materiálů, které ovlivňují získaná data v podobě mračen bodů, byly materiály rozděleny do kategorií: dobře skenovatelné materiály, materiály obsahující velmi jemné prvky, lesklé materiály a transparentní materiály. Názvy jednotlivých kategorií charakterizují vlastnosti těchto materiálů. Kategorie materiálů ukazují, jak vlastnosti povrchu souvisí s obtížností získání mračna bodů s vysokou hustotou a zda je třeba povrch před skenováním nějakým způsobem upravit.

Aby bylo možné zpracovat data z měření strukturovaného světla 3D skenováním, bylo potřeba mít vhodný základ v podobě mračna bodů. Mračna bodů mají v různých částech modelu různou hustotu bodů a právě hustota ovlivňuje přesnost výsledného modelu. Lze tvrdit, že čím vyšší je hustota mračna bodů, tím vyšší je přesnost výsledného digitálního modelu. Důležitý je také požadavek na přesnost, protože pro různé aplikace jsou požadovány různé míry hustoty mračna bodů. Byly analyzovány různé materiály a následně hodnoceno, jak jejich vlastnosti ovlivňují hustotu mračna bodů. Zároveň byla pro materiály, které si vedly špatně při hodnocení hustoty mračna bodů, navržena povrchová úprava, která výrazně zlepšila povrchové vlastnosti těchto materiálu při pořizování snímků.

Pro povrchovou úpravu byly použity různé metody úpravy podle druhu materiálu. U materiálů s jemnými prvky úprava spočívala ve vyhlazení povrchu (česání). U lesklých a průhledných materiálů spočívalo první ošetření v nanesení tenké vrstvy matovacího spreje (křídový sprej nebo suchý šampon) tak, aby původní povrch vzorku byl stále mírně viditelný. Druhé ošetření spočívalo v nanesení silnější vrstvy matovacího spreje (křídový sprej nebo suchý šampon) tak, aby původní povrch vzorku byl zcela zakryt a nebyl vidět.

Publikace je Přílohou č. 5.

Na základě analýzy výsledků provedených experimentů, které zahrnovaly 3D skenování různých materiálů s různými texturami povrchu, bylo zjištěno, že povrchové vlastnosti materiálů mají významný vliv na hustotu bodového mračna. Například materiály s jemnými prvky, lesklé materiály a transparentní materiály vykazovaly nižší hustotu bodového mračna ve srovnání s materiály s hrubšími texturami povrchu. Dále bylo zjištěno, že aplikace různých úprav povrchu, jako je použití matných povrchových látek nebo mechanické úpravy, mohou zvýšit hustotu bodového mračna tím, že eliminují nežádoucí vlastnosti materiálů a zlepšují schopnost skeneru získávat bodová data.

Celkově lze tedy potvrdit hypotézu, že textura povrchu má významný dopad na hustotu bodového mračna a různé úpravy povrchu mohou optimalizovat proces akvizice dat pro tvorbu digitálních modelů. Tato zjištění mají důležité důsledky pro praxi, jelikož umožňují lépe porozumět procesu 3D skenování pomocí optických metod a identifikovat vhodné úpravy povrchu pro získání vysokokvalitních bodových mračen. Hypotéza IV byla potvrzena.

6 PŘÍNOSY DISERTAČNÍ PRÁCE

Disertační práce pojednává ve čtyřech konferenčních publikacích o využití optických metod v procesu tvorby 3D dokumentace stávajících objektů, konkrétně za využití metod 3D triangulace a Structure from Motion. V páté publikaci demonstruje texturu povrchu zájmového objektu a její vliv působící na kvalitu výsledného modelu.

6.1 Shrnutí práce

Disertační práce se zaměřuje na využití optických metod pro tvorbu 3D dokumentace existujících objektů, především s použitím 3D triangulace a metody Structure from Motion. Práce prokázala, že výběr a aplikace optických metod významně ovlivňují kvalitu výsledných 3D modelů, zejména v kontextu jejich přesnosti a detailnosti.

V první části jsou představena teoretická východiska a metodologie optických skenovacích technik, které byly následně aplikovány na konkrétní příklady, včetně historických a kulturně významných objektů. Bylo zdůrazněno, jak výběr techniky skenování a nastavení skeneru ovlivňují kvalitu získaných dat, což bylo demonstrováno na různých typech materiálů a objektů.

Druhá část se podrobněji věnuje vlivu textury povrchu zkoumaných objektů na hustotu a kvalitu bodového mračna. Bylo zjištěno, že různé povrchové textury materiálů mohou výrazně ovlivnit výsledky skenování, a že určité povrchové úpravy mohou zlepšit akvizici dat, což umožňuje dosáhnout lepších výsledků při vytváření digitálních modelů.

Práce dále diskutuje význam kombinace různých metod skenování pro zvýšení přesnosti modelů, což bylo prokázáno na příkladu historicky významné budovy, kde kombinace pozemní a letecké digitální fotogrammetrie umožnila dosáhnout vysoké úrovně detailu a přesnosti.

V závěru jsou shrnuty hlavní poznatky a doporučení pro praktické využití výsledků výzkumu, včetně možností dalšího rozvoje a aplikace optických 3D skenovacích metod ve stavebnictví, archeologii a dalších oborech, kde přesná 3D dokumentace hraje klíčovou roli.

Celkově disertační práce přináší nový pohled na možnosti a omezení optických skenovacích metod a nastavuje směr pro další výzkum v této oblasti. Disertační práce definuje čtyři výzkumné otázky, které jsou adresovány a diskutovány na základě předložených publikací.

1. Jaký je vliv použití různých metod zpracování dat a kombinace více skenů na přesnost a efektivitu tvorby digitálních modelů složitých forem, jako jsou sochy, reliéfy a složité tvary, pomocí optických 3D skenerů?

Výzkum ukázal, že kombinace různých metod zpracování dat a aplikace více skenů výrazně zvyšuje přesnost a efektivitu při vytváření digitálních modelů složitých objektů. Použitím sofistikovanějšího softwaru pro zpracování a integrace několika skenů do jednoho modelu bylo možné dosáhnout vyšší detailnosti a minimalizovat chyby způsobené pohybem objektu nebo skeneru. Tyto výsledky jsou klíčové pro zachycení složitých detailů v uměleckých dílech a archeologických artefaktech.

2. Jaký je vliv kombinace pozemní a letecké digitální fotogrammetrie na přesnost a detailnost digitálních modelů historicky významných budov?

Kombinace pozemní a letecké digitální fotogrammetrie poskytla významně lepší výsledky v přesnosti a detailnosti modelů historicky významných budov. Tento přístup umožňuje získat širokoúhlý pohled a detailní snímky složitě přístupných oblastí, což vede k vytvoření kompletnějších a přesnějších 3D modelů. Tyto modely jsou neocenitelné pro restaurování, konzervaci a výzkum historických staveb.

3. Jaký je dopad různých textur povrchu zájmového objektu na hustotu bodového mračna při 3D skenování pomocí optických metod a jak

mohou různé úpravy povrchu optimalizovat proces akvizice dat pro tvorbu digitálních modelů?

Výzkum potvrdil, že textura povrchu má zásadní vliv na kvalitu a hustotu bodového mračna při 3D skenování. Hladké a lesklé povrchy často vedou k nízké hustotě bodů a nesprávnému mapování povrchu. Aplikace matujících sprejů nebo jiných povrchových úprav před skenováním zlepšila data, což umožnilo získat vyšší přesnost a kvalitu 3D modelů. Tato zjištění mají praktický význam pro skenování objektů s problematickými povrchy, jako jsou kovové sochy nebo průhledné plastové materiály.

4. Jaký je vliv kombinace pozemní a letecké digitální fotogrammetrie na přesnost a detailnost digitálních modelů lineárních konstrukcí, jako jsou umělá říční koryta, s důrazem na přesnost, úplnost a simulaci proudění vody pro účely stavebního plánování a analýzy?

Výzkum ukázal, že kombinace pozemní a letecké digitální fotogrammetrie je mimořádně efektivní při tvorbě digitálních modelů lineárních konstrukcí, jako jsou umělá říční koryta. Tato metoda umožňuje dosáhnout vysoké úrovně detailu a úplnosti, které jsou nezbytné pro následnou simulaci proudění vody. Použití těchto dvou přístupů společně zvyšuje přesnost modelů, což je klíčové pro účely stavebního plánování a analýzy. Tento způsob zpracování umožňuje inženýrům lépe modelovat a předvídat chování vodních toků v umělých říčních korytech, což má přímý dopad na návrh a bezpečnost těchto staveb.

6.2 Plnění cílů

Cíle práce byly splněny.

Využití optických metod v procesu tvorby 3D dokumentace stávajících objektů bylo popsáno a objasněno. Byla definována textura povrchu zájmového objektu a její vliv působící na kvalitu výsledného modelu. V rámci práce je veškerý vývoj dokumentován prostřednictvím publikací prezentovaných vědecké komunitě.

6.3 Doporučení pro další výzkum

V předchozích kapitolách byl popsán přínos této práce v oblasti využití optických metod v procesu tvorby 3D dokumentace stávajících objektů.

Ve výzkumu popisovaném v publikaci A1 došlo k vyhodnocení několika zvolených materiálů z hlediska jejich vlivu na hustotu bodového mračna. Výsledky tohoto výzkumu, a i dalších paralelních a pozdějších výzkumů v této oblasti jednoznačně prokázaly, že povrchy jednotlivých materiálů mají významný vliv na hustotu bodových mračen. Zároveň bylo navrženo řešení pomocí krycích sprejů. Do budoucna je ale potřeba aplikovat tento výzkum v rozsáhlejším měřítku, aby mohla vzniknout například knihovna materiálů včetně ověřených možností úpravy jejich povrchu při rekognoskaci snímaných objektů, čímž by došlo k výraznému zkrácení doby zpracování dat ze 3D skenerů a digitální fotogrammetrie.

Další oblast, ve které by měl výzkum pokračovat, je digitální fotogrammetrie, která se stává za pomoci mobilních aplikací dostupná pro širší veřejnost, v kontextu zavádění BIM do stavebnictví a správy budov. Informační modely vznikají v různých úrovních detailnosti (LOD) grafických dat a vzhledem k časové náročnosti snímání a zpracování dat z digitální fotogrammetrie se jeví jako potřebný výzkum závislosti optimálního využití digitální fotogrammetrie na požadavcích vyplývajících z jednotlivých úrovní LOD. Touto problematikou se autor práce již aktivně zabývá.

6.4 Shrnutí příspěvků autora

Autor disertační práce věnoval aplikovanému výzkumu využití optických metod v procesu tvorby 3D dokumentace stávajících objektů několik posledních let a podílel se na několika národních i mezinárodních projektech. Následuje krátké shrnutí dosažených výsledků. Mezi přínosy autora do oblasti výzkumu využití optických metod v procesu tvorby 3D dokumentace stávajících objektů lze zařadit následující položky:

- Řešitel v projektu APLIKACE – VÝZVA IX., Výzkum a vývoj inovativní linky Building Data Warehouse (BDW) k zajištění kvality a kontroly procesů ve výstavbě a údržbě, Číslo projektu: CZ.01.1.02/0.0/0.0/21_374/0027275, doba řešení: 2021 – 2023.
- Řešitel v projektu Development of BIM knowledge in higher education to boost the competencies of young people and reinforce the interdisciplinarity in European Universities – BIM4HEI, EU Project, KA2 – Cooperation for innovation and the exchange of good practices, doba řešení: 2021 – 2024.
- Řešitel v projektu InVoucher – AVAG (vývoj aplikace pro zpracování dat z letecké fotogrammetrie a pro následné výpočty v digitálním modelu), doba řešení: 2021 – 2022.
- Řešitel v projektu SGS (Metody získávání , zpracování a využití BIM dat pro podporu procesů ve stavebnictví), doba řešení: 2021 – 2024.
- Řešitel v projektu InVoucher – 3D skenování, úprava dat, 3D tisk (60 tváří významných současných českých osobností z pole vědy, politiky, sportu, medicíny, umění atd.), doba řešení: 2020 – 2021.
- Řešitel v projektu SGS (Modelování procesů ve stavebnictví), doba řešení: 2020 – 2023.
- Řešitel v projektu InVoucher – Prvok (první 3D tištěný dům v ČR), doba řešení: 2020.
- Řešitel v projektu SGS (Optimalizace a automatizace procesů navrhování, realizace a provozu staveb s využitím BIM a GIS dat), doba řešení: 2019 – 2022.
- Spolupráce na několika zakázkách v rámci tvorby 3D modelu pomocí optických měřících metod, např.: Rekonstrukce kapličky, digitální model nejstarší vesnice v Portugalsku, digitální model přírodního koryta pro divokou řeku v Kadani, digitální model pro tvorbu formy pro obnovu původních šambrán, digitální model čtyřkolky pro Dakar 2022, digitální model Jiřího Prskavce a další.

- Člen pracovních skupin BIM&GEO pod záštitou CZBIMu a BIM&EDU pod záštitou ČAS.
- Propagace 3D optických metod na národních konferencích a zahraničních univerzitách (Portugalsko, Norsko, Německo, Rumunsko, Albánie).

7 ZÁVĚR

Výzkum jednoznačně prokázal, že kombinace různých metod zpracování dat a použití více skenů vede k výraznému zlepšení přesnosti a efektivity tvorby digitálních modelů objektů. Sofistikovanější software umožňuje integrovat data z více skenů a minimalizovat chyby způsobené pohybem objektu i skeneru, což je klíčové pro zachycení detailů v uměleckých dílech a historických artefaktech.

Kombinace pozemní a letecké digitální fotogrammetrie poskytuje významné zlepšení v přesnosti a detailnosti modelů historických budov. Tento přístup umožňuje získání širokoúhlého pohledu a detailních snímků z těžko dostupných oblastí, což vede k vytvoření komplexnějších a přesných digitálních modelů, klíčových pro restaurování, výzkum a obnovu historických staveb.

Výzkum dále potvrdil, že textura povrchu má klíčový vliv na hustotu a tím i kvalitu bodového mračna při 3D skenování. Použití matujících sprejů nebo jiných úprav při rekognoskaci objektu výrazně zlepšuje přesnost a kvalitu 3D modelů, což má praktický význam pro problematické povrchy, jako jsou lesklé, kovové nebo průhledné a průsvitné materiály.

Kombinace pozemní a letecké digitální fotogrammetrie je mimořádně efektivní při tvorbě digitálních modelů lineárních konstrukcí, například umělých říčních koryt. Tento přístup umožňuje dosažení vysoké úrovně detailu a úplnosti, což je klíčové pro simulaci proudění vody a plánování stavebních projektů. Tímto způsobem zpracování lze lépe modelovat a předvídat chování vodních toků, což má zásadní vliv na bezpečnost a účinnost těchto staveb.

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Influence of Material on the Density of a Point Cloud Created Using a Structured-Light 3D Scanner

Jiří Kaiser and Martin Dědič *

Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7/2077, 166 29 Prague, Czech Republic
* Correspondence: martin.dedic@fsv.cvut.cz

Abstract: Global digitization affects all sectors, including construction. Indeed, 3D scanning and digital photogrammetry methods are increasingly being used to obtain 3D data of buildings. The data obtained by these methods are a cloud of points, and our research is focused on this cloud's density. From the literature and our own previous research, it is known that different materials have different properties that are manifested in the structured-light 3D scanning of the surface of the measured object. We have selected materials with the assumption that their properties would negatively affect the density of the point cloud. The article describes the methodology of how the measurement of selected materials was performed and suggests material surface treatment possibilities to improve the properties of the materials for structured-light 3D data acquisition. The influence of suggested surface treatments on objects and/or materials was not investigated. Each intended case of using the suggested surface treatments needs to be considered individually to avoid object deterioration and/or material deterioration. Thanks to this research, it is possible to estimate the problem areas in terms of the materials during the reconnaissance of the measured object. The results of our experiments show that the treatments used can improve the accuracy of the measured object model and reduce the need to manually complete the model or scan the measured object several times.

Keywords: building information modeling; structured-light scanning; materials; surface treatment; point cloud density

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1. Introduction

Current research in the field of creating 3D models of real objects is moving in the direction of obtaining very high-density and voluminous point clouds, either by laser 3D scanning or structured-light 3D scanning [1]. Although these methods provide relatively high-density data in the form of point clouds, it is very time- and cost-intensive to process these data for the creation of digital models [2]. The current need to quickly provide as many 3D models [3] of historic buildings, infrastructure structures [4,5], etc., as possible, especially for maintenance, repair, and passporting purposes [6–8], requires finding scanning and data processing methods that are faster and more cost-effective. One such method is digital photogrammetry, during which images of the object's surface are taken, and a digital model is then created from them using software. Antón et al. [9], in their study of historical building data acquisition, show that for higher density point clouds, it is better to use a structured light 3D scanner than laser 3D scanning. This is valid in the case of historic buildings and their significant elements, decorations, reliefs, etc. [9]. At the same time, it is proven that the purchase of a quality camera, a drone with a high-resolution camera, and image processing software is significantly cheaper than the purchase of a laser 3D scanner with accessories [10].

It is obvious that when the amount of data contained in a point cloud is limited, distortions and inaccuracies occur in the creation of a 3D model [10]. However, in many cases, the mere geometry of the shapes of the scanned object will be sufficient, and we will not need to acquire data about the surface texture of the material or its color [1,11]. It turns out, however, that when scanning processes are simplified, the density of the scanned point clouds will be directly influenced by the type of surface in question [12,13].

Therefore, the research that we designed and carried out focused on obtaining information about which materials affect the quality of the acquired data and how surfaces of materials can be treated so that their surface can be scanned in higher quality. Subsequently, this approach will make it significantly easier to obtain very high-quality 3D models at a relatively lower cost and in a short time [9]. This could speed up the passporting of a wide range of existing buildings and provide very high-quality documentation at a favorable price, even for investors who are limited by budget [14]. This research is a follow-up to the diploma thesis entitled "The influence of the material, texture, and shape of the object on the density of the point cloud created using optical measurement methods" [15] and expands the number of measurements for some materials and, at the same time, selects other materials that have not yet been investigated from this point of view. The point clouds are also examined regarding other issues, like arrangement of points in point clouds, distribution of points in the measured area, and vertical dispersion of points, which may also influence the process of 3D data acquisition and its results.

At a time when laser 3D scanning and structured-light 3D scanning are no longer new, we focus on the issue of different characteristics of materials and their impact on the resulting quality of the 3D model of real objects. When improperly chosen structured light 3D scanning measuring technology is used, instead of a digital model, we can only obtain an incomplete point cloud that appears to resemble a digital model [16]. Many researchers in the field of laser 3D scanners and structured-light 3D scanning mention this issue (see Section 2.1) but do not examine it. It is, therefore, an unexplored topic in the field of structured-light 3D scanning measurement, which can help to speed up measurement and refine digital models in the future.

The density of the point cloud can be evaluated by various metrics. For our research, the point-to-point metric was chosen. This metric is quite commonly used. The points from the original point cloud are compared with the points from another point cloud after the surface of the scanned object has been treated [17]. It is known that the reflectivity of the surface and its shape have a great influence on the resulting density of the point cloud [11]. The article aims to suggest the treatments of the surface of materials and conditions in data acquisition so that the density of the point cloud reaches the required values.

Based on previous experience with structured-light 3D scanning measurements and work with point clouds, we assume that materials with a glossy surface will have significantly worse results than materials with a matte surface. It can be expected that after the application of the opacifying agent, the results of materials with a glossy surface and transparent materials will be improved. Furthermore, we assume that materials with a fine structure will perform worse than materials with a uniform appearance [12].

The structure of this article is as follows. Section 1 presents the topic and issues of working with point clouds in the creation of digital models. Section 2 examines the current identified problems with point cloud density and clarifies the research questions for the described research. Section 3 delves into a comprehensive description of the proposed research methods, selection of research materials, and sample acquisition. This section also describes the research process and the equipment used. Section 4 describes the results of all measurements divided into four subsections according to the main properties of the investigated materials. Section 5 discusses the research results. Finally, Section 6 concludes the article by summarizing the essential findings and insights gained from the study, answering the research questions, and suggests potential directions for future research.

2. Literature Review and Research Questions

2.1. Literature Review

Structured-light 3D scanning technology is most often used in reverse engineering, quality control, control of the presence of parts on the equipment [18], and in general where it is necessary to achieve the capture of complex or otherwise difficult to measure objects (hot, soft, large, etc.) Although structured-light 3D scanning measurement does not achieve the most accurate results, the use of a coordinate measuring machine (CMM) for these objects would be inefficient [19]. Structured-light 3D scanners use so-called triangulation to capture the third dimension of an object. The principle of triangulation is based on the situation when the beam is reflected from the scanned object at a constant angle, so the distance of impact of the reflected beam on the sensor face is proportional to the distance of the scanned object from the sensor face. This means that neither the intensity of the incident beam nor the time of its flight is evaluated, but, rather, the place where the reflected beam hits is measured. For this reason, scanning is significantly more reliable and more resistant to interference, because the scannability condition is only the ability of the sensor's optical receiver to detect the impact of the reflected beam with an intensity that will be greater than the minimum detectable value [20].

The structured-light 3D scanner uses light to scan, so light scattering affects the resulting image. The light of the parallel rays incident on the plane interface will be parallel again. However, if the interface is not planar, the rays will bounce in all directions and, thus, scatter light. Therefore, if light is not reflected at either the planar or non-planar interface, the sensor would have nothing to capture and evaluate. Therefore, transparent or translucent materials cannot be scanned without surface treatment [1]. The color of the scanned object is closely related to light scattering and the scanning itself. Each color has its specific properties and, depending on the wavelength, is easier or harder to scan. Light is defined as a visible beam of an electromagnetic wave with a wavelength in the range of 380–780 nm. Visible light can be divided into seven spectral colors from the color with the shortest wavelength: purple, indigo blue, blue, green, yellow, orange, and red. When all of these colors are combined, colorless sunlight is produced. The human eye perceives the colors of an object as the reflected light or light passing through the object changes the wavelength and intensity of the light [21].

The coefficient of reflection or albedo indicates how much of the incident energy is reflected into the space, as follows [22]:

$$\rho(\lambda) = (Er(\lambda))/(Ei(\lambda)), \tag{1}$$

where $Ei(\lambda)$ is the intensity of radiation incident on the surface of the object and $Er(\lambda)$ is the intensity radiated back after reflection, corresponding to the wavelength of electromagnetic radiation. The coefficient of reflection depends on the wavelength of the incident radiation, the surface properties of the incident (ability to absorb radiation), and the three angles that describe the relationship between the light source $\boldsymbol{L}$, the observer $\boldsymbol{V}$, and the local orientation given by the normal n. The scalar product of vectors and, therefore, the reflectance function R, is described by three scalar products of vectors, as follows [22]:

$$R = R\,(\mathrm{n} \cdot \boldsymbol{L}, \mathrm{n} \cdot \boldsymbol{V}, \boldsymbol{V} \cdot \boldsymbol{L}). \tag{2}$$

The surface reflectivity of a material is always somewhere between two extremes, namely the Lambert and ideal mirror surface [22].

A Lambert, or ideally matte, ideally diffuse surface reflects light energy evenly in all directions, and, therefore, the glow (brightness) from all directions is constant, i.e., it does not depend on the direction of view. The name was first mentioned in Johann H. Lambert's book *Photometria* [23] published in 1760, in which the word albedo was also used for the first time. Thus, there is no perfectly matte Lambert surface. The examples of reflectivity can be: a white drinker with a reflectivity of 0.8, white writing paper with a reflectivity of 0.68, a white ceiling or yellow paper with a reflectivity of 0.6, dark brown paper with a reflectivity of 0.14, and dark velvet with a reflectivity of 0.004. These materials correspond approximately to the center of the visible spectrum. The ideal mirror surface reflects radiation according to the law of reflection (the angle of incidence is equal to the angle of reflection). Thus, the surface itself is not visible but only shows an apparent mirror image of the light source [24].

C. Bernal et al. [25] examined the accuracy of the Comet L3D measurement system using adhesive tape, which they used instead of anti-reflection coating. They compared the measured white opaque tape with a thickness of 0.06015 mm with the measurements of the object treated with white powder, which did not occur in the end, because it was impossible to control the thickness of the applied layer [25]. Paloušek et al. [26] described the problems that can occur when scanning without the use of opaque sprays and also explained when it is appropriate to use spraying. As the spray manufacturers state very precise using conditions (temperature, lighting, and experienced personnel), the conditions may not always be ideal, and the measurement result may be affected in this way.

2.2. Research Questions

As assumed from the literature review, research in the field of structured-light 3D scanning data acquisition and processing is ongoing, but it is focused on the semi-automation of data processing and the modeling of imperfectly scanned parts of objects. This article aims to answer the following research questions. RQ1: To what extent is the density of the point cloud predictable during building object reconnaissance? RQ2: How can the material surface be easily treated for higher point cloud density? RQ3: Can the data acquisition process bemore efficient with knowledge of the appropriate surface treatment? Answering these questions can increase the overall density of the point cloud of the scanned objects, especially for the problematic parts of these objects, and can also possibly increase the efficiency of the data acquisition process.

3. Materials and Methods

The structure of this section is as follows. Section 3.1 presents the methodology and further describes the selection of the investigated material samples. Section 3.2 describes the applied research process using an annotated process diagram. Section 3.3 dives into a comprehensive description of scanning activities. Then, Section 3.4 describes the methodology of scanning results evaluation, the division of the samples according to the main characteristics, and the description of surface treatments of the samples to improve the density of the obtained point clouds. Section 3.5 describes the equipment and software used.

3.1. Methodology

The research was focused on investigating the relationship between the material, its surface characteristics, and the density of the scanned point clouds. Point cloud density was used as the main indicator, but while performing the experiments, some other issues were raised. These issues are horizontal lines in the point cloud, missing points in the middle of the scanned area, and the excessive point noise of the point cloud. More details on these issues are provided in the Results section.

It was necessary to select the materials on which experiments were made. Previously described selection processes and methods (e.g., [27]) often stress a specification of selection criteria. The materials used for the experiments were selected on the basis of the following three criteria:

- The materials are commonly used on the surface of buildings.
- There is a sufficient diversity of the materials.
- The materials have not yet been investigated regarding their influence on point cloud density.

For some materials, the influence of various treatments on point cloud density has also been tested. These treatments could at least partially eliminate a material’s undesirable properties and improve the resulting point cloud density and, consequently, the polygon network generated from the point cloud. The treatments are briefly described in the Methodology of Scanning Results Evaluation subsection. More details about surface treatments’ application to the particular materials, together with the influence of the treatments on point cloud density, are given in the Results section. From the existing objective metrics of the point cloud density assessment [17], we chose point-to-point quality metrics, which are commonly used [17,28]. This method compares the degraded point cloud and the original point cloud point by point, even if both clouds do not have the same number of points. Furthermore, a multi-scale model for cloud comparison modeling (M3C2) was used, as the method allows the combination of data from multiple scan positions or data sources with different degrees of uncertainty [29].

The distance between points and finding the nearest neighbor in a point cloud measure point-to-point quality metrics. For each point in the reference point cloud A, the nearest neighbor that is in the degraded point cloud B is found [17]. The resulting distance between two points is called the error vector dB, $^{A}(i)$ and can be evaluated in two ways point-to-point, as follows.

The Hausdorff (Haus) metric is the maximum distance that can be measured between all points in cloud B and their nearest neighbor in reference cloud A. The Hausdorff distance is defined as follows [17]:

$$d_{Haus} = \max_{\forall i \in B} d^{B,A}(i) \tag{3}$$

By averaging the distance from all points in B (the number of NB points) and their nearest neighboring points in reference cloud A, the average distance, or root mean square distance (RMSD), is produced, as follows [17]:

$$d_{RMSD} = \frac{1}{N_B} \sum_{i=1}^{N_B} d^{B,A}(i) \tag{4}$$

The above metrics (both RMSD and Hausdorff) are calculated symmetrically in both directions. The distance is calculated between B and A (dB, A) and between A and B (dA, B). The maximum operator is used to obtain the symmetric versions of the ds RMSD and Hausdorff metrics, as follows: [17]:

$$d^{S}_{RMSD} = \max\left(d^{A,B}_{RMSD}, d^{B,A}_{RMSD}\right) \tag{5}$$

$$d^{S}_{Haus} = \max\left(d^{A,B}_{Haus}, d^{B,A}_{Haus}\right) \tag{6}$$

The following materials were selected and scanned:

1. Hairy substance;
2. Transparent holographic foil;
3. Clear textured glass;
4. Woven carpet;
5. Glazed roof tile;
6. Full burnt brick;
7. Wooden parquets;
8. Reed;
9. Granite;
10. Marlstone;
11. Sheet metal;
12. Polycarbonate.

All samples of materials were taken during the reconstruction of existing buildings. These are old or historical materials from buildings located in the Czech Republic. The dimensions of the scanned area were 10 cm × 10 cm, which was determined by a frame that was cut out in a black quarter (black color absorbs radiation the most, so it is easily recognized during data processing).

The origin of the particular material samples is as follows:

- Hairy substance—historical damaged woven fabric on the wall;
- Transparent holographic foil—interior door filling from the 20th century;
- Clear textured glass—interior door filling from the 20th century;
- Woven carpet—interior carpet from the 20th century;
- Glazed roof tile—historical roofing from a chapel;
- Full burnt brick—part of a wall without plaster;
- Wooden parquets—interior parquet floor from the beginning of the 20th century;
- Reed—interior suspended ceiling from the 20th century;
- Granite—interior staircase from the 19th century;
- Marlstone—exterior wall cladding from the 20th century;

- Sheet metal—roofing from the 20th century;
- Polycarbonate—skylight filling from the 20th century.

3.2. Applied Process for the Research

Figure 1 shows the process map, which was created according to the Business Process Model and Notation (BPMN) standard [30], of the process that was applied in this research. For this research, we have chosen a variety of materials (A1) that exhibit, in our own experience from previous research and in the experience of other researchers (see theoretical background) and practitioner colleagues working in this area, problems during scanning and data processing with either low point cloud density or no scanned points (D1). Such scanned objects have to be manually remodeled. This reduces the accuracy of the model compared to the original and also significantly increases the time needed to edit the scanned data. To evaluate the data in a relevant way, we had to choose the parameters for data capture, ensuring the same lighting conditions for each image, distance, and time of capture (A2). For the selected materials, we chose a scoring system (A3) that has three basic criteria with scores ranging from 1 to 10 (D2). A material rating of 1 indicates the greatest difficulty in obtaining data. A score of 10 indicates a slight problem with data acquisition. This activity is similar to building object reconnaissance, which is performed before scanning of a building object in practice. During the reconnaissance, issues with the scannability of a building object and its parts are estimated by experts. More details are provided in Section 3.4. This evaluation is important for the final evaluation of the measured data. This was followed by the first data capture of each material (A4). Each material was scanned five times, each time under the same conditions, which are described in Section 3.3. The scanning activities were performed five times to solve possible deviations and measurement errors, which are discussed in Section 5.1. Point clouds (PC) were created from which we evaluated the data (A5). The main parameter was the density of the point cloud across the entire area. Then, this was converted to the number of points per square centimeter. Materials with point clouds reaching a density of 2200 points/cm^2, which is in our experience sufficient to make 3D models of building objects, were excluded from the list and we continued only with those that did not reach these values (A6). These materials had to be treated to make their surface more suitable for sensing structured-light 3D scanning data. In most cases, it was the translucency/transparency or reflectivity of the material that needed to be reduced. In the remaining cases, it was the finer elements that needed to be made more compact (A7). The modified materials were scanned five times under the same conditions as in the previous data acquisition (A8). Additional point clouds (PCs) were created and evaluated on the basis of the above criteria (A9). Based on this evaluation, it was possible to exclude additional materials that already met the point cloud density requirement (A10). However, there were still materials whose point cloud was too sparse. Therefore, further treatment of their surface (A11) was designed and implemented to achieve a higher point cloud density on the same surface. The materials were scanned again five times under the same conditions mentioned above (A12), and the resulting point clouds (PC) were then evaluated (A13). From the evaluation, we found that after the surface modifications made to each material, the point clouds were already mostly dense enough to allow further work on them without reducing the density of the resulting model. More details about resulting point cloud density for particular materials and their treatments are given in the Results section.

3.3. Scanning Activities (A4, A8, A12) and Conditions

Each scanning activity was performed five times, and each of them was carried out under the same conditions to eliminate the effects of the environment, which could also affect the density of individual measurements. By these conditions, we mainly mean lighting, angle, distance of measurement, and time of data collection. All materials were scanned indoors in daylight, without direct sunlight. This eliminates other adverse effects of weather (wind, rain). Each sample was scanned five times for five seconds, and then the sample was replaced with another, and the scanning was repeated to allow the scanner to collect approximately the same amount of data. The scanner was pointed perpendicular to the object at a working distance of 520 mm; this is the ideal distance for the Artec Eva device used [21]. An area for scanning was also defined, with the help of a frame formed by a black quarter, in which a square measuring 10 cm × 10 cm (Figure 2) was cut out and placed on a flat object made of the selected material [9]. This method of measurement was chosen so that the density of the measurement was not affected by the remaining shape of the object and to make it easier to assess the density of a point cloud from areas of the same size, which were obtained due to the square cutout. Furthermore, the quarter was glued to hard cardboard to prevent it from deforming when placed on any of the surfaces [19].

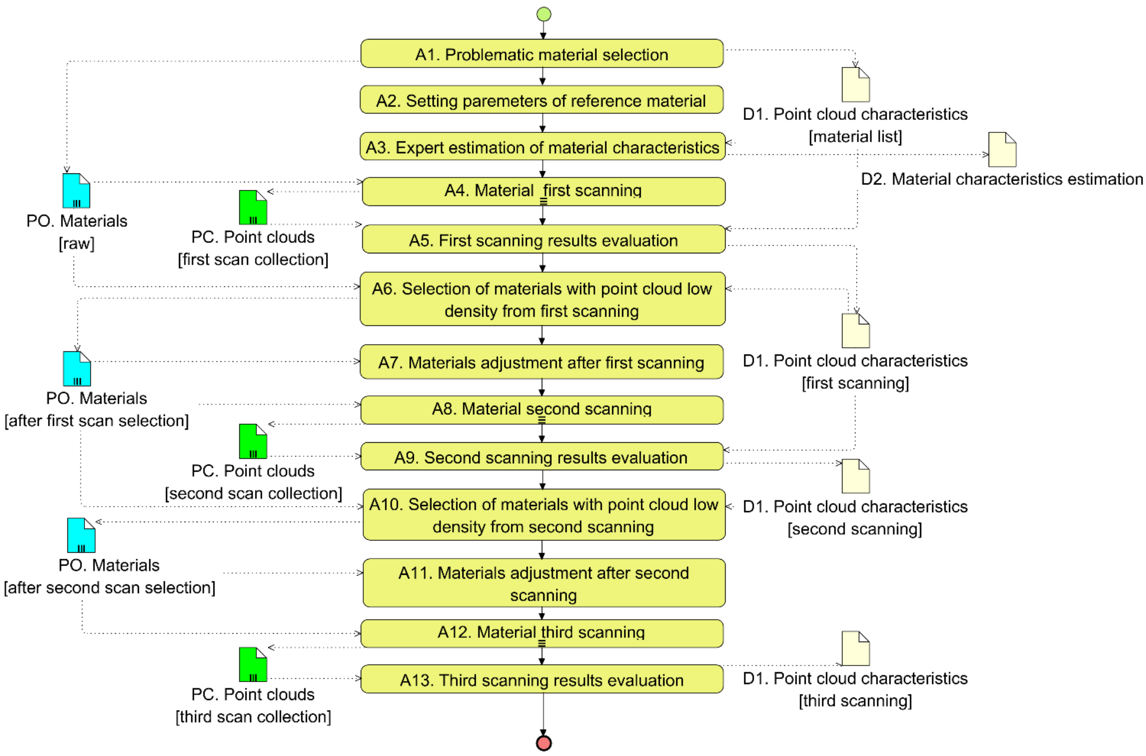


Figure 1. The map of the process applied to the research.

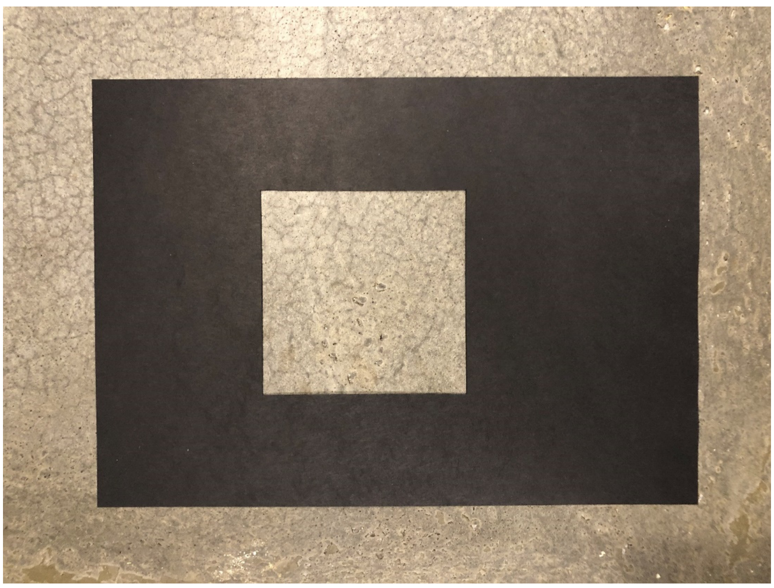


Figure 2. The 10 cm × 10 cm squares for sample measurement.

Data on individual measurements were recorded, the density of the point clouds of individual scans was determined, and then the samples were compared with each other according to density [17].

3.4. Methodology of Scanning Results Evaluation (A5, A9, A13)

To evaluate individual materials, the idea of the so-called ideal material was created. This is a material that we assume is ideal for scanning purposes and which will not create a very sparse point cloud that could result in a poor-quality polygon network [31].

Based on previous experience with the Artec Eva Lite scanner, we assume that this is a material that has the following properties [11,32]:

1. Is not translucent, or in the worst case transparent;
2. Is neither shiny nor reflective;
3. Does not contain very fine elements (hair, fur, fluff, etc.).

Based on the idea of an ideal material, we can expect that scans of some materials will have enough point cloud density without any surface treatment. We call these materials "well scannable". Then, we can recognize material characteristics that by expectation can worsen material scannability and, as a result, decrease point cloud density. These characteristics are as follows:

1. The material contains very fine elements;
2. The material is glossy;
3. The material is transparent.

As already mentioned, the point evaluation is based on the criteria of the ideal model given in the previous part of this section. To evaluate each of the criteria, a scale with points 1–10 was chosen, which allows for sufficient variability. Point assessment, which falls under object reconnaissance, was assigned by an expert estimate. The reason for this inclusion is the fact that the determination of the need to modify the material's surfaces before scanning is also determined by expert estimation. If the criterion is unconditionally met, the given object will be awarded the full number of points, i.e., 10. It follows that the ideal material described above should have the full number of points for all criteria. However, if there is partial or complete non-compliance, points are reduced according to the degree of violation. This depends on the degree of violation of the evaluated criteria, that is, the transparency, gloss, and fineness of the texture of the scanned material.

We used different methods according to the type of material for surface treatment.

For materials with fine elements, the treatment consisted of smoothing the surface (combing). For glossy and transparent materials, the first treatment consisted of applying a thin layer of matting spray (chalk spray, or dry shampoo) so that the origin surface of the sample was still slightly visible. The second treatment consisted of applying a thicker layer of matting spray (chalk spray, dry shampoo) so that the original surface of the sample was completely covered and not visible.

The coefficient of variation represents the ratio of the standard deviation to the mean [33]. The coefficient is useful for comparing the degree of variation from one data series to another even if the means are drastically different from one another [34–36]. Due to the large difference from one another, the coefficient of variation and not the standard deviation was used. The standard deviation measures how far the average value lies from the mean, whereas the coefficient of variation measures the ratio of the standard deviation to the mean [35]. The values of the coefficient of variation were calculated using R version 4.3.1.

3.5. Description of the Equipment Used

Artec Eva Lite 3D scanner

The Artec Eva Lite (Figure 3) handheld structured-light 3D scanner from Artec 3D, which has been operating on the market since 2007, was used to scan all materials (activities A4, A8, and A12). This type of 3D scanner was chosen due to the principle of data acquisition. "Eva" works on the principle of photogrammetry. It is this method that is significantly more widespread than laser scanning due to the purchase price of both devices [6]. When comparing the Artec Eva Lite with most other 3D scanners on the market, it is clear that the price/performance ratio is the best for this type of 3D scanner, which is why it was the choice for this research. Examples of prices are as follows. The price of a used Artec Eva 3D scanner with an accuracy of 0.1 mm is USD 15,000. A comparable handheld scanner with laser technology and 20 mm accuracy costs USD 53,710. The examples of prices are indicative and obtained as of 6 January 2024 and can be found in [37].

Figure 3. The used notebook and the structured-light 3D scanner Artec Eva.

As the word "Lite" in the name suggests, this is a cheaper and less demanding version of the Artec Eva scanner. This needs to be taken into account, as the results of data collection from two seemingly identical scanners can be very different. Although the Artec Eva Lite has the same accuracy as its full version, it cannot capture the optical texture and color of the object, and, thus, has a lower resolution. This also means that, unlike the full version, it focuses only on the geometry and the shape of the object, and not on its color and texture; however, even these factors could affect the quality of the scans [38].

Undoubtedly, the advantage of the simplified version is also the fact that, thanks to the scanning of only simple object geometry, we collect and then work with a much smaller volume of data, and, thus, the Lite version is less demanding in terms of power consumption and the required minimum computer power. While the Lite version can capture up to 2 million dots per second, the full version is able to capture up to 18 million dots per second.

The Artec Eva Lite scanner uses structured light technology for data collection. The device has a total of 12 LED light sources, which are used to project a special light pattern on the object. In Figure 4, where this pattern is projected onto the wall, it can be seen that these are alternate rows of smaller and larger points, which are placed in regular rows, but in an irregular order.

The shape of the scanned object distorts this light pattern; the scanner can capture this distorted shape using three cameras to create a point cloud corresponding to the actual shape of the object. It is important to maintain the working distance, which is about 0.4–1 m.

From the principle of structured light technology, it is assumed that some materials may be more or less problematic to scan with this technology if, for example, structured light passes through them or is reflected at a different angle than the object's shape [39].

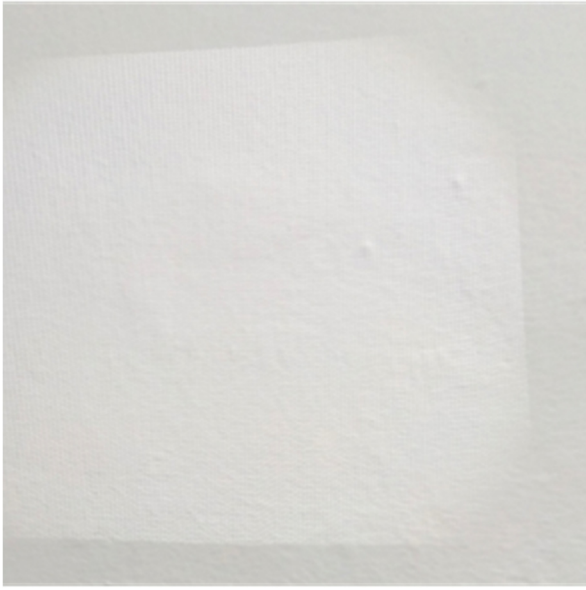


Figure 4. The light grid of the used structured-light 3D scanner.

Notebook

A Dell Precision M3800 notebook (Figure 3) with a fourth-generation Intel® Core-i7-4702HQ quad-core processor, NVIDIA Quadro K1100M graphics card, and 8 GB of RAM was used for scanning and subsequent work with the acquired data. It is also equipped with a touch screen and a fast SSD disk. Windows 10 is installed on the laptop.

Artec Studio 12 Professional

This is specialized software from Artec 3D, which is intended for data collection and subsequent processing. For this research, we worked with basic functions for editing individual scans, including removing the background or ambient noise, the possibility of filling holes or smoothing the surface, as well as joining individual scans together. The software also enables semi-automatic data processing, which we also used due to the large amount of data. We exported individual scans (or their networks) to STL and OBJ formats, which are compatible with a wide range of other software, including the Meshlab software, in which we further worked with the data.

MeshLab

We used the software Meshlab 2022.02 (www.meshlab.net, accessed on 3 October 2022) to create polygon meshes from the raw data in the form of a point cloud. At the same time, we diagnosed (determining the number of points in a specified area) the models that were also used in this research.

4. Results

To be able to process data from structured-light 3D scanning measurements, we need to have a suitable basis in the form of a point cloud. Point clouds have different point densities in different parts of the model, and it is the density that affects the accuracy of the resulting model. It can be argued that the higher the density of the point cloud, the higher the accuracy of the final digital model. The precision requirement is also important, as we need different types of point cloud density for different applications. We have analyzed the different materials and evaluated how their properties affect the density of the point cloud. At the same time, for materials that performed poorly in the point cloud density evaluation, we suggested surface treatment that significantly improved the surface properties of the material during image acquisition.

The following graph (Figure 5) shows the average density values of point clouds from all five measurements (vertical part of the graph) for each of the materials and their treatments (horizontal part of the graph). The modifications made on some materials are distinguished by color. The results of the first 3D scanning (A5) performed without any material surface treatment are marked in blue. The results of the second 3D scanning (A9) with the first material surface treatment (application of a small amount of dry shampoo, chalk spray, or surface compactness adjustment) are in red. The results of the third 3D scanning (A13) with the second material surface treatment (application of a larger amount of dry shampoo or chalk spray) are in green.

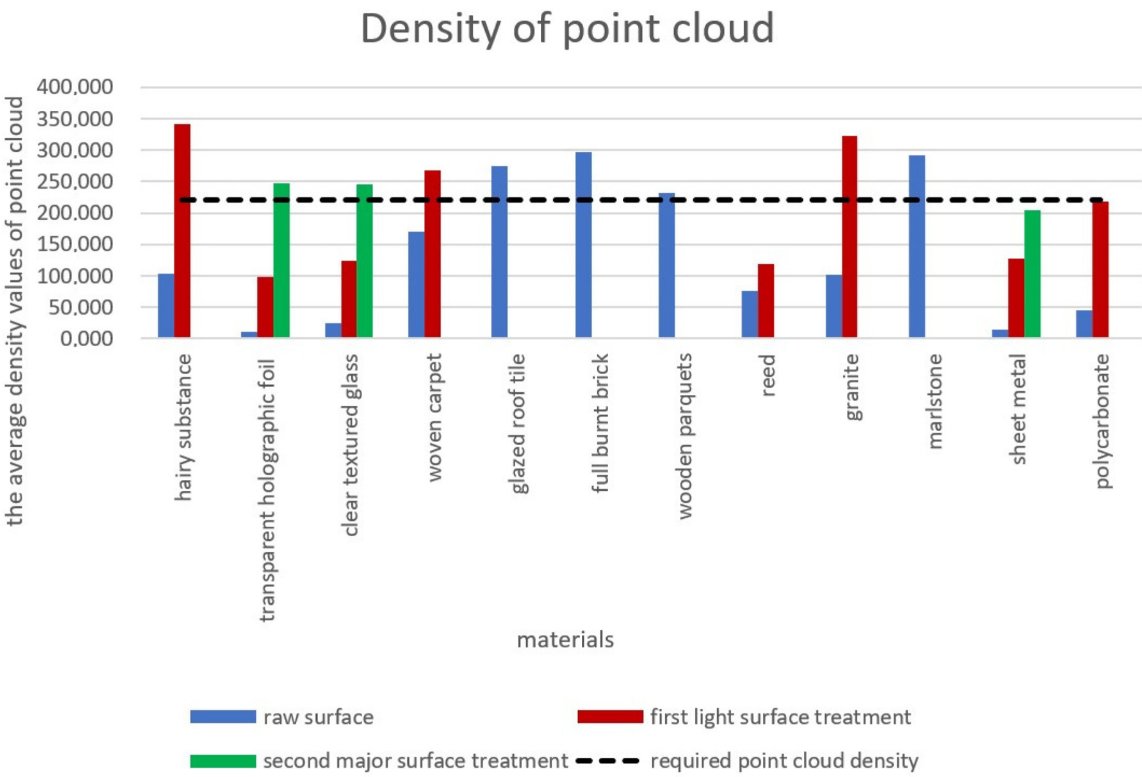


Figure 5. Average point cloud density as a result of scanning (activities A5, A9, and A13 from Figure 1).

Based on the properties of the surfaces of individual materials, which influence the obtained data in the form of point clouds, the materials were divided into categories: well-scannable materials, materials containing very fine elements, glossy materials, and transparent materials. The names of the individual categories characterize the properties of these materials. The material categories show how the surface properties relate to the difficulty of obtaining a high-density point cloud and whether the surface needs to be treated in some way before scanning. In the next sections, the process of how the surface was treated is described, as well as what effect various surface treatments have on the resulting density of the point cloud.

4.1. Well-Scannable Materials

This group of materials includes those materials whose surface was successfully scanned over the entire sample area with sufficient point cloud density without further treatments and measurements. The required point cloud density was set to 2200 points/cm^2. This value was chosen concerning the density of the 3D model according to the level of detail [40]. Figure 5 shows the average density of point clouds for each scanned material with the minimum required density level of point clouds.

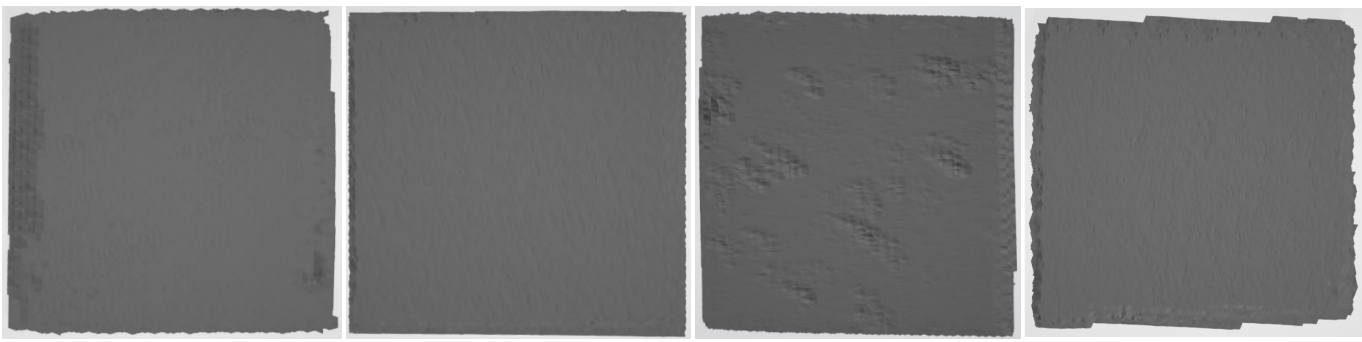
According to Figure 5, which shows average point cloud density, the well-scannable materials are glazed roof tile, full burnt brick, wooden parquets, and marlstone.

The average density of a point cloud related to the sample area for materials included in this category ranged from 220,000 points upward, i.e., about 2200 points/cm^2. Each material was scanned five times, and the density of the acquired point cloud was always above this threshold, with one exception, which is wooden parquets. For wooden parquets, the point cloud density for one scanning did not reach the value of 2200 points/cm^2. Unfortunately, none of the surface treatments suggested are applicable for wooden parquets, since chalk spray and dry shampoo can permanently damage the surface, and the compression of the surface is not practically applicable for wooden parquets. On the basis of the results, we may expect that for wooden parquets the required point cloud density may not always be reached. The average values of point cloud density, coefficient of variation, and the percentage of measurements with a point cloud density below 2200 points/cm^2 can be seen in Table 1.

Table 1. Well-scannable materials' point clouds.

Material		Glazed Roof Tile	Full Burnt Brick	Wooden Parquets	Marlstone
Point cloud density—raw	Average	275,405	297,529	231,108	291,284
	Coefficient of variation [%]	3.63	1.93	5.39	4.93
	Measurements below 2200 points/cm^2 [%]	0	0	20	0

In all point clouds of samples with a smooth surface, the phenomenon was evident that there was a higher concentration of points in regular horizontal lines. This phenomenon was significantly noticeable in the following samples: glazed roof tile, full burnt brick, and wooden parquets. Figure 6 shows meshes of all well-scannable materials. The concentration of points in regular lines was also observed on the auxiliary square frame that formed the surrounding area of the sample. All material samples examined were measured on a flat surface, yet there were slight waves in the arranged lines of points. This phenomenon is most pronounced with wooden parquets (Figure 6c).



(**a**) (**b**) (**c**) (**d**)

Figure 6. Meshes from point clouds—glazed roof tile (**a**), full burnt brick (**b**), wooden parquets (**c**), marlstone (**d**).

4.2. Materials with Very Fine Elements

The overall rating of materials with very fine elements is shown in Table 2. The characteristic evaluation row shows how far from the view of the very fine elements containment is from the ideal material.

A total of three materials were included in this category: hairy substance, woven carpet, and reed. From the description of the ideal material, it can be assumed that they could be problematic for scanning. When these materials with raw surface were scanned, no acquired point cloud reached the required density, as we can see from the percentage of measurements below 2200 points/cm^2 values in Table 2. None of the materials managed to scan the entire sample area without further treatments. This can be seen in Figure 7.

Table 2. Point clouds of materials with very fine elements.

Material		Hairy Substance	Woven Carpet	Reed
Characteristic evaluation		1	3	5
Point cloud density—raw	Average	103,151	169,861	75,709
	Coefficient of variation [%]	15.51	12.61	16.58
	Measurements below 2200 points/cm^2 [%]	100	100	100
Point cloud density—1st treatment	Average	341,420	267,523	119,204
	Coefficient of variation [%]	5.10	9.77	9.93
	Measurements below 2200 points/cm^2 [%]	0	0	100


(**a**) (**b**) (**c**)

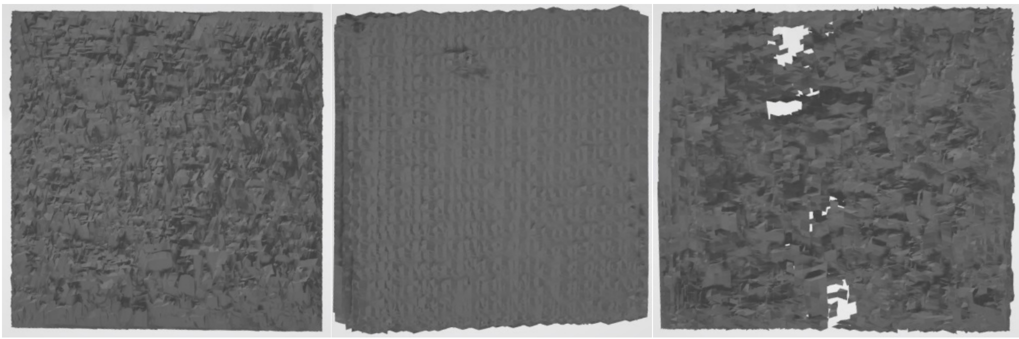
Figure 7. Meshes from point clouds of raw surface—hairy substance (**a**), woven carpet (**b**), reed (**c**).

In all of them, a higher concentration of points can be observed, especially along the edges of the samples, suggesting that adjacent materials with different properties may appear to interact with each other. This phenomenon is most visible on the reed point cloud, where the density of points in the area is very low, and at the same time it has the lowest average point cloud density/sample area of all materials.

On the contrary, in the center of the sample, there are places where no data on the sample surface could be obtained. At these places, the point cloud density per unit area is zero or significantly lower than at the edges of the sample. This means that it is not possible to create a polygon network in its entire area from these point clouds.

We carried out the surface treatment on the hairy substance, woven carpet, and reed, which could theoretically improve the density of the point cloud. Therefore, a second series of measurements was performed on each of these materials.

The hairy substance and the woven carpet were smoothed to form a uniform surface, thus eliminating the undesired effect of individual fine elements. A similar example could be, for example, human hair when scanning a human head, where, based on previous experience [32], hair which is, for example, pulled into a braid, is better scanned than dissolved and tousled hair. In this case, the treatment of the sample greatly helped to increase the overall average density of the point cloud. Woven carpet's average point cloud density improved by more than 57% in the measured area, and the hairy substance improved by even more than 230% in the measured area. All point clouds acquired from the scanning of these materials after treatment reached the required density of 2200 points/cm^2, as can be seen in Table 2. Furthermore, the coefficient of variation decreased significantly. The fact that the hairy substance is slightly shiny was not a problem either; on the contrary, it belongs among the materials that had the highest point cloud density when measured. A comparison of the formed meshes can be seen in Figure 8:



(**a**) (**b**) (**c**)

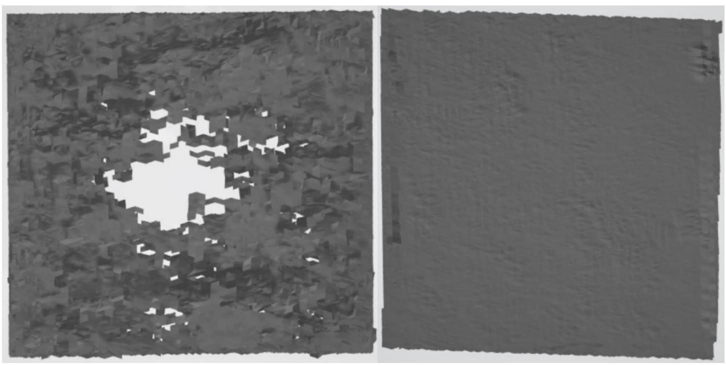
Figure 8. Meshes from point clouds of the first treatment surface—hairy substance (**a**), woven carpet (**b**), reed (**c**).

Since reeds could not be arranged as easily as a carpet, they were at least supported by a wooden plank. We encounter this solution on construction sites when creating models of reed ceilings. As a result, the gaps between individual straws were reduced, and its surface was more uniform and compact. However, even after this modification, the desired value of the number of points in the measured area was not reached in any acquired point cloud.

4.3. Glossy Materials

Materials that were slightly glossy have already been mentioned in the previous subsections. However, no negative effect on the resulting point cloud density was observed. To sufficiently assess the influence of this particular characteristic of the material on point cloud density, we selected some other samples which are only glossy, but meet other criteria of the ideal material, so they are not transparent or do not contain very fine elements. The samples that were selected were granite and sheet metal.

The first of these materials is granite, which contains mica particles, which shine when light falls on them at different angles. As for the reflection, only vague outlines are visible in it. When scanned without any treatments, it achieved a surprisingly relatively high average point cloud density of 101,012 points per sample area; see Figure 9a. All scanning attempts had a resulting point cloud density below the 2200 points/cm^2 threshold. As a treatment, a dry shampoo was used for the test on the next attempt, which was supposed to cover the shiny surface. Due to this surface treatment, it was possible to cover the shiny parts. The average point cloud density increased by more than 220% in the measured area after application, and all acquired point clouds had a density above the 2200 points/cm^2 threshold; see Figure 9b. As can be seen in Table 3, the coefficient of variation has decreased.



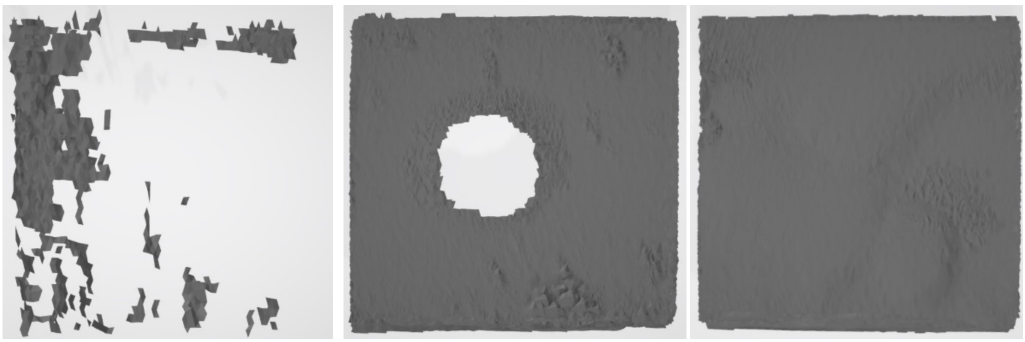
(**a**) (**b**)

Figure 9. Meshes of granite with a raw surface (**a**) and 1st treatment (**b**) with dry shampoo.

Table 3. Point clouds of glossy materials.

Material		Granite	Sheet Metal
Characteristic evaluation		8	2
Point cloud density—raw	Average	101,012	14,674
	Coefficient of variation [%]	9.34	44.50
	Measurements below 2200 points/cm^2 [%]	100	100
Point cloud density—1st treatment	Average	323,417	128,050
	Coefficient of variation [%]	8.29	15.87
	Measurements below 2200 points/cm^2 [%]	0	100
Point cloud density—2nd treatment	Average		204,092
	Coefficient of variation [%]		8.89
	Measurements below 2200 points/cm^2 [%]		80

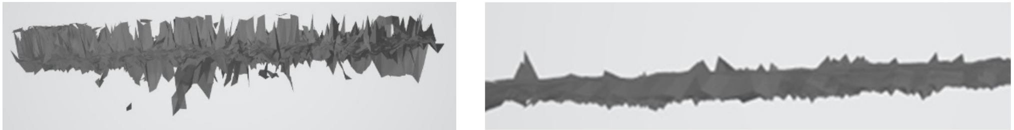
The second of these materials is sheet metal, which is very shiny, almost like a mirror. When scanned without any treatments, it achieved a very low average point cloud density of 14,674 points per sample area. A chalk spray was used as a treatment for the next test to cover the shiny surface. Two applications were made, first in a thin layer and then in a thick, opaque layer. Thanks to this surface treatment, it was possible to achieve its complete opacity, and the average point cloud density during the first and second applications increased by more than 770% in the measured area after the first surface treatment and by 1290% in the measured area after the second surface treatment. The meshes can be seen in Figure 10. Despite the increase in point cloud density, the threshold of 2200 points/cm^2 was reached only in one case of scanning activity of the material after the second surface treatment (the thick opaque layer).



(**a**) (**b**) (**c**)

Figure 10. Meshes of sheet metal with the raw surface (**a**) and first treatment (**b**) and second treatment (**c**) with chalk spray.

It is also worth noting that the application of the chalk spray also reduced unwanted noise, which was probably caused by the incorrect reflection of light from the reflective surface and could reduce the quality of the resulting model. The noise is visible when looking at the point cloud from the side and is located above but also below the surface of the cloud, which should represent the sample itself, which is only a flat surface. After the application of chalk spray, this phenomenon is largely eliminated, and on the resulting point cloud, there are more visible stripes with a higher concentration of points, which occurred especially on well-scannable smooth surfaces. The original and treated material (after the second spray application) and their meshes are shown in the following Figure 11.



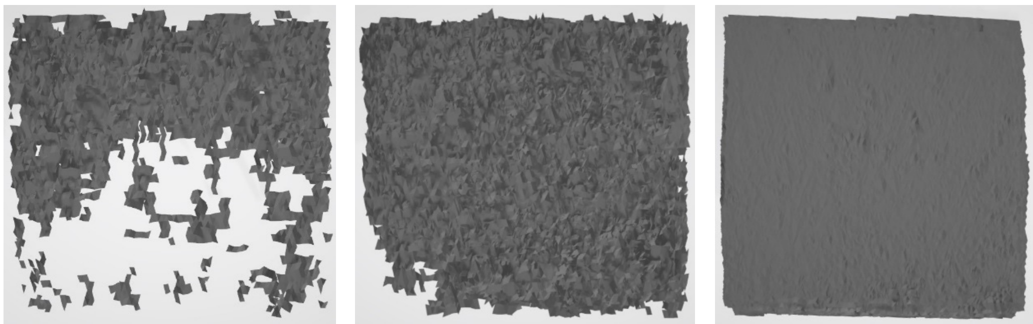
(**a**) (**b**)

Figure 11. The noise of the point cloud before (**a**) and after (**b**) chalk spray treatment.

4.4. Transparent Materials

In general, the most problematic group consists of transparent materials. Samples of materials that are partially or completely transparent were selected and subsequently scanned to assess how much this characteristic affects the density of the point cloud. All samples were placed so that there was no other material behind them in the working distance of the scanner that could affect the scanning result. The transparent materials were as follows: transparent holographic foil, clear textured glass, and polycarbonate.

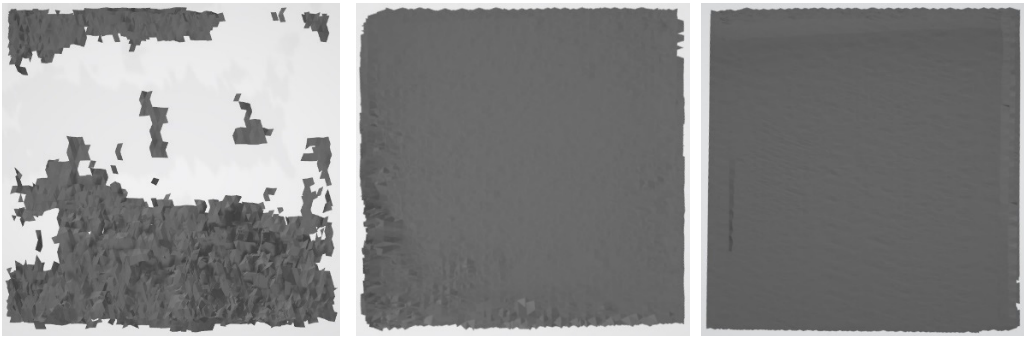
The first of the transparent materials is transparent holographic foil. When scanned without any adjustments, it achieved a very low average point cloud density of 10,938 points per sample area. As a treatment, a chalk spray was used for the test for the next attempt, which ensured the opacity of the material. The average density of the point cloud after the first surface treatment increased by more than 800% in the measured area after application. Nevertheless, the average value of the density of the point cloud was still insufficient; therefore, the chalk spray was applied in a thick layer, increasing it by more than 2150% in the measured area. (Figure 12). After the second treatment, 60% of scanning attempts resulted in point clouds with a density of more than 2200 points/cm^2. Also, the average value of the point cloud density was above the threshold. The foil has a smooth surface, so the point arrangement is again reminiscent of some well-scannable materials, but at the same time, there is noticeable point noise below and above its surface level.



(**a**) (**b**) (**c**)

Figure 12. Meshes from point clouds of transparent holographic foil with the raw surface (**a**) and 1st treatment (**b**) and 2nd treatment (**c**) by chalk spray.

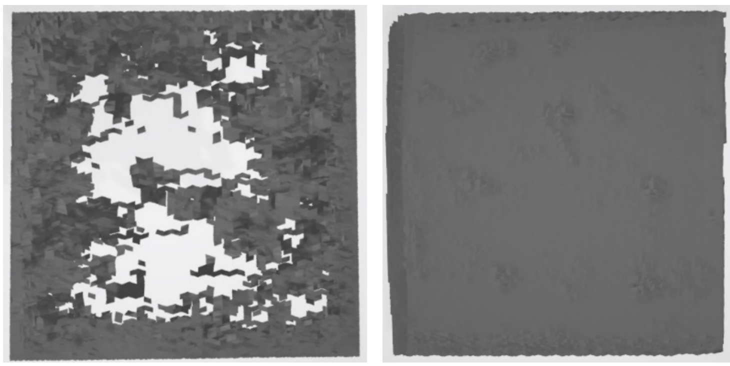
Figure 13 shows a point cloud made of clear textured glass, which is less transparent than transparent holographic foil but is slightly colored compared to it, which could have affected the density of this point cloud. The density of the point cloud is twice as high as that of transparent holographic foil. The average density of the point cloud is 24,033 points per sample area. As a treatment, a dry shampoo was used for the test for the next attempt, which ensured that the material was opaque. The average density of point clouds after the first surface treatment increased in the measured area by more than 410% after application. Nevertheless, the average value of the density of the point cloud was still insufficient; therefore, the dry shampoo was applied in a thicker layer, increasing it by more than 920% in the measured area. The average value of the point cloud density was above 2200 points/cm^2, but in 20% of scanning activities the resulting point cloud did not reach the threshold.



(**a**) (**b**) (**c**)

Figure 13. Meshes from point clouds of clear textured glass with the raw surface (**a**) and the first treatment (**b**) and the second treatment (**c**) with dry shampoo.

The last material examined is polycarbonate (Figure 14), which is the least transparent of this group of materials; it is straight, smooth, and colorless. Due to these properties, the average point cloud density of the material in its raw state was 44,346 points in the measured area, which is 4× more than the transparent holographic foil and 2× more than the clear textured glass. As a treatment, a chalk spray was used for the test for the next attempt, which ensured the opacity of the material. The average point cloud density after the first surface treatment increased in the measured area by more than 415% after application. The average value of the density of the point cloud was already sufficient, but in three cases the resulting point clouds did not reach the 2200 points/cm^2 threshold. As such, we decided to apply the second surface treatment (a thick layer of chalk spray) where the value of point cloud density was above the threshold in the case of all scanning activities.



(**a**) (**b**)

Figure 14. Meshes from point clouds of polycarbonate with the raw surface (**a**) and the first treatment (**b**) by chalk spray.

In the case of all materials, the treatments lead to a decrease in the coefficient of variation; see Table 4.

Table 4. Point clouds of transparent materials.

Material		**Transparent Hol. Foil**	**Clear Textured Glass**	**Polycarbonate**
Characteristic evaluation		2	5	4
Point cloud density—raw	Average	10,938	24,033	44,346
	Coefficient of variation [%]	37.25	33.58	18.01
	Measurements below 2200 points/cm^2 [%]	100	100	100

Table 4. *Cont.*

Material		Transparent Hol. Foil	Clear Textured Glass	Polycarbonate
Point cloud density—1st treatment	Average	98,845	123,292	228,581
	Coefficient of variation [%]	20.01	19.32	10.86
	Measurements below 2200 points/cm^2 [%]	100	100	60
Point cloud density—2nd treatment	Average	246,622	245,488	307,285
	Coefficient of variation [%]	13.61	9.05	2.61
	Measurements below 2200 points/cm^2 [%]	40	20	0

5. Discussion

The applicability of the 3D structured-light scanner to different types of cultural heritage has been proven in many studies. G. Pavlidis et al. [41] and D. Rieke-Zapp et al. [42] describe methods of digitizing important cultural heritage. F. Diara [43], S. P. McPherron et al. [44] and R. H. van der Marwe [45] deal with the digitization of archaeological finds using a 3D structured-light scanner. J. Montusiewicz et al. [46] used a structured-light 3D scanner to create a digital model of exposed historical clothing. J. Kesik et al. [47] describes structured-light 3D scanning of heritage objects in a museum environment. Also, our own research [11] was focused on the creation of a digital model of Adalbert Stifter's monuments using structured light. The mentioned studies have been solving the point cloud quality issue in various ways. R. H. van der Merwe [45], J. Montusiewicz et al. [46], and J. Kesik et al. [47] modify some parts of the digital model using software. F. Diara [43] changes the lighting conditions for scanning. S. P. McPherron et al. [44] do not need such high precision (hundredths of a millimeter). D. Rieke-Zapp et al. [42] use a bleaching spray.

This article focuses on evaluating the effect of surface properties of the selected materials on the density of the point cloud. The density of the point cloud is an important indicator of the quality of the point cloud, but the quality is also affected by other phenomena, such as holes in the point cloud, point noise (especially horizontal), or the distribution of points in the measured area (some parts may have very densely located points and others very sparsely located points). Research has shown certain repeating elements in certain types of material surfaces or their deformations.

5.1. Surface Treatment Evaluation

It can be said that the first and second modifications were important because their application resulted in a significant increase in the density of the point cloud in all cases. The coefficient of variation after the application of surface treatments has always decreased. From the measurement results and the essence of the coefficient of variation, it follows that the lowest possible value of the coefficient of variation is desirable, because it indicates a lower dispersion of the data values compared to the average [36]. We can also notice that some materials, even after applications of surface treatments, despite a sufficient average value of point cloud density, have not reached the required point cloud density in all particular measurements. These include sheet metal and transparent materials, except polycarbonate. It would be more appropriate to re-measure these materials with various modifications to obtain more data and information about what could cause the differences in particular measurements.

The reason for the differences in the results may have more aspects. These can be manual cropping of the point cloud in the measured area (10 cm × 10 cm square) from the scanned surroundings, or the 3D scanner catching different points every time it scans. Another aspect can be the time for which scanning activity of each sample was performed. This time may slightly differ for each measurement. These aspects may result in a different number of points in each particular scan. For these reasons, the scanning was performed five times to solve possible deviations and measurement errors.

5.2. Point Cloud Density and Deformation

Some of the materials seemed to have a problematic surface. However, point clouds with a relatively high density were obtained without surface treatments. Granite contains pieces of shiny minerals. Nevertheless, we achieved a value of 101,012 points in the scanned area. Furthermore, woven carpet is a material with very fine elements, for which we assume problematic scanning and, therefore, also a very low density of the cloud of points, but this was not confirmed. For this material, we achieved relatively high average values of 169,861 points in the scanned area.

However, we cannot take into account only the numerical data, but must also consider the less significant variability of the points that we can see on the specific results and the results of individual point clouds, which is described in the results section. For example, granite achieved a relatively high point cloud density, but the resulting deformations and the absence of points in some parts did not allow the creation of a model corresponding to reality.

5.3. Horizontal Lines in the Point Cloud

An interesting phenomenon is the formation of horizontal lines in the cloud of points, especially for materials that contain a very smooth surface. This phenomenon affects the resulting 3D model but does not affect its accuracy due to the density of point clouds. Since the scanner did not move in any direction during the measurement and there were always horizontal lines, it can be assumed that this is the effect of the projected light pattern, which has the same arrangement. There was no deformation or displacement of this pattern on a flat surface when sensing its reflection back into the instrument. Unfortunately, with this category of materials, it was not possible to eliminate the influence of horizontal lines. This phenomenon was visible in the following samples: glazed roof tile, full burnt brick, wooden parquets, marlstone, sheet metal, and polycarbonate. However, it did not harm the results.

5.4. Applicability of Surface Treatments in Practice

The price of 150 mL of chalk spray is around EUR 6 [48]. The price of 200 mL of dry shampoo is around EUR 4 [49]. The prices are indicative and obtained as of 2 January 2024 in the Czech Republic and, in comparison with the costs of the whole data acquisition process of a building, can be considered as negligible. When creating a digital model of an existing object/building, the required accuracy must be specified in advance. Usually, high precision is required for important elements, such as reliefs, casement windows, etc. These elements are usually parts of historic buildings.

We have been removing dry shampoo via rinsing using water in the experiments. We have been removing chalk spray using a damp cloth in the experiments. The influence of the suggested surface treatments on objects and/or materials is not known.

The influence of suggested surface treatments on objects and/or materials is not the subject of this article. This is the main disadvantage of this study. A study of these influences fits to the fields of material science, chemistry, and heritage. The authors are not experts in these fields. For these reasons, each particular surface treatment application must be carefully considered and consulted with experts in these fields before the application to avoid object deterioration and/or material deterioration.

Another disadvantage of the suggested treatments is the impossibility of modifying the entire surface of the building in this way.

6. Conclusions

To investigate the influence of material properties on point cloud density, a total of 12 different materials were selected, whose samples were first scanned without any modifications. For some materials, additional scanning was carried out with a material surface treatment that could eliminate the influence of their negative properties on the density of the point cloud. The measured values of the point cloud density and the arrangement of the points, density changes in the sample, and noise were monitored.

From our own experience working with the creation of digital models [2,11,32] from point clouds, we know that a very accurate 3D model can usually be semi-automatically created at a density of a point cloud of 2200 points/cm^2. For this reason, we have scanned each material to find out if the point cloud density reaches this limit. For those materials where scans have not reached the desired point cloud density, we have used a surface treatment to increase the point cloud density.

6.1. RQ1: To What Extent Is the Density of the Point Cloud Predictable during Building Object Reconnaissance?

In Figure 5, it is possible to see the results of scanning individual materials. On the basis of the properties of these materials, the materials were divided into the following four groups: well-scannable materials, materials with very fine elements, glossy materials, and transparent materials. Before scanning, each material was scored 1–10 points according to visible properties. The results show us that these visible properties according to the point scale are not always directly proportional to the density of the obtained point cloud. Clear textured glass has five points and polycarbonate has four points, which are very close values. However, their point clouds have completely different results, with raw surface values 24,033 and 44,346 points in area and 123,292 and 228,581 points in area after the first surface treatment, respectively. For other materials, the point evaluation corresponds to the obtained point cloud results. The results show that surface properties can significantly affect the point cloud density, but an estimation of the point cloud density based on the visible properties of the material only may be misleading in some cases.

6.2. RQ2: How Can the Material Surface Be Easily Treated for Higher Point Cloud Density?

Materials classified as having very fine elements, glossy materials, and transparent materials had to be treated to achieve the required point cloud density values in the sample area. However, according to the results, we can say that the treatments made to eliminate undesirable properties had a positive effect on the average value of the point cloud density relative to the sample area.

The solution for glossy materials could be to decrease their reflectivity. The solution for transparent materials could be to decrease their transparency. For the experiments, we used chalk spray and dry shampoo to achieve this.

For materials containing very fine elements, the solution could be to make the surface more compact. Although the reed did not successfully reach the required threshold in any measurement, the density of the point cloud improved significantly. This finding could be helpful, for example, in human hair [32].

Since the reed could not be adjusted as easily as the fabric, it was at least supported by board material—planks. As a result, the gaps between the individual stalks have become smaller and the surface more uniform and compact. Although it was not possible to scan the entire surface, even such a surface treatment proved to be effective and was able to increase the total average density of a point cloud from 75,709 to 119,204 points per sample area, which is about a 50% increase.

The surface treatments were used to improve the scannability of materials. It can be expected that the application of suggested surface treatments is not suitable for all objects and/or materials. It needs to be taken into consideration whether intended treatment may harm the object and/or material, and/or cause permanent damage to the object and/or material. The influence of the suggested surface treatments on scanned objects and/or materials is not the subject of this article. Each intended case of using the suggested surface treatments needs to be considered individually to avoid object deterioration and/or material deterioration, as is stated in Applicability of Surface Treatments in Practice subsection of Section 5.

6.3. RQ3: Can the Data Acquisition Process Be More Efficient with the Knowledge of the Appropriate Surface Treatment?

Overall, the results show that material properties can have a demonstrably large effect on the density of the point cloud, with the presence of fine elements and transparency having the greatest effect. To a lesser extent, gloss also affected it. It was also shown that the treatments made had a positive effect on the measurement results in all cases and in some cases enabled the complete scanning of materials. The measurement results also show that even materials that are adjacent to each other could interact with each other.

The results of the research show for which materials it is suitable to use structured-light 3D scanning measurement under the given requirements for the density of a point cloud intended for the creation of a digital model of building object. In practice, this means that during reconnaissance before the measurement itself, it is possible to estimate, based on these results, if the structured-light measurement method is suitable for particular parts of the measured object according to the type of its surface material.

From the results, it can be expected that the knowledge gained from this research can speed up the process of passporting existing buildings.

6.4. Open Problems for Future Work

Conclusions regarding the formulated research questions were presented in the previous Sections 6.1–6.3, but there are still open problems left.

The first issue is the presence of a formation of horizontal lines in the cloud of points, especially for materials that have a very smooth surface. It is possible that this phenomenon could be eliminated by using another 3D scanner, most likely a laser one. This will need to be verified in the next continuation of the research.

Second, the article suggests the treatments of various material surfaces, but the influence of the suggested surface treatments on objects and/or materials is not the subject of this article. The influence of suggested surface treatments on objects and/or materials was not investigated. In real-world applications, it needs to be taken into consideration if the intended treatment may harm the object and/or material, and/or cause permanent damage to the object and/or material. This should be the subject of future research. We expect that the influence of suggested treatments on building objects may not be negligible, for example, for some building objects of high value (e.g., historical value, etc.).

Finally, RQ3 has dealt with the question of the efficiency of a data acquisition process. Based on the results, we can expect that the knowledge gained from this research can speed up the process of passporting existing buildings, but the measurement of such a data acquisition process is another topic for future research. Knowledge of the time requirements for the whole data acquisition process can be very useful for practitioners, especially for the purpose of cost estimation.

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Příloha č.2 – publikace A2:

3D scanning and analysis of acquired data of historically and culturally significant objects referring to the work of Adalbert Stifter

Martin Dědič[1,*]

[1]Faculty of Technology, The Institute of Technology and Business, Okružní 517/10, 370 01 České Budějovice, Czech Republic

Abstract. The aim of the paper is to bring new findings from ongoing specific university research. Within this project, the light scanner scanned historically and culturally significant objects referring to the work of Czech-Austrian writer Adalbert Stifter in South Bohemia and Lower Austria. It also analyzed the data obtained with the light 3D scanner. The data was generated as a cloud of points. With respect to object´s size, multiple parts of each object were scanned individually. By combining individual scans and removing unwanted points (noise), models - digital twins of objects - were developed. Created models are valuable for their use for virtual tours of historically and culturally significant places. The final models were modified for printing on a 3D printer, where they were subsequently printed.

1 Introduction

Nowadays technology 3D scanning takes an important position in the field of civil engineering. Its application has also role in other fields, including archeology, medicine, film industry, and mechanical engineering. This technology evolves very quickly and provides a number of new options for users. Using a 3D scanner allows to collect object data such as information about its shape, structure, and eventually color. Depending on the way this data is collected, we can divide the scanners into laser scanners and light scanners, which work on the principle of photogrammetry.

3D geometric content acquisition from real world is an essential task for many applications in computer graphics. Unfortunately, even for static scenes, there is no low-priced system, which can provide good quality, high resolution distance information in real time. [1]

In the construction industry, 3D scanning is mostly used for the reconstruction of historic and listed buildings - for this purpose, laser scanners are used, and further in the creation of modern architecture or art. Light scanners are used for creation BIM libraries for specific projects - smaller objects such as sculptures, or for scanning room surfaces. The data thus obtained can serve as a very accurate and detailed basis for the creation of replicas of, for example, sculptural works, that are part of a reconstructed building. At the same

* Corresponding author: dedic@mail.vstecb.cz

time, it is possible to work with the digitized objects in professional software as needed, including the software commonly used by architects and designers. There is the opportunity to transfer any object to their project and visualizations. 3D scanning technology also provides the ability to print scanned object in reduced form using a 3D printer.

Specific university research, which this paper describes, deals with the creation of digital twin of Adalbert Stifter´s memorials. The first scanned monument is the statue of this master in Horní Planá.

2 Basic information about the scanned object

The subject of this research is the analysis of data obtained by scanning important historical objects related to the work of the Czech-Austrian writer, painter and pedagogue Adalbert Stifter and the subsequent use of data for the creation of a digital twin.

Oversized statue embodying Adalbert Stifter was scanned and digitized. The monument (Fig. 1), of which the statue is part, is located in Horní Planá. In this South Bohemian town on the shores of Lipno water reservoir, Adalbert Stifter was born in 1805. His birth house is now used for exposure purposes.

Fig. 1. Monument of Adalbert Stifter in Horní Planá

The monument is located in a park north of the square by the way to the Chapel of Good Water. It was built in 1906. It is placed on a pedestal on which it is possible to climb the stairs. On both sides of it, there are stones placed in the ground. There are two stone blocks on the pedestal. At the first block, the writer's statue is standing on and his name is carved in. The statue with the book in its hand is leaning on the second block and a bronze table with text is placed on it. The statue itself is also cast from bronze and is about two meters high. Since 31 December 1963 is a protected monument.

3 Data acguisition

3.1 Technical equipment

For scanning, Artec Eva Lite 3D light handheld scanner was used to create high-quality and accurate scans without color and texture. This more affordable model is particularly suited for objects that have a rough surface that the scanner is oriented accordingly. It works on the principle of so-called trigonometric triangulation. This means in practice that the scanner projects a light pattern consisting of regular shapes on a scanned object. The scanning sensor is then oriented along the edges of these shapes to derive the shape of the object. The raw model is a cloud of points. Suitable objects for scanning by this scanner are, for example, the human body, so this type of scanner finds use in scanning sculptures, archeological or artwork. Less suitable objects are those that are not sufficiently diversity shaped or with flat (even textured) surfaces.

For this reason, it was decided that the stone blocks, that are part of the statue, will be modeled on the computer. There are not any points that the scanner could capture. If the surface of the scanned object is too uniform and straight, it is easy to interchange the checkpoint for another. This may distort the complete scan. Shiny objects, from which the reflected light will be reflected at a bad angle, aren´t also suitable. However, this problem can be solved by chalk sprays, which can reduce the reflectivity of the surface, and the scanned object is not impaired.

The Artec Eva Lite scanner can be amended by extension enabling to scan color and texture of the selected item. Outdoor equipment includes an external scanner battery that lasts about 5 hours.

The Dell Precision M3800 was used for data processing. It has a touch screen display, quad-core processor, NVIDIA Quadro K1100M graphics card and 8GB operating memory.

The software includes Artec Studio 12 Professional software, which stores individual scans, and in which the data is further processed. The Archicad 21 softtware was used to model the blocks. The individual models were exported in the .stl format, where both 3D objects were then joined together.

3.2 Preparation for scanning

At first, the object needs to be cleaned of all impurities, such as fallen leaves in this case. If it is not possible for some reason to remove some of the impurities manually in physical reality, it could be done with subsequent editing of model on the computer by deleting a portion of the cloud of points that the unwanted element is represented by.

It was also necessary to lay out how the sculpture would be scanned. Scanning can´t be done at one time with respect to such a large object, so it is necessary to determine the parts in which scanning is performed separately. The suggestion was to scan the sculpture progressively from the bottom to the top and separately scanned parts were overlapped in lanes. Mainly buttons on Stifter´s coat were used as capture points. Buttons should be part of most of the scans to make it easier to combine them.

3.3 Scanning

Before scanning, it is necessary to prepare the scanner. He must be connected to an external battery and the notebook to which the data is transferred during scanning. The Artec Studio software must also be running in the notebook. In this program, you need to create a new project that will save all scans. In the left part of the window next to the main menu, there is a scanning setting where we check that the required sensitivity and speed are selected - not always the highest sensitivity and scanning speed leads to the best result.

Now you can start scanning by layout. First, when you press the play button on the scanner, a preview appears on the computer monitor. We set the scanner at the required distance to point to the selected part of the object that was in this case the legs of the statue. Then you can push the "scan" button. In the preview in the notebook, we see the parts that have already been scanned (gray color) and from which data is being collected (green color). The sculpture must not be enlightened by direct sunlight during work. If so, it would have the same effects as if it were made of glossy material. That´s why the statue was shaded by an umbrella during scanning.

All the time, you need to keep the scanner distance from the scanned object. In right side of the monitor, there is the scan settings graph that expresses this distance and varies according to the current situation. The ideal situation is, when the graph is roughly half of it, which is a distance of about 700 mm from object to scanner. If we were outside the graph, it would lose signal, and then the scan could be distorted. In this case, the best solution is to delete the distorted scan and create a new one. Deformation can occur even when scanning overly flat surfaces.

When scanning the statue of Adalbert Stifter in Horní Planá, a total of 28 successful and partially successful scans were created (Fig. 2), from which the final 3D model was created. The problem area was, for example, a book that was flat and thin and had to be scanned from all sides (that is from a side that was close to one of the stone blocks). Another such place was the bottom of the coat and the space between the coat and the boots. This part of the sculpture was poorly accessible, and there were points close to each other that had a large difference in the distance from the scanner, so it was very important to do it very carefully. The access problem was generally with the entire upper part of the statue, which could only be reached with a folding ladder. The last obstacle was the coat that was very straight, so there was often a deformation of the scans being made.

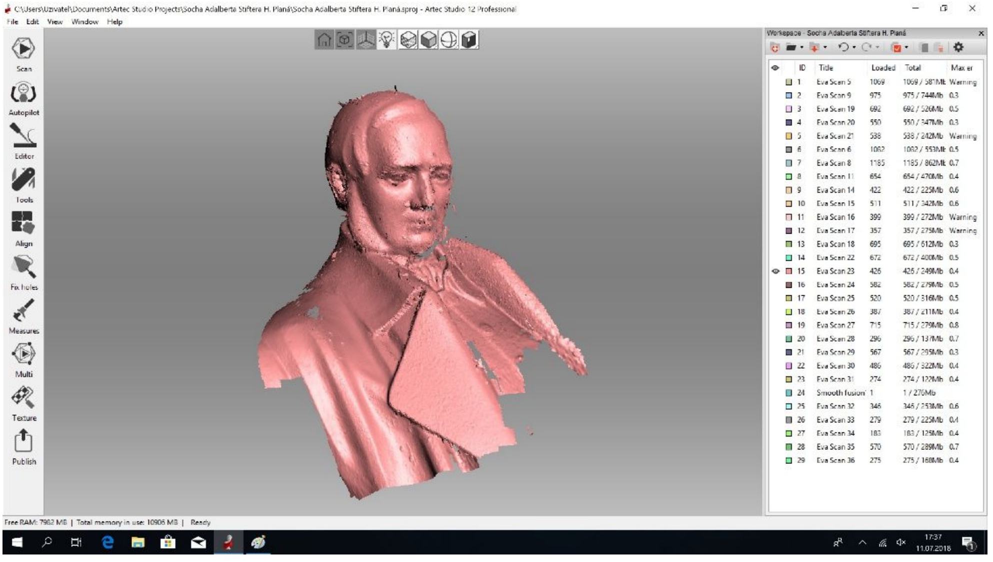

Fig. 2. Scan without modification

3.4 Processing the data

Parts that the software has been able to assign itself were assigned together by function auto-alignment. This was made possible by scanning in the above-mentioned partially overlapping lanes. In this method of cloud point coupling, the method of minimal distance of surfaces in overlapping areas is usually used to determine the transformation key. The algorithm of this method is part of most professional scanning measurement software programs. [3] The guideline is the recurring shapes that make the software orientated and the individual scans together. Some problematic parts have to be assigned manually because the software is not always able to detect where the scan should be moved. Especially if there are parts of smaller dimensions or there are several similar parts on the whole item (eg coats of the same shape, the figure has two very similar boots, etc.). This method is done by selecting at least 6 appropriately selected points, which should overlap after pairing of two scans. A suitable point is a place that is shape different from its surroundings and can be easily found and marked on both scans (in this case, for example, the center of the button, the corner of the book, etc.).

In the next step, all scans can be joined together using the global registration function. To do this, just select this feature and the program can handle the connection without any help from the user. Regarding the scanning accuracy, one of the main problems is the noise.[2] Then it is advisable to remove points that are too deflected from others and delete ambient noise. Both can be done using two more outlier removal software functions and then a small object filter. After all the steps mentioned above, it is necessary to check and eventually to scan the missing parts, which was needed, for example, in the aforementioned problematic sites.

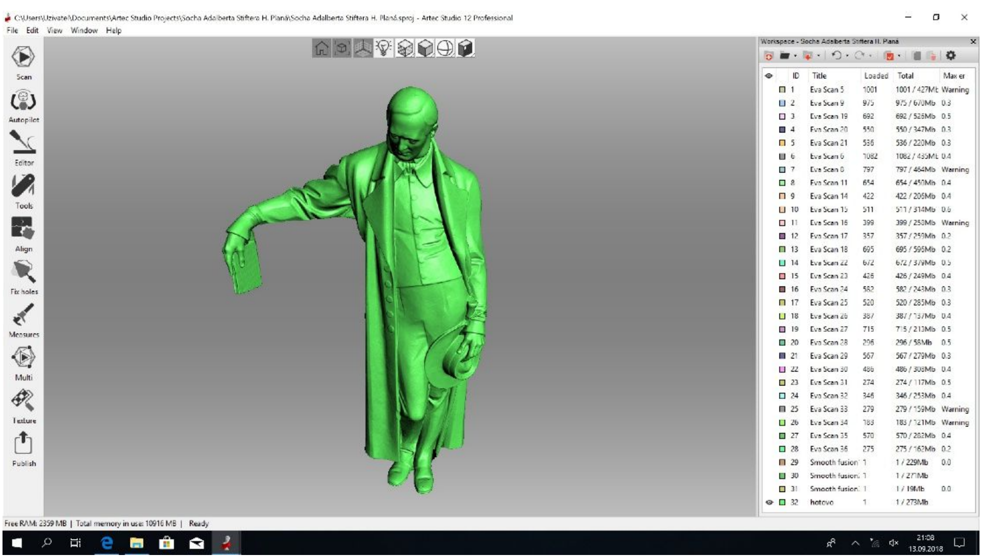

Fig. 3. Final 3D model

Consequently, it is necessary to fuse the merged scans into one and smooth it. We have two features: sharp fusion and smooth fusion. They differ from each other mainly by drawing detail. When selecting the first option, the resulting model will be more detailed, or even smooth with smoothing. In the case of statue of such size, it was sufficient to use smooth fusion. If a part is not drawn in the final model, it is necessary to rewrite it and then edit the new scan (just like the ones previously edited) and join it. Smaller holes can be filled with function hole filling, either all at once or separately. In this way, even larger parts that could not be scanned, both the back and the lower part of the statue, were filled.

The final model Fig. 3 was exported in STL format and connected to stone blocks in Archicad 21 and printed on a 3D printer.

4 Conclusion

Choosing the right scanner and the level of difficulty of processing the acquired data depends on the properties of the particular object. In the case of the Artec Eva Lite light scanner, shape, material and dimensions play an important role. If there are points that are substantially spaced apart from the scanner, it will be very difficult to scan some parts. Such places are depressions or, on the contrary, very protruding and thin areas. The opposite is also the case where there are almost no clues on the subject, which could be artificially created in some cases. The obtained 3D digital data provide a convenient data set, which can be used to quantitatively analyze and calculate the characteristic indices for the natural joint, such as the roughness, magnitude and angularity.[4]

From the point of view of the material, any matte surfaces are suitable. In the case of shiny surface, it can be treated with a chalk spray for the purpose of scanning, which can be easily washed after completion of the work. The sculpted statue of Adalbert Stifter is made of bronze - this is not a suitable material for scanning because of its gloss. The sculpture is already covered with patina because of its age and therefore it was not necessary to use a chalk spray. The final model is in very good condition when no further editing is needed before 3D printing.

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Utilization of Modern Optical Methods for Creation of Digital Model of Human

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Utilization of Modern Optical Methods for Creation of Digital Model of Human

Martin Dědič [1]

[1] Czech Technical University in Prague, Faculty of Civil Engineering, Department of Applied Informatics, 166 29 Praha 6 - Dejvice, Czech Republic

martin.dedic@fsv.cvut.cz

Abstract. The aim of the paper is to describe the methodology of creating a digital model of human using an optical 3D scanner. This methodology consists of several main phases, such as preparing the scan for human movement, scanning in the shortest possible time, and processing the data obtained by scanning. The data processing itself is divided into other sub-phases, which describe the individual steps necessary to create a digital model. The paper describes obstacles that need to be eliminated or minimized during 3D scanning in order not to disrupt the integrity of the model and to create a digital model.

1. Introduction

Currently, modern optical measurement methods can be divided into three groups, optical 3D scanning, laser 3D scanning, digital photogrammetry. In this paper we focus on creating a digital model of human. But the human body cannot be completely immobilized. Even when not moving, one has to breathe, creating movement that reduces the quality of the point cloud obtained. For this reason, it is necessary to choose the method as quickly as possible, with this requirement it is possible to avoid digital photogrammetry, which is time consuming. An important aspect is also the safety of the person being scanned, when scanning with a laser scanner is dangerous for the eyesight. Therefore, the most suitable method is 3D optical scanning, which scans the surface of the scanned object using structured light and does not endanger the health of the person being scanned.

The Artec Eva Lite handheld 3D scanner was used to create highly detailed and accurate scans, which does not scan texture or colors in this version. This optical scanner is suitable for acquiring 3D data of objects up to 3 m in size, such as archaeological artefacts, sculptures or works of art.

2. Related Work

3D scanners are usually used to acquire 3D models, which are usually static. An example can be study[1], which describes process[2,3] of application of 3D scanning and acquired data processing to get model of a building.

There are various purposes of acquisition of 3D data. Usuall purpose is simple visualisation, but there can be also project-spedific purposes. In construction industry acquired 3D data can be used for obtaining[4] and sharing[5] data for building information model or can be used to obtain usefull data for construction projects[6,7]. These data can be defined based on project priorities and scope[8,9].

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Another example of 3D scanning applications is in craniomaxillofacial surgery[10]. It can be expected that importancy of acquisition of 3D models using 3D scanning will be growing with continuous implementation of industry 4.0 principles[11,12].

3. 3D scanning and data processing

For the scanning of living creatures, in our case humans, it is very important to prepare the scan itself. Division of the scanned object into parts, suitable selection of overlays. All of these actions aim to ensure that the actual scanning takes place in the shortest possible time.

For overlapping scans, the best figure for the overall figure is the fuselage area, which is the easiest to scan - there are no protruding parts and the scanner works at a uniform distance. Thus, each individual scan begins in this part of the body and then scans further away from it. During the scanning process, we can monitor the captured dots on the display. The problem areas are hair that is too fine for us to use the optical 3D scanner, and therefore we chose an account that will make hair compact. Another such part is the eyes, which should be closed while scanning the face, although the optical scanner is not dangerous for eyesight. The last element is shiny metal objects such as earrings, piercings or belt buckles, but these items can be put away before scanning.

During scanning, the movement of the person being scanned cannot be detected. We do not reveal these movements until the data is processed. Figure 1 shows the raw data of all scans. There are eleven of them in total and all overlap. In order to eliminate the deviations caused by motion, we chose the reverse procedure of data editing. The classic approach is to combine individual scans into one point cloud before cleaning, smoothing and modeling the point cloud. In our case - human scanning - we first modify the individual scans and then join them one by one.

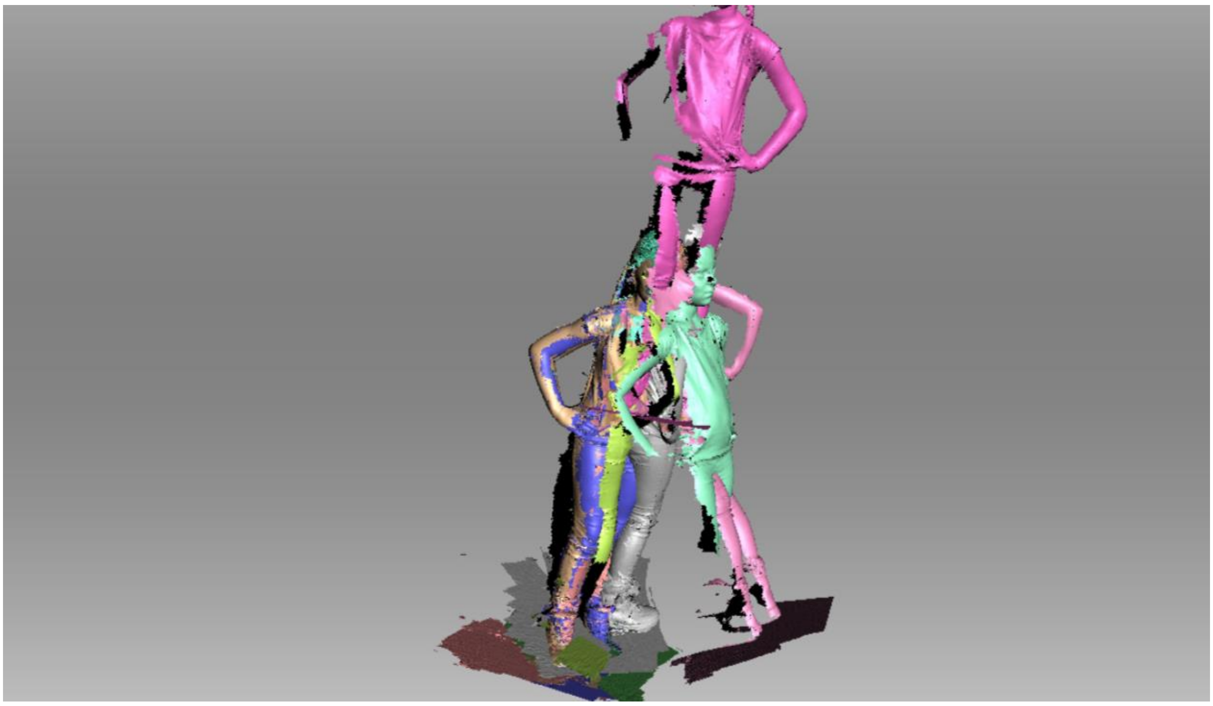

Figure 1. Raw data from optical 3D scanner

The whole process of data editing is demonstrated graphically in Figure 2. All tasks are performed in the software by delivery together with the used 3D Artec Eva Lite optical scanner called Artec studio 11, which allows most tasks to be performed automatically due to the shape difference of the scanned object, in our case mainly due to precise pre-scanning preparation and sufficient overlap of individual scans. In the first phase of data processing, we need to eliminate point noise. These are the points outside the main model that always occur during scanning and need to be removed. This part is fully automatic and is not time consuming. Using an optical scanner does not create too many of these points, unlike a laser scanner.

The second phase of the data processing process is to smooth the scan. Scanning smoothing refers to the unification of the surface of the model into a triangular mesh at our preferred density. At this stage it is already possible to see the form of an almost final virtual model of the part of the object from which the scan originated. This process is fully automatic but the time required increases according to the size of the scan.

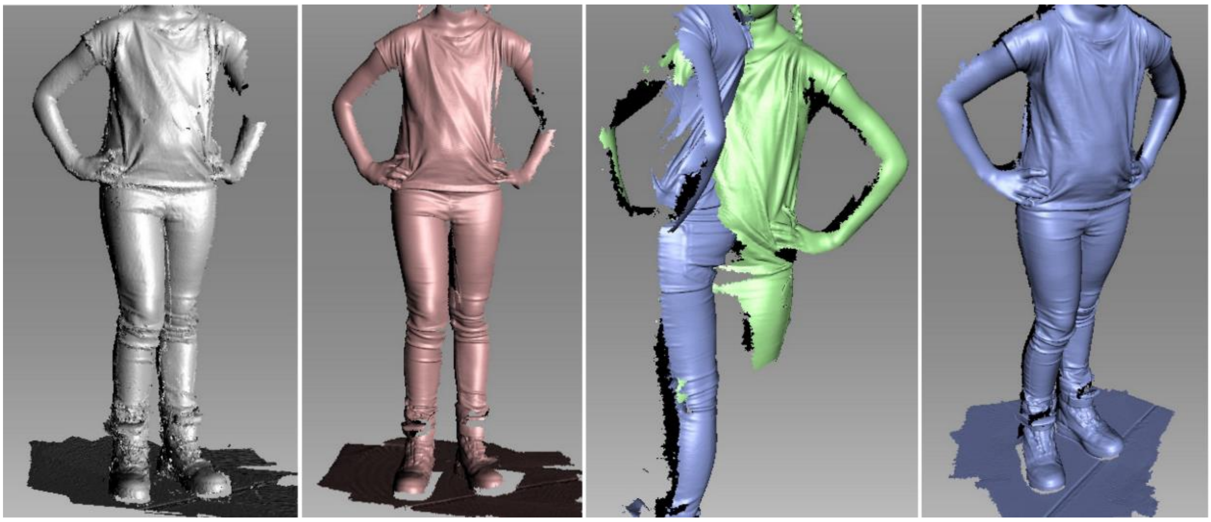

Figure 2. Process of data editing

The next step is to combine individual scans. This part is the most complex in this type of model, in our case man. Joining takes place one scan at a time. Scans need to be carefully selected to build on and to contain areas that need to be replenished. It may happen that the same area in two scans does not correspond positively to each other during scanning. This is caused by the movement of the person being scanned during scanning. Here it is necessary to select the most suitable scan very sensitively and to delete this part from the others in order to avoid duplication in the final scan. This can be seen in Figure 3. These deviations occur most frequently in the hands and feet, as it is impossible to hold them for several minutes, then in the chest area because of the person's breathing and neck area, especially children bending their heads down for a short while in a virtual model it is not easy to attach a head to the body.

The next part is to fill the holes in the model, which can occur for various reasons listed at the beginning of the article. Here again we use the automatic function, by means of which the model is enclosed in one unit. In our case, there were no holes in the model, but we know from experience that this can happen.

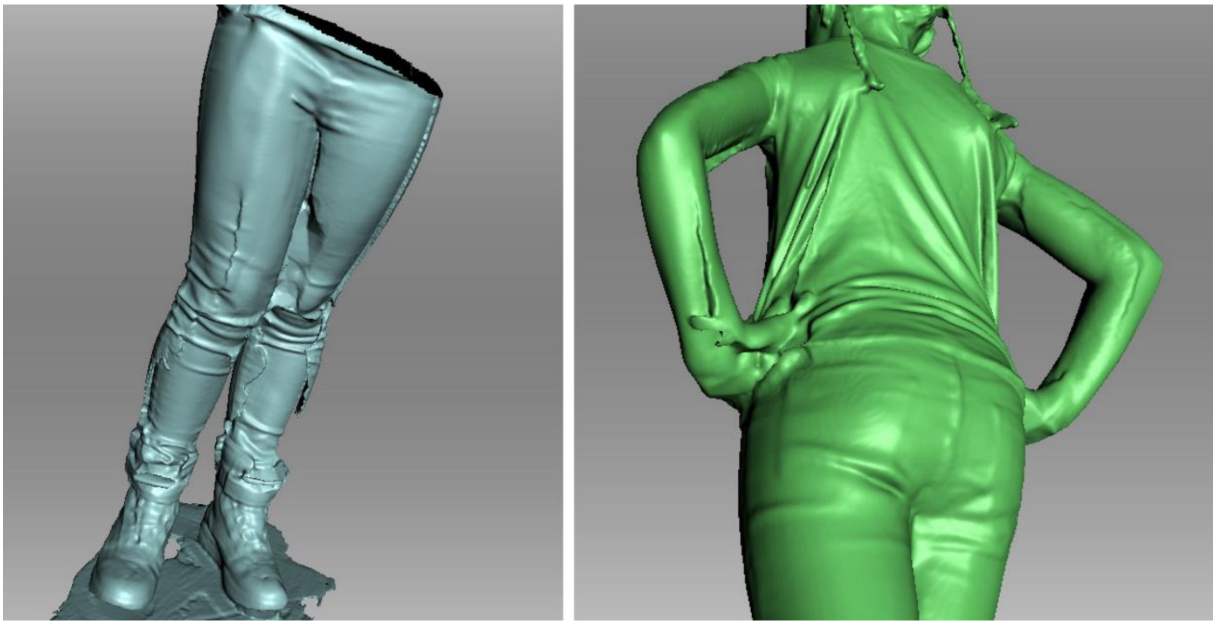

Figure 3. Duplication of scans due to the movement of a person during scanning

All described parts of editing data from 3D scanner were done automatically by software. In the final model, however, there are errors that can be seen in Figure 4 and need to be corrected manually. These are not scanned hair, poor connection of hands or feet. These places tend to be in places where the scanner cannot get high-quality images (armpits, lower chin, etc.). The work is sensitive to the scanned person to make the virtual model as accurate as possible.

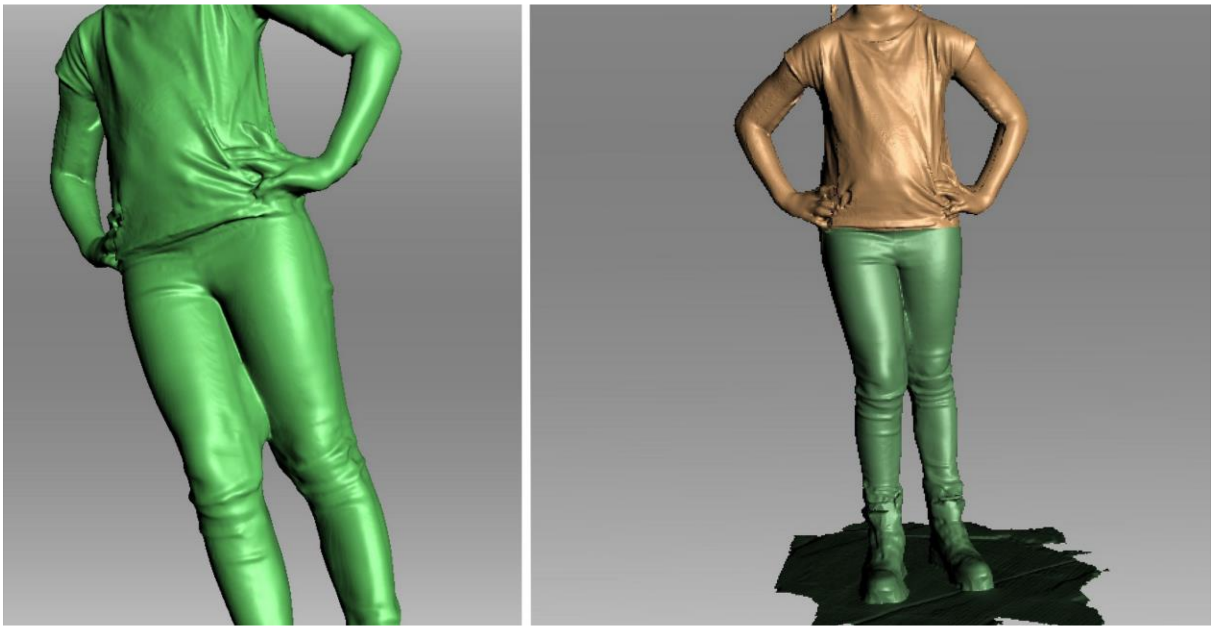

Figure 4. Combining scans from both scanning

In our particular case, we performed the entire scan of the person twice independently of each other. This tactic was chosen intentionally due to the age of the person being scanned and the assumption that they would not stand still throughout the scan. Both scans contained parts that could not be joined precisely because of the movement of the person being scanned. In the first model, there was a doubling of the left arm, which would be very complex to model and we could not guarantee the accuracy of the model. The second model had very damaged legs, which could not be modeled even at the loss of accuracy model. The compromise was to use the highest quality of each model and combine both into one digital twin, which can be seen in Figure 4.

4. Conclusions

Precise recognoscation is even more important when scanning a person than when scanning static objects to reduce the scanning time. Each additional minute increases the risk of the person being scanned and thus decreases the quality or totally degraded data. The process of data editing is the same as when scanning static objects but the individual parts are performed in another order. Instead of the usual combination of scans and then cleaning, smoothing and finishing, the point cloud was first cleaned and smoothed, and then some parts of the selected scans were joined and deleted to make the digital model as accurate as possible and eliminate inaccuracies caused by whether by breathing or balancing. The final step remains to model parts that cannot be scanned perfectly. The resulting model in our case consists of two separate scanning processes, in each of which there was a certain movement, which depreciated the resulting model.

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Digital Model of an Existing Building a Wild Riverbed in Tokyo

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Digital Model of an Existing Building a Wild Riverbed in Tokyo

Martin Dedic [1]

[1] Czech Technical University in Prague, Faculty of Civil Engineering, Department of Applied Informatics, 166 29 Praha 6 - Dejvice, Czech Republic

martin.dedic@fsv.cvut.cz

Abstract. This paper presents an application of photogrammetric methods for so-called image based modelling and rendering. Digital photogrammetry technology was used for the real use of a digital model of an artificial riverbed for a wild river in Tokyo. This technology was applied using two software programs, where we evaluate their compatibility and propose measures that should increase efficiency in the future in the creation of digital models of existing buildings. We describe the process of creating a model in both software separately and evaluate their use for a given type of object. In this paper, we describe the individual processes from the selection of photographs through the cleaning and smoothing of the point cloud to the final model. We present the practical use of the created digital model. In the pictures we show the solved structure, the process of joining individual photographs and the final model for the overall idea of the application of this method. The results and discussions section describes the evaluation of both software and proposals for measures for their use, especially for water structures of a linear nature containing recurring elements such as water barriers.

1. Introduction

Many digital model creation processes [1, 2] focus on projects of new buildings. An Example of an apartment building design process can be found in [3]. Examples of road-building construction processes can be found in [4, 5, 6]. A digital model of new building provides detailed information, which is very useful through the whole building lifecycle, for the future existence and operation of the building [7, 8].

Currently, there are various methods for creating a digital model of an existing building. At the Department of Engineering Informatics at the Czech Technical University in Prague, we deal with the creation of digital twins of objects with high accuracy. In the previous paper, we described the methods of 3D scanning from pre-scanning preparation through data processing from a 3D scanner to the final digital model of the building.[9] In this paper we will present the application of the photogrammetric method, specifically ground photogrammetry. Of all the optical methods, terrestrial photogrammetry is the least device-intensive (common digital camera) and is therefore the cheapest optical method for obtaining digital data.

It can be expected that importance of the acquisition of 3D models of existing buildings will be growing with continuous implementation of industry 4.0 principles [10] and a necessity to acquire data in BIM formats such as IFC [11]. BIM models of buildings and their accuracy will help not only to reduce failures rate in the building project, time and financial savings during construction, but especially in the operation of the building through its whole lifecycle [12].

2. Digital model creation process

The aim of our research, set based on priorities and scope [13], was to find easy to use and inexpensive technology for the construction of a wild riverbed in Tokyo Olympic in Figure 1. The reason for creating the digital model was disputes over the placement of obstacles on the race track. Water barriers affect the flow of water and thus the difficulty and safety of the plant itself. Obstacles can be moved by rails and moved by their height using additional parts. During the construction design, a race track was designed, including water obstacles, by experts from the Czech Technical University, but the organizers of the Olympic Games arbitrarily changed some obstacles. It was necessary to compare both variants using digital simulation.

A Canon EOS 250D digital camera with a resolution of 24.1 Mpx and an 18-55 mm lens was used to take photographs. A total of 1800 photos were taken. The images were divided into groups according to individual parts of the wild riverbed into 3 parts (starting part, middle part, finish part). In the target part there was a water surface, which we evaluated as potentially problematic in terms of high surface reflectivity. After dividing and deleting the photos, there were 1200 left for the possibility of creating a digital model.

Figure 1. General view of the construction of an artificial riverbed for a wild river in Tokyo.

At the Department of Engineering Informatics, we had software in two options available for image processing using photogrammetric methods. In the first case, we created a digital model using Autodesk Recap Photo software. This software allows you to upload a maximum of 200 photos at a time. For this reason, the photos were divided from the original three into six groups. We divided each part into the right and left bank of the riverbed. The individual parts of the model were of good quality after processing the photographs, but the part of the target part of the riverbed, where the water was located, was not drawn correctly. Before connecting the individual parts, it was necessary to clean the point clouds from digital noise, using the automatic function and manual cleaning. Furthermore, the individual parts were smoothed to make the connection as simple as possible. Puncture points were not used during the photo shoot and therefore it was not possible to combine the individual generated parts of the digital model into one whole. We had to use manual connection using the points we specified, which were always in both connected parts. The character of the building - an artificial riverbed for racing on a wild river - did not allow manual connection of all parts, because it is a line building with constantly recurring water obstacles. It was not possible to distinguish which obstacle is located in which part of the racing riverbed. We consider this attempt to create a digital twin to be unsuccessful.

The second software we have is Reality Capture, which also allows automatic processing of images into a digital model. For the first attempt, we divided the photos into two groups according to which part of the riverbed was the water surface. A total of 1200 (900 + 300) photographs were used. The first group was without water surface, the second with water surface. The water surface was located in the finish part of the riverbed. After generating both parts of the model, process you can see in Figure 2, we had to clear the data of data noise and combine both parts into one final model. Although both parts were processed in sufficient quality, it was not possible to combine them purely into one whole. In the part of the riverbed where the water level began, there were different lighting conditions during the rental of the pictures. Due to this, it was not possible to combine the model into one whole.

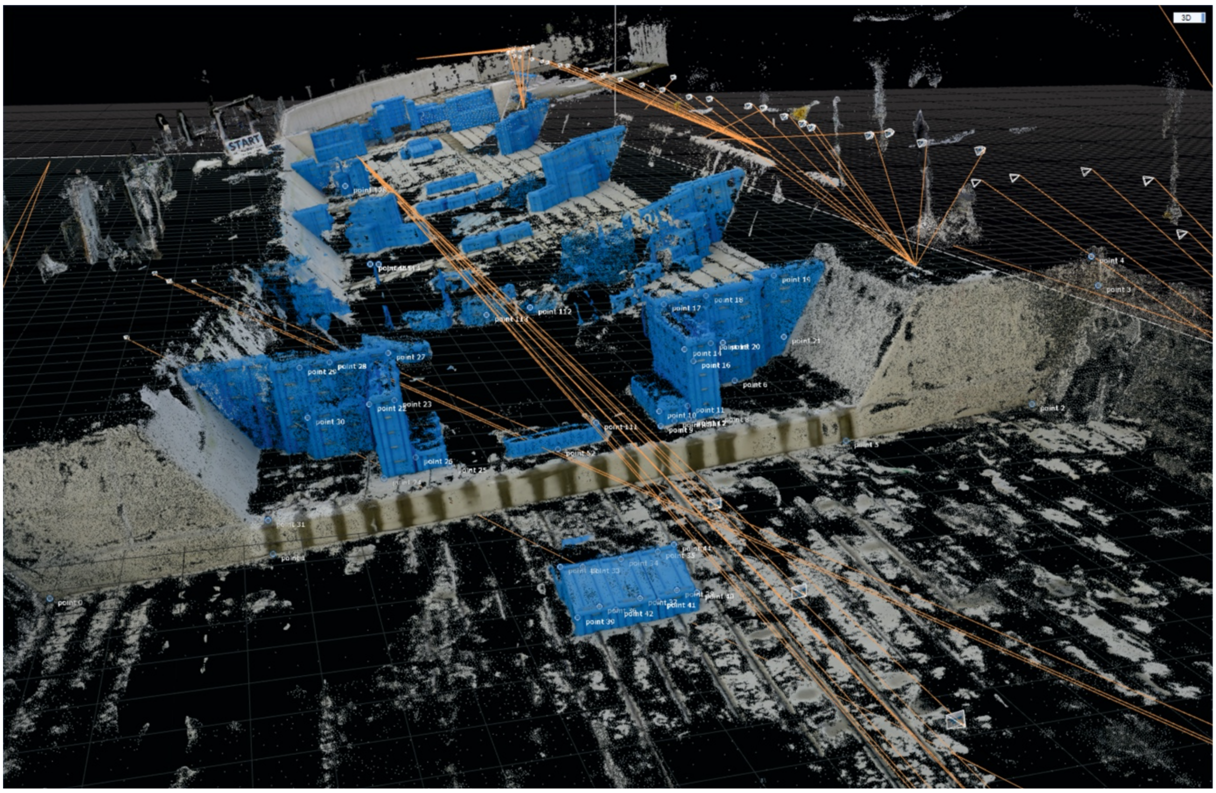

Figure 2. The process of creating a point cloud in Reality Capture software.

The quality of the digital model in the second software was sufficient to simulate the flow of water. We had to change the technique of creating a model so that we would create only one model without having to connect to another part. So we uploaded to software 200 photos from the right bank of the starting and middle part of the race track. After a thorough inspection of the generated model, we gradually uploaded more images of the right bank of the finish part, which contained the water surface. This technique didn´t work, so we took photos with a water surface again and chose photos from the left bank of the starting and middle part of the riverbed. This part of the model was processed correctly on the first attempt. Other photos - those that contained the water surface, we added manually with the exact designation, always 3-4 points identical to the points that contained the already created part of the model as well as the inserted photo. This process you can see in Figure 3. Because the water surface was also the first part of the riverbed, especially in the places of obstacles that retained water, it was necessary to use this technique in these places. This process has worked well. The point cloud was complete. Furthermore, the data had to be manually cleaned of digital noise and then smoothed using the automatic function.

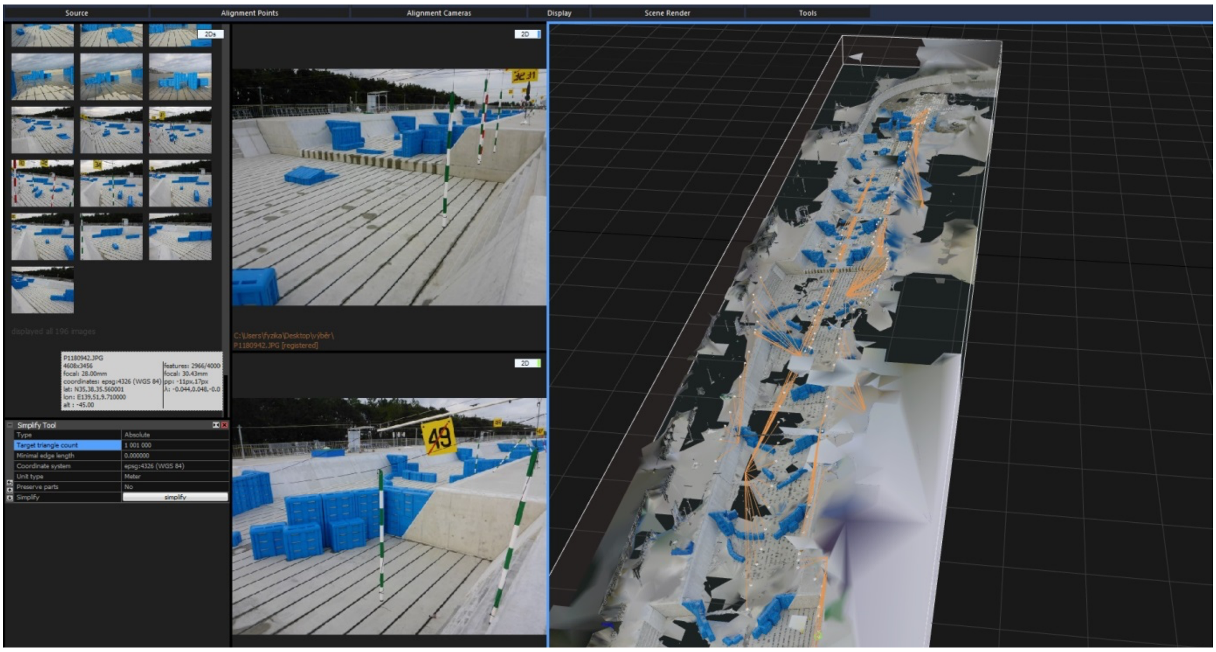

Figure 3. The process of sequentially uploading photos.

3. Results and discussions

The final model in Figure 4 consists of only 800 of the 1800 photos taken. From the experience of other projects focused on the creation of digital twins using digital photogrammetry, we know that appropriate preparation before the actual shooting is the most important aspect of the whole process. It is necessary to precisely plan the process of taking photographs, especially for larger or linear constructions. Furthermore, the setting of the camera angle, focal length and, last but not least, lighting conditions. Outdoor photography is unpredictable, but that is why it is necessary to carefully plan the photography so that the shortest possible time runs so that the lighting conditions do not change much during the photo shoot. In this particular case, it would be possible to use aerial photogrammetry using a drone, which we unfortunately didn´t have at the time of the photo shoot.

There are more software that supports digital photogrammetry, but each works a little differently, so you need to take photos according to the capabilities of the software used. The last thing that would be good to use are puncture points, which would make it easier to connect the model. Especially for objects that have a large number of the same or very similar parts such as flat surfaces or repeating masses (in our example, water barriers).

Figure 4. Finished digital model in Reality Capture software.

4. Conclusions

From the presented results it can be said that both software can be used for the creation of digital models. The accuracy of the model is the same but if the model contains glossy surfaces the Reality Capture software is significantly better. In addition, this software is more suitable for large objects that need more than 200 photos, which is the maximum possible number per upload in Autodesk Recap Photo software. For example, a lower number of photographs is sufficient for a digital model of a sculpture, but for larger objects such as buildings, the number of photographs is usually in the hundreds. Both software are suitable for editing the point cloud and then exporting the data.

The price for digital photogrammetry, as opposed to 3D scanning, is mainly supported by the price, when the price of the equipment needed to take photographs is significantly lower than the purchase price of a 3D scanner. Furthermore, the evaluation of data is largely automatic - certainly in the example we selected, it was necessary to connect part of the model manually, but only because it was a very demanding object.

Digital photogrammetry can be used as well as 3D scanners in construction. In particular, linear and tall buildings will be possible to better and more accurately model using aerial photogrammetry, especially today, when drones are becoming more available. The future is a combination of both of these methods. The digital model created in this way can serve as a basis for a building information model (BIM).

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RESEARCH ARTICLE | SEPTEMBER 27 2023

Acquisition and analysis of data of a historically significant building using digital photogrammetry

Martin Dědič

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Acquisition and Analysis of Data of a Historically Significant Building Using Digital Photogrammetry

Martin Dědič[1, a)]

[1] *Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7/2077, 166 29, Prague, Czech Republic*

[a)] Corresponding author: martin.dedic@fsv.cvut.cz

Abstract. The aim of the paper is to bring new knowledge from ongoing specific university research. As part of this project, optical data collect locally and historically significant states of the chapel in Horní Nivy were collected using aerial and ground digital photogrammetry. The obtained data are subsequently analyzed for the needs of creating a virtual model. Data are generated from individual photographs as a point cloud. With regard to the parameters of the object, the data are captured partly from the ground using a camera and partly from the air using a camera mounted on a drone. By combining the exterior and interior model and removing unwanted points (noise), a model - a digital twin building - ai develop. The created model serves as a basis for the processing of construction technical and construction historical research.

INTRODUCTION

Digital 3D technologies already have a strong place in construction. [1,2] The use of digital modeling processes can be demonstrated in projects of new buildings [3], transport constructions [4,5], technological constructions [6] but also in existing buildings. Digital models can be supplemented with information according to the requirements of the client [7] that defines priority of requirements and project scope [8]. Such models are called building information models, which are, especially if stored according open standards as IFC [9], useful as a source of data for information systems [10] for maintaining buildings throughout their life cycle. [11,12] A special chapter is the existing buildings, which are historically significant and often protected as monuments. Existing buildings cannot be digitized by a routine data acquisition process, but a very detailed reconnaissance of the scanned object is needed so that the obtained data of individual important elements has sufficient quality in the required detail.

The chapel in Horní Nivy, located in the Karlovy Vary Region in the Czech Republic, was chosen as the research facility. The mentioned chapel is the oldest building in this village and at first glance shows construction defects that need to be documented with high accuracy. It also contains several original significant elements. The digital model will serve as a basis for construction engineering and construction history research.

Various data acquisition methods can be used to digitize existing buildings. These are laser 3D scanning, optical 3D scanning or ground or aeronautical digital photogrammetry. The use of individual methods was written in [13]. The construction of the chapel in Horní Nivy, which we have solved, will be scanned by ground and aerial photogrammetry using professional software suitable for processing a large number of photographs and creating a digital model.

DIGITAL MODEL CREATION METHOD

The aim of the research is to develop a digital twin of historically significant building using ground and aerial photogrammetry. The reason for the elaboration of the digital model is the construction technical and construction historical survey. The construction of the chapel in Horní Nivy (figure 1) contains building defects, as well as valuable

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building elements. It is the oldest building in the village, and therefore it was necessary to pay special attention to these parts of the building when collecting data.

The Canon EOS 250D digital camera with a resolution of 24.1 Mpx and an 18-55 mm lens is used for ground photography. The DJI Mavic mini drone with a 1 / 2.3 "CMOS camera with a resolution of 12 Mpx is used for aerial photography. A total of 421 images from the drone and 137 images from the camera (table 1) are used, which are divided into 2 parts - interior and exterior. image processing used professional Reality Capture software [https://www.capturingreality.com/], which can semi-automatically generate a digital model from sorted images.

FIGURE 1. The main view of the chapel in Horní Nivy

The first stage of creating a digital model of a historically significant building is a detailed reconnaissance. By inspecting the nearest surroundings, the possibility of a route for a possible drone flight is evaluated in order to comply with aviation regulations and to avoid a collision with trees in the vicinity of the building. This is followed by a tour of the exterior of the building and the identification of valuable elements by an employee of the National Monuments Institute. Specifically, it is an inscription above the front door and a cross on the roof of the entrance to the chapel. In the interior, the statue of the Virgin Mary on the altar and paintings depicting the crucifixion of Jesus Christ, which do not need to be included in the digital model, are marked as valuable elements. Another requirement is the recording of construction failures, especially cracks and humidity maps on the walls for the needs of construction and technical survey of the building. Now all that remains is to find suitable places for the puncture points [13], which connect the exterior and interior models of the chapel. Both windows, the floor at the front door and the skylight of the front door are chosen as suitable places. All these places are well visible from interior and exterior.

The interior is photographed from different height levels in segments formed by wooden benches in the chapel. Altitude levels are chosen according to the width of the shot, the requirement for image overlap 70-80%. Height stability for all segments is fixed on the tripod. It is a height of 1.0 m; 1.6 m and 2.2 m and the angle of the camera against the plane of the wall is fixed at 15°. This process is repeated at all heights in each segment. The remaining segment is formed by the altar, which is in space. The altar is photographed separately later. From a height of 2.2 m, the ceiling vaults are again photographed, again with a fixed inclination of 15°. A total of 353 images were taken in this part of the stage.

After capturing the total volume of the interior of the building, the focus is on details such as the altar, prayer benches, wooden windows, entrance doors, and especially on the statue of the Virgin Mary located on the altar. These elements need to be captured with a larger number of images so that they are in sufficient detail in the resulting digital model to allow them to be refurbished or restored. Thus, height is not important for shooting, as these images only densify the network of images already taken, but the shooting angle of 15°, which remains constant throughout the shooting time. The statue of the Virgin Mary is not part of the building, but it is the most valuable element of the interior, here the procedure is different from the previous elements. There is no need to keep the camera angle of the sculpture constant to its plane throughout the shooting. The statue does not have one plane, so the angle is always different. Sufficient image overlap is essential, which is at least 90% between individual images. This ensures sufficiently detailed data for the subsequent processing of the digital model, and with the help of several overall photographs, the altar and the statue can be combined into one model with the interior of the chapel. A total of 72 images were taken in this part of the stage.

During reconnaissance, the flight levels related to the chapel building are determined. They are implemented in real height drone using height measurement. This is the height level from the real terrain at the entrance to the chapel 2.5 m, 4.0 m and 5.5 m for the main part of the building, and in addition the height levels 6.5 m and 8.0 m for the bell tower. The tilt angle of the drone camera is 15° from the plane of the chapel downwards. In the individual flight levels, the chapel is surrounded at the same distance, as shown in Figure 2. The cross on the roof and the inscription above the main entrance are photographed separately due to their greater detail. A total of 160 images are taken in this part of the stage.

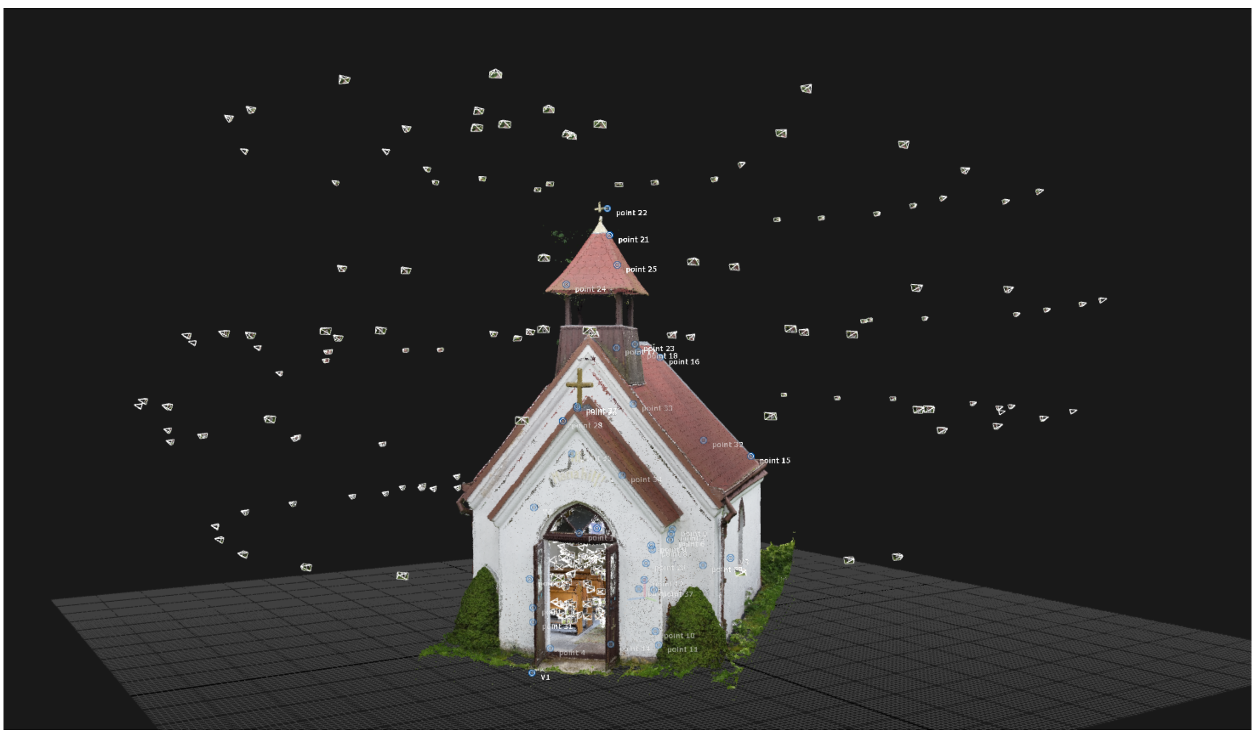

FIGURE 2. Marking the positions of images from the drone

The last phase of data collection is the camera's capture of the under-drip ledge, as the camera on the drone cannot be tilted upwards. Due to the large height, it is not possible to maintain a slope of 15° here, but it is necessary to adjust it to 35° upwards. A total of 28 images were taken in this part of the stage.

TABLE 1. An overview of images taken and used.

Images Taken by	Number of Images Taken	Number of Images Used	Number of Images combined into the model
Drone	160	137	133
Camera	453	421	418
Total	**613**	**558**	**551**

The second stage is the processing of the acquired images. Professional Reality Capture software is used, which processes the model on an external cloud and, therefore, unlike other software, does not require above-standard performance requirements for individual computer components. The captured images need to be divided into three parts - exterior, interior and valuable elements. Further sort out blurred images, as well as those that show a difference from most images, such as significantly different lighting conditions, the shadow of one of the devices used, or images that show a colleague who entered the camera.

There are two options to create a digital model. The first option is to assemble the interior of the building separately and the exterior separately, and then join them together by manually placed fitting points. The second option is to compose the whole model at once by gradually adding groups of images.

FIGURE 3. Point cloud interior of the chapel

The second option is chosen due to the maximum use of automatic software functions. Groups of images of the interior of the building are uploaded to the software and a model is generated (Figure 3). The used fitting points can already be seen in the digital interior model (figure 3 - left of the lower pane of glass in the window on the right side of the figure). Each of the four points is marked in the model for software to recognize. Next, groups of images containing an insertion point from the exterior are added and a newly generated part of the digital model is checked. The procedure is repeated for all four fitting points. To complete the digital model, images of valuable elements remain to be uploaded. This creates a high-quality point cloud with an increased density of points in places of valuable elements.

The third stage is the conversion of cloud points to mesh. This step is automatic, the only specialty is the generation of a separate mesh for the statue of the Blessed Virgin Mary, which was requested by the National Monuments Institute of the Czech Republic. The final digital twin can be viewed in a classic 3D viewer and at the same time the distances of cracks in the masonry or humidity maps can be measured very accurately. It will thus be preserved for a possible virtual tour, and at the same time it serves as a basis for building historical and building technical research.

DISCUSSIONS

It should be emphasized that even though the software generates the model from the images automatically, the main part of the work - data acquisition - remains manual work. In the future, it is possible to use a 3D scanner such as Leica BLK360 for interior images and manually scan only valuable parts. The exterior can be photographed automatically by entering the coordinates of individual images into the drone, but this is not possible in this case due to the close location of tall trees.

This project demonstrated the thesis that the most important part of creating a virtual model using digital photogrammetry is initial reconnaissance. If the basic parameters of the construction are known, the location of the fitting points, the progress of the images, their location, the angle of inclination to the plane of the construction, the distance and the lighting conditions can be arranged. For the exterior of the building, the surroundings of the building can be evaluated and the correct scanning method, height levels and scanning angle can be selected. For the safety of drone flight, it is necessary to know the weather forecast and evaluate the most suitable time of day in terms of lighting conditions.

CONCLUSION

In the described process of ground and air digital photogrammetry focused on a historically significant building, reconnaissance, data collection and analysis, including the creation of a digital twin, are described. The individual stages are described in detail so that the process can be repeated and thus verified. Digital photogrammetry is an integral part of the creation of digital models in construction, and thanks to the expansion of drone capabilities, it is increasingly applied especially in line constructions. Digitization of a historic building with an emphasis on valuable elements is one of the most demanding processes. Digital photogrammetry allows the user to focus on certain parts of the building more, thus increasing the density of the point cloud. In the future, it seems to be the optimal combination of digital photogrammetry for valuable building elements and a 3D scanner for the main premises of the building.

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