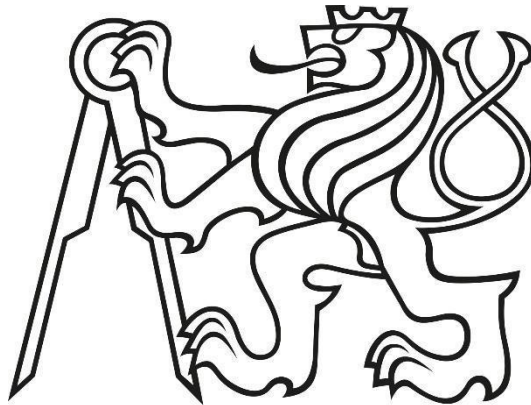


CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF CIVIL ENGINEERING

STUDY PROGRAM GEODESY AND CARTOGRAPHY

STUDY FIELD GEOMATICS



MASTER THESIS

DOCUMENTATION OF HISTORICAL OBJECTS USING MODERN
TECHNOLOGIES OF GEOMATICS

Thesis supervisor: prof. Dr. Ing. Karel Pavelka

Department of Geomatics

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce: Dokumentace historických objektů moderními metodami geomatiky

Název diplomové práce anglicky: Documentation of historical objects using modern technologies of geomatics

Pokyny pro vypracování:
Proveďte rešerši literatury na téma dokumentace historických objektů metodami geomatiky, specializujte se na blízkou fotogrammetrii, využití dronů, laserové skenování a mobilní laserové skenování. Zhodnoťte stav dokumentace moderními metodami v Severní Makedonii, soustřeďte se na vhodná naleziště a památkové objekty. Vyberte vhodný objekt v Severní Makedonii a proveďte dokumentaci dostupnými metodami. Vytvořte 3D model a najděte vhodný způsob prezentace objektu pomocí prohlížeče 3D modelů, případně dalšími metodami (AR, VR). Zhodnoťte výsledky, proveďte diskusi a formulujte závěry z práce.

Seznam doporučené literatury:
Aber, James & Marzoff, Irene & Ries, Johannes. (2010). Small-format Aerial Photography: Principles, Techniques and Geoscience Applications, Elsevier, ISBN: 9780444532602
Lillesand, T.M.; R.W. Kiefer, and J.W. Chipman (2003). Remote sensing and image interpretation, 5th ed., Wiley. ISBN 0-471-15227-7.
Pavelka, K.; Pavelka, K.; Matoušková, E.; Smolík, T.
Earthen Jewish Architecture of Southern Morocco: Documentation of Unfired Brick Synagogues and Mellahs in the Drâa-Tafilalet Region, Applied Sciences. 2021, 11(4), 1-25. ISSN 2076-3417.
Pavelka, K.; Hůlková, M.; Šedina, J.; Pavelka, K., RPAS for documentation of Nazca aqueducts European Journal of Remote Sensing. 2019, 52(1), 174-181. ISSN 2279-7254.

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Podpis vedoucího katedry

III. PŘEVZETÍ ZADÁNÍ

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ABSTRACT

This thesis presents the usage and integration of modern geomatics technologies to capture and process data of the church of St. Panteleimon, located near Skopje, Macedonia. It is devoted to preparing extended digital documentation in the form of two and three-dimensional outputs that can be used to facilitate further recording management of the building. The first part of the thesis provides background information, including a review of existing literature and an introduction to the study area. It is followed by a presentation of the used geomatics methods and data capturing and processing technologies and their advantages, as well as the benefits of using them to fulfill the goals of the thesis. The main 3D outputs are a model generated from imagery data and a BIM model transferred into a virtual reality environment.

KEY WORDS

Close-range photogrammetry, RPAS, TLS, PMLS, SfM, 3D Modelling, BIM, Virtual reality, Cultural heritage

ABSTRAKT

Tato diplomová práce představuje využití a integraci moderních technologií geomatiky k získání a zpracování dat kostela svatého Panteleimona, který se nachází nedaleko Skopje v Makedonii. Věnuje se přípravě rozšířené digitální dokumentace v podobě dvou a trojrozměrných výstupů, které lze využít k usnadnění další správy objektu. Na úvod, práce poskytuje základní informace včetně přehledu existující literatury a představení zkoumané oblasti. Následuje přehled použitých metod geomatiky a technologií sběru a zpracování dat a jejich výhod a přínosů využití pro naplnění cílů této práce. Hlavními 3D výstupy jsou model generovaný z obrazových dat a BIM model, který byl převeden do prostředí virtuální reality.

KLÍČOVÁ SLOVA

Blízká fotogrammetrie, RPAS, TLS, PMLS, SfM, 3D Modelování, BIM, Virtuální realita, Památková péče

DECLARATION

Herewith I declare that I have written the master thesis on my own and I have cited all the sources.

Prague, 2022

Pane Kuzmanov

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I would like to express my sincere appreciation to my supervisor prof. Dr. Ing. Karel Pavelka for sharing his professional expertise and for providing his valuable suggestions and guidance throughout the whole project. Additionally, this project would not have been possible without the organizational support and assistance from the department of archaeology on the Faculty of Philosophy, Ss. Cyril and Methodius University in Skopje. Furthermore, I am also grateful to Ing. Karel Pavelka and Ing. Paulina Raeva Ph.D. from the department of geomatics on FCE, CTU in Prague for their valuable advices and help in the process of making the 3D outputs of this thesis.

To conclude, I would remiss in not mentioning my close friends and family to whom I am specially thankful for the support they have expressed during the entire period of my studies.

LIST OF ABBREVIATIONS

ALS	Airborne Laser Scanning
AR	Augmented Reality
BIM	Building Information Modeling
CTU	Czech Technical University
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
INU	Inertial Navigation System
LiDAR	Light Detection and Ranging
MLS	Mobile Laser Scanner
PMLS	Personal Mobile Laser Scanner
RPAS	Remotely Piloted Aircraft System
SFAP	Small Format Aerial Photography
SfM	Structure from Motion
TLS	Terrestrial Laser Scanning
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VR	Virtual Reality

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Preface

The church of St. Panteleimon in Nerezi, just outside Skopje, is one of a very few surviving five-domed buildings of the twelfth-century Byzantium that represents this historically significant architectural type. Moreover, it still contains its architectural sculpture, which gives valuable information on liturgical furnishings of the twelfth century and especially on the structure of the iconostasis and is distinguished for its elegant and beautifully painted cycle. Since all monumental cycles from this mid-twelfth century in the Byzantine capital have been destroyed, St. Panteleimon preserves a record of artistic tendencies in the monumental art of Constantinople.

Even though it is recognized by scholars as one of the major surviving monuments of Byzantine art, just like many similar historically important buildings in Macedonia in general, there is a lack of digital documentations for the means of the national cultural heritage. Thus, one of this thesis' goals is to bring the idea and possibility of using the modern technologies of geomatics for documentation of the historical buildings in Macedonia.

This thesis endeavors to present different easy-to-use and low-cost photogrammetric methods as a very powerful tool in the areas of cultural heritage and archaeology. Also, the possibility to combine these different technologies to fulfill the main goal of the thesis, creation and visualization of a 3D model of the building, is presented in the following text.

In cooperation with the department of archaeology on the Faculty of Philosophy, Ss. Cyril and Methodius University in Skopje, the actual field measurements were possible and done without any obstacles and moreover, possibilities for other future collaborations with the department of geomatics on the Faculty of Civil Engineering, CTU in Prague were discussed.

1 Introduction

Geomatics experts, researchers and practitioners have witnessed a dramatic change in the way surveying is conducted over the last two decades. The rapid development of the electronics on the market, brought new and quality data acquisition tools and processing applications that are changing the way different areas deal with given problematics. Many hardware and software solutions that enable a 3D visualization and reconstruction have become available and are being regularly used within cultural heritage and archaeology.

Surveying and 3D modelling techniques such as laser scanning and photogrammetry have become extremely important for documentation of a historical buildings. The geomatics survey is generally focused to obtain 3D point clouds and 3D models, but some traditional photogrammetric products like orthophotos or different 2D drawings (plans and sections) are still very useful for cultural heritage studies.

The complexity and multiplicity of built heritage sites define a wide range of possibilities and solutions to acquire good quality 3D data. Therefore, it is difficult to define standard procedures and the integration of different technologies, often is the best solution. Integration of several 3D data acquisition techniques is commonly used practice in geomatics and is becoming an important resource in cultural heritage surveying of valuable historical monuments. It provides complete and multi-scale information according to the monument complexity, the accessibility of the area and the different level of detail required (Gagliolo et al., 2017).

This thesis is focused on integrating and analyzing the modern technologies of geomatics to capture and process data of a chosen historical building in Skopje, Macedonia and prepare a complex documentation that could be used in the future for different purposes.

From the beginning, this thesis provides with a background information including a review of an existing literature and an introduction to the study area. Following is a presentation of the used geomatics' methods and data capturing and processing technologies and their advantages and benefits of using them to fulfill the goals of the thesis.

As a case project, a historical Byzantine monument – the church of St. Panteleimon was selected.

2 Literature review

Remotely Piloted Aircraft Systems (RPAS) are considered as a revolutionary of the modern photogrammetry and have been a phenomenon in the field of archaeology for documentation of historical sites and constructions. In a combination with laser scanners and with terrestrial close-range photogrammetry, high quality and detailed outputs can be processed. The wide usage and the meaning of these modern technologies for different fields and areas have been an interesting topic for the articles and projects in the last two decades. The literature review regarding this topic was made from several books from the library of the Czech Technical University (CTU) in Prague and The Saints Cyril and Methodius University in Skopje as well as many professional articles online.

The importance of this chapter is that it allows the researcher to become more familiar with the subject and gets to know about the major theories and evidence that have already been done in the field and, to compare the latest ways of approaching to particular problematics.

In addition to this chapter, following a review of a selection of literature, the key opinions that will serve as a base for the ongoing topic will be presented. As the main outputs from this research will be a 3D model, BIM model and a presentation of the model in virtual reality, the main focus of this review will be on these topics.

Three-dimensional information acquired from imaging sensors is widely used and accepted. The field of photogrammetry, optical 3D metrology and 3D imaging is still growing, especially in areas which do not have traditional link to photogrammetry and geodesy. However, it still requires an engineering technique where quality and accuracy play an important role. The three-editions book *Close Range Photogrammetry and 3D Imaging* (Luhmann T., Robson, S., Kyle, S. and Boehmis, J., 2020) is a well-known guide to close-range photogrammetry, which provides a thorough presentation of methods, mathematics, systems and applications that use accurate imaging techniques to analyze the three-dimensional shape of manufactured and natural objects. The first edition, published in 2006 was very well received by the large international community of photogrammetrists, metrologists and computer vision experts and, the success was further recognized by the International Society of Photogrammetry and Remote Sensing (ISPRS).

Then, the second edition (2014) reflects the new (for that time) methods and systems for 3D imaging, particularly in the field of image analysis. In the latest version, popular techniques, such as, structure-from-motion, semi-global matching and simultaneous localization and mapping have been presented in more details. Further, new content covers low-cost 3D sensors, mobile indoor mapping, robot-based metrology systems and registration of point clouds, which are just the few topics that have been widely discussed. What makes this three-edition book special is that its structure assumes different levels of pre-existing knowledge and the idea of the authors is to create a closer link between different fields.

Another well-known book containing chronologically the development of photography in general, is *Small-Format Aerial Photography – Principles, Techniques and Geoscience application* (Aber, J., Marzloff, I., Ries, J., 2010). The book presents both the basic and advanced principles and techniques of small-format aerial photography (SFAP) with an emphasis on digital cameras. The second edition of this book (Aber, J., Marzloff, I., Ries, J., & Aber, S. E. W., 2019) has seen minor to major changes throughout all chapters in order to reflect the considerable development in the field of aerial photography. However, it is the images, not the aircraft used for SFAP, that is the main concern of the authors. Both editions of this book have three major portions. An introductory material including history and basic principles; SFAP techniques, unmanned aerial systems (UAS) and visual interpretation with analysis as second part and case studies with emphasis on geoscience and environmental applications as the main part of the book.

In their projects, researchers often combine data acquisition from unmanned aerial vehicle (UAV) with terrestrial, close-range photogrammetry and laser scanning (Lambers et al., 2007). Digital photogrammetry and laser scanning efficiently record the archeological sites even in unfavorable conditions. The possibility of UAV in characterizing individual tree variables, forest structure, tree stump detection and real-time monitoring has dramatically increased its application in forest inventory. Moreover, UAV 3D topographic representation is an excellent alternative to costly airborne laser scanning (ALS) or even terrestrial laser scanning (Clapuyt, 2016; Gruszczynski, 2017). Compared to ALS technology, the weakness of photogrammetric data is the lack of precise digital terrain models. This data cannot capture ground structure under tree crowns, but it has been successfully exploited for canopy cover documentation (Matese et al., 2017).

The possibility of usage and application of ALS in the field of archeology in the Czech Republic was presented at the international exhibition *Lety do minulosti – Flights into the past* (Gojda, 2007). In the article *Archeological remote sensing by means of ALS* (Gojda et al., 2011) Gojda reports on the goals, theoretical and methodological bases and the application of ALS as the most recent sophisticated method of remote sensing used for identification and 3D documentation of landscapes. The usage of the ALS and its application for mapping the surface are also presented by Dolanský, T. (2004) in his work. He is making a summary of the theoretical principles and possibilities for using the LiDAR technology in practice.

The situation regarding 3D documentation of historical objects in the Czech Republic depends mainly on the university environment and a few specialized companies. K.Pavelka (CTU in Prague, FCE) created a specialized group dealing with the documentation of historical objects using close-range photogrammetry and laser scanning as early as the late 1990s. Recently, his publications and contributions are focused mainly on using the modern technologies of geomatics for the needs of archaeology and cultural heritage. With his wide international experience, the author has given many professional articles that have been fundamentally for the purpose of this thesis. The method of close-range photogrammetry, *structure-from motion*, has become very popular in the last ten years and has infiltrated several fields other than geodesy (Pavelka, K. et al, 2021).

It is linked with the development of electronics, digital cameras, a major increase of the performance of personal computers and the development of fully automatic data processing software. With the latest technologies it is possible to collect data within a few centimeters' accuracy outside and inside infrastructure by various methods of photogrammetry. Within those methods there are combined precise high-performance laser scans, GNSS units, inertial measurement unit (IMU) devices, simultaneous localization and mapping technologies and 360 degrees panoramic cameras. The challenge is to integrate all those inputs, such as colored point clouds, 3D textured meshes, 360 degrees panoramic images and 3D vector data in building information modeling (BIM). In order to attract a wide range of users of these methods, technologies for displaying should be based on modern technologies like WebGL, virtual reality (VR) and optimization on server sites (Pavelka jr., K., Raeva, P., 2019). The amount of data that can be produced with today's technology is enormous and it is very important for further development to deal with the problem of storing the data (Pavelka, K. et al, 2022). It is currently being addressed by high-capacity server storage or other different suitable methods.

In general, RPAS is a system of a flying vehicle, ground-based controller and a system of communications between the two, equipped with a camera and brought together to fulfill a specific task (Colomina, I., Molina, P., 2014). Three main UAS components are commonly identified: unmanned aircraft, ground control station and communication data link.

The magazine *RPAS: The Global Perspective – Edition 2013/14* endeavors to present a photograph of the worldwide RPAS situation in that time. With the intention to bring the global RPAS community together and to present their views, this yearbook has been produced with contributions from a lot of European as well as international organizations and the development and application of RPAS in different countries are reported.

RPAS are basically described in the book *Remotely piloted aerial systems - RPAS* (Pavelka, K. et al, 2016). The collective of authors of this book are demonstrating detailed usage of RPAS, its advantages and disadvantages and some examples from their wide experience from the photogrammetric laboratory in the Faculty of Civil Engineering, CTU. Also, the development of unmanned devices in former Czechoslovakia is demonstrated chronologically, from simple flying models with a camera, to sophisticated instruments remoted by using the Global Navigation Satellite System (GNSS). RPAS platforms are a valuable source of data for mapping and 3D modeling issues. The main outputs, 3D models, DSM generation and orthophotos, can be produced in a completely automated way. The development of image processing methods in photogrammetry, mapping and 3D modeling, as well as the outputs from RPAS are reported in the article *UAV photogrammetry for mapping and 3D modeling* (Remondino et al., 2011). RPAS or UAS technology is known worldwide and used in many fields. A specific field is using of UAS in close-range photogrammetry, mainly in archaeology (Casana et al., 2014), precise mapping (Rijsdijk et al., 2013), ecology (Ivošević et al., 2015), cultural heritage documentation (Šedina et al., 2016), etc. For the potential use of RPAS to accelerate the production of parcel boundary map and registration of land parcels of cadaster maps up to a scale of 1:1000 in Indonesia, it has been written by the authors Rokhmana et al. (2019) for the international conference on Geodesy, Geomatics and Land Administration.

Another usage of RPAS is for the monitoring of glaciers motion. For many years, expeditions to Greenland have been sent and the main aim was always the geodetic survey of continental glaciers height. Monitoring them in a changing climate, as it is nowadays, it is very important. Experiences and results of a two-year-lasting project are discussed in the paper (Pavelka et al., 2018) specifically for using the RPAS for glacier motion monitoring in Greenland. Fixed-wing and multirotor drone were tested in this project, as well as satellite images. The international project held by the authors above, *RPAS for documentation of Nazca aqueducts* (Šedina, J., Hůlková, M., Pavelka, K., Pavelka, K. jr., 2019), shows the recent applications of RPAS to document sites and process the acquired data into quality outputs.

Automated photogrammetry, nowadays, for creating of textured 3D objects has different terms: structure from motion, image-based modeling and rendering, etc. The quick development of photogrammetry places the field in a competition with laser scanners, especially when it comes to price. In many cases it is more accurate and detailed than laser scanning. The biggest advantages are that they are easy to use, their mobility and that they are easy to transport (Banfi, 2020).

Three-dimensional scanning nowadays is commonly used technique for creating high-precision 3D models of real-world objects. Cultural heritage benefited a lot from it, when it comes to detailed documenting different types of constructions. However, not always it was accessible from normal users' point of view. The possibility of digitizing heritage artworks is briefly reviewed in the article *3d digitizing of cultural heritage* (Pieraccini, M. et al, 2001). The authors are pointing out the needs of applying the 3D digitizing techniques into the field of cultural heritage, and the main focus is on motivations, issues and technical specifications. Digital archives of 3D models, remote fruition, digital restoration and monitoring of cultural heritage are some of the reasons why the digitalization was needed. In the first ten years of this century, direct 3D documentation techniques were very popular and in a great advancement. Various 3D scanning devices that are capable to collect hundreds and thousands of 3D points per second appeared on the market. Bohler, W. (2005) is comparing different types of scanners among one another and against other 3D measurement techniques. It concludes that 3D scanning is not the proper technique for all documentation tasks, but also that there are examples where it was used to achieve results that had not been possible with any other technique in the past.

3D scanning became a practical reality in the field of heritage preservation. In the paper *3D Scanning and Replication for Museum and Cultural Heritage Applications* (Melvin, J. et al, 2009) the authors are giving a review of the current state of 3D imaging in culture heritage field, methods of physical replication, different systems used in applications, criteria for choosing the system and the techniques used for working with the acquired data. Also, attention was given to identifying those objects that are not likely to be suited for 3D scanning.

Nonetheless, these systems had the disadvantage in the very high price and expensive processing software. All instruments were very expensive with the need of a special software for processing the measured data. Also, transportation of 3D scanners was causing issues with the possibility of damaging and special taxes for transport were needed to be paid. For these reasons, a simple and automated technique using close-range photogrammetry documentation is very important (Pavelka, K. & Řezníček, J., 2011). The paper *New Low-Cost Automated Processing of Digital Photos for Documentation and Visualisation of the Cultural Heritage* describes the experience of the authors with the software solution for automatic image correlation techniques and their utilization in close-range photogrammetry and historical objects documentation.

An overview about the developments and the state of the art of the early years is given in (Breuckmann, B., 2014). The paper presents a short overview on the history of 3D scanning technologies and discusses thoroughly the state of art of 3D scanners including its current limitations and restrictions. With some interesting and challenging projects presented, the author gives an outlook on upcoming and expected future developments.

In 2010s, 3D scanning has gone a long way since its first appearance in cultural heritage digitalization and modeling and has become an important resource in many fields. As a consequence of the miniaturization of electronic components, it was possible to produce a new category of 3D scanners, also known as terrestrial mobile laser scanners (MLS). The costly and bulky scanners from before are lagging behind the new emerging technologies, which are delivering a long-term dream in the field of cultural heritage: fast, accurate, low-cost scanning with a hand-held device. Handheld scanners combine a relatively low cost with the advantage of portability (Allegra, D. et al, 2017). The technology is proven to produce high quality 3D models of architectural details and make the digitalization of the cultural heritage easier and faster with affordable economical efforts (Allegra, D. et al, 2016).

3D Printing is in phase of rapid technological changes and promises more enhancing experiences for the field of cultural heritage. New technologies provide the means to record images of cultural assets and subsequently process them to obtain virtual or physical items, guaranteeing greater respect for their physical integrity. These multi-sensorial forms of experiencing culture also have a great benefit for the accessibility of cultural heritage, especially for people with learning difficulties, for children, the elderly, for blind or visually impaired visitors (Neumüller, M. et al, 2014), (Balletti, C. et al, 2017). The information obtained in the digital process is not only useful to know the current state of preservation of the asset, but also a source of knowledge, study and promotion of this heritage. There is a rising importance of virtual reintegration and 3D printing techniques, as it will entail a reduction of material costs and improve the efficiency and effectiveness, which are aspects of great importance in the restoration and conservation process. There are many types of materials for 3D printing, each of them with different characteristics regarding strength, flexibility, resistance and chemical interaction. These characteristics must be assessed before their use in the reintegration of heritage. Therefore, the study of the printing materials and their suitability for the physical restoration of cultural heritage might become an innovative field of research (Higueras, M. et al, 2021), (Fotia, A., et al, 2021).

Another modern technology of geomatics for presenting 3D models or any 3D data in general, is virtual and augmented reality (AR). It is no longer just using this technology as technical assistance in fields such as healthcare, military or gaming industry, but it is also used as one of the most modern visualization technologies for 3D models, processed from close-range photogrammetry or from laser scanning. At their most basic, AR apps in heritage tourism use devices, typically a smart phone or tablet to deliver content that enhances a user's experience of a real-world environment (Nevola, F. et al, 2022). It can take place in real space and real time during in-person visits or even they can compromise virtual visits as forms of 'chair-tourism', as a substitute for physical travel. AR applications exist for a range of urban heritage settings from individual sites or attractions to routes through towns and cities connecting locations, districts or suburbs (Liang, L. & Eliot, S., 2021), (Garau, C. & Iardi, E., 2014). A big advantage of presenting heritage through AR and VR is not only to preserve and manage heritage, but to enrich the visitor's experience and subsequent engagement with history (Bec, A. et al, 2021). AR and VR experiences provide opportunities for small museums to enhance their resilience and competitiveness and are attractive for entrepreneurs (tom Dieck, C. & Jung, T., 2018), (Graziano, T. & Privitera, D., 2020).

Initially, in the wide world of cultural heritage, the aim of VR was to implement high impact applications and functional purposes. A virtual model of cultural heritage can have different values – scientific, educational, historical etc. depending on the information that it provides. It can also be used to assess the evolution of the environment by comparing 3D reconstructions made at different times. A team of Italian researchers present the final step of a multidisciplinary research project (*A VR-WEB-BIM for the Future Maintenance of Milan's Cathedral*) conducted on the Milan Cathedral for eight years. They are resulting with a complex and accurate digital 3D model of the main spire of the cathedral and of other parts of the building and transpose the BIM system in a VR environment. The combination of VR and AR will allow the technical staff to simulate the start and the arrangement of a restoration process. These virtual operations made on reality-based models managed in BIM will help to improve the prediction of costs and the duration of operations, as well as to simulate future scenarios (Fassi, F. et al, 2016).

In the recent decade, there has been a growing interest of the construction sector being observed in using building informational models due to many benefits and resource savings during design, planning and construction of new buildings. Terrestrial laser scanning has been improved over the years and its use is now extending for the architecture and construction industry, where the benefits of having a 3D scanned model could be used for a BIM model of a building. Using the point cloud data as a source for BIM and replacement of unsafe and error prone methods of conventional measurement, could give a new life for existing buildings (Raza, M., 2017). Overall, once the geodetic surveys (close range photogrammetry, terrestrial laser scanning, mobile laser scanning...) have been done, the point cloud or the mesh generated from the point cloud, are modelled into BIM objects (Alegra, V. et al, 2020). From the point cloud to BIM model, several methods have been developed, which is shown in many articles and studies (Khodeir, L. et al, 2016), (Ewart, I. J. & Zuecco, V., 2019). BIM can be used as a highly advanced system to present a desired reality in a 3D interactive environment accompanied with 3D reality captured data. BIM has been employed in the context of heritage (known as HBIM, or Heritage Building Information Modeling) for different purposes, such as to provide as-built information with the ability to interact with the end user and uploading information (e.g., historical photographs, documents about materials, or any past restoration projects) into the BIM model (Baik, A., 2021).

Virtual reality as a method of promoting architectural cultural heritage and cultural memory (Namicева, E., & Namichev, P., 2019) is a paper that deals with the different methods of mixed reality, AR and VR, through examples of the palaces in the urban core of Skopje as well as other examples from around the world. The aim of the paper is to emphasize the possibilities of virtual reality and its use as a platform for cultural heritage digitization. Digitization of Skopje's cultural heritage buildings from the early 20th century presents a digital method of reviving 'captured' data and their interactive presentation. The authors are focusing on the residential buildings for which the projects were created in the first half of 20th century; buildings that no longer exist, due to the earthquake in 1963 and the revival of their memory through different forms, such as VR.

For the application of GIS technology in the documentation and research of immovable archaeological heritage is writing Talevski, H., (2021) in his paper. The final product represents a spatial visualization of several selected landscapes and environments. Implementing GIS on archaeological sites is very practical and has unlimited possibilities for adaptation in accordance with the requirements. The archaeological site *Stobi* in Macedonia has been of a scientific and expert interest for at least 150 years. (Talevski, H., et al, 2017) are making a summary of a huge quantity of various information to be easily accessible, easy to upgrade, change and present. The project was carried out in several stages, with collection of archive data, drawing plans, 3D laser scanning and data processing.

Vrbjanska chuka is another archaeological site in Macedonia that was under archaeological research in the past few years. Photogrammetric methods were used as part of the complex multidisciplinary research in the process of digitizing the site, such as close-range photogrammetry, RPAS and 3D scanning and modeling of the trench and the interior structures. An exceptional documentation was created, which can be used for analysis and research in a virtual space through a detailed examination, even after the field work (Naumov, G. et al, 2021), (Naumov, G. et al, 2019), (Naumov, G. et al, 2016).

One of the non-destructive techniques in the process of recognition of archaeological resources, is geophysical survey. A test survey was conducted on two sites in the town Negotino in Macedonia, and it consisted of magnetic measurements and earth resistance measurements applied in order to examine the potential of this non-invasive technique for future fieldwork planning (Wroniecki, P., & Jaworski, M., 2015).

The increasing of the new technologies in photogrammetry is leading to a growing demand for new image processing tools. A vast range of software exists for image processing and deciding which one to use depends on a large degree on the intended analysis. Aspects of geometric corrections, image enhancement techniques, image transformations as well as stereoscopic viewing and photogrammetric analysis are particularly useful for digital image analysis (Aber, J., Marrzloff, I., Ries, J., 2010).

There are different types of software for the digital treatment of the information obtained. They can be classified, based on their purpose, in applications for the treatment, representation (generation of 3D models), modeling and 3D treatment of images. Some of the most recommended programs are Agisoft Metashape (photogrammetric mapping), AutoDesk (CAD), Meshlab (modeling and 3D treatment), Visual SFM (photogrammetric survey), iWitness Pro (photogrammetric mapping) and Blender (modeling and 3D treatment), among others (Davis et al, 2017). It is important to highlight that certain programs are free and open-source software, consequently reducing costs and improving the efficiency of those resources allocated to the digitalization process.

The purpose of this review was to go through some of the works and research in composition studies, done about 3D environment and its application. It is clear from these studies that modern methods of geomatics, as RPAS, ALS, TLS, MLS etc. are popular around the world for documentation and 3D models generation and presentation. 3D scanning technology and its application in different areas increasingly took the attention of many researchers over the last two decades. There are many scientific papers, dissertations and books written about these fields, however, there is still long-term ongoing research.

3 Used methods

At present, each of the 3D objects that is displayed in a digital presentation is made up of a 3D mesh that can be generated by using a wide range of different techniques. Documenting real-world objects into digital models for the purpose of monitoring, reconstruction or following their deformation, is a commonly task done by geodetic methods. Along with the rise of digital technologies and the development of microelectronics, geodetic measurements have become more accurate and easier. Moreover, computer performances rapidly developed and enabled automatic and complex data processing. This influenced photogrammetry and its methods for good and enabled its implementation into many branches of science and technology.

Three easy-to-use methods were tested for this project. The idea was to try to compare the 3D models processed by different technologies and methods, and to point out the potential of combining close-range photogrammetry and laser scanning for recording and documenting in the field of cultural heritage. In addition to this chapter, a short presentation will be given to outline the used methods:

- terrestrial close-range photogrammetry,
- aerial / drone photogrammetry,
- terrestrial/mobile laser scanning.

3.1. Terrestrial close-range photogrammetry

Photogrammetry is a part of geodesy and can be described as the science and art of measuring and interpreting imagery to reconstruct metrically objects either in 3D or in 2D. Close-range photogrammetry usually applies to objects ranging from a few decimeters up to 200 meters in size and 300 meters in distance (Lerma, J. L. et al, 2010).

On one hand, close-range photogrammetry has the benefits of being relatively cheap and easy to set up; the portability of taking mainly the cameras (sometimes tripods) to different sites is an advantage that makes it appropriate for recording many objects and sites. Also, it does not require special permits and usually is allowed in many places. On the other hand, limitations of this method are the lack of fully automatic solutions that yield satisfactory results (mainly when dealing with texture-less imagery), operator's expertise is required, certain mandatory requirements on the observation environment etc. Digital SLR cameras are mostly used in close-range photogrammetry, but simpler cameras for smaller tasks can be used too.

The modern method of photogrammetry for the creation of textured 3D objects – Structure from Motion (SfM), is a new modern technology, which has become very popular in the last ten years and has infiltrated several fields. SfM offers the possibility of fast, automated and low-cost acquisition of 3D data, which has inevitably created great interest amongst the geomorphological community. It is a photogrammetric imaging technique for estimating 3D structures from 2D image sequences.

The complete photogrammetric workflow derives metric and reliable information from imagery consists of: (i) design, i.e., sensor and network geometry, (ii) 3D measurements, (iii) structuring and modelling, (iv) texture mapping and visualization (Remondino and El-Hakim, 2006). Nowadays, different commercial packages can perform these tasks. They allow, after the tie point measurement and bundle adjustment¹ phase, to obtain sensor calibration and orientation data, 3D object point coordinates and wireframe or textured 3D models.

For this thesis, terrestrial close-range photogrammetry was used for data acquisition from the lower – external parts of the object, where it was reachable for capturing. This is the reason why aerial photogrammetry was included as well, because of the roof and the hard-to-reach segments of the building (more in 3.2.). As the SfM method requires multiple photographs with large overlap, collected from different positions and directions, the imagery acquisition was done following those requirements (Figure 1.). After the plan for the camera survey was made in advance, the whole object was captured first and then its details, ensuring that everything is captured adequately. Particular attention was paid for appropriate coverage and enough overlapping of the images (Figure 2.).

¹ Bundle adjustment is used to calculate the exact parameters of the camera internal and external orientation

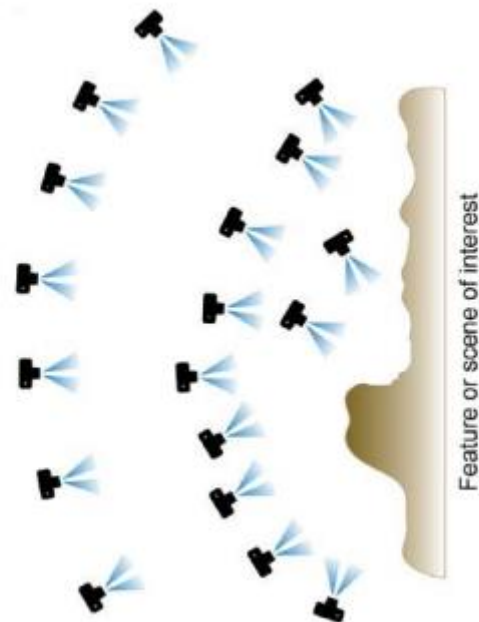


figure 1 - Camera position for close-range photogrammetry (SfM)

In contrast to traditional photogrammetry, SfM does not explicitly require a use of ground control points - clearly identifiable locations with known or assumed real-world coordinates. Consequently, the resulting model is neither scaled, nor aligned and is therefore unrelated to an established external coordinate system. This is not a problem for many applications, especially if the requirements are just for 3D visualization or a simple spatial record. In these

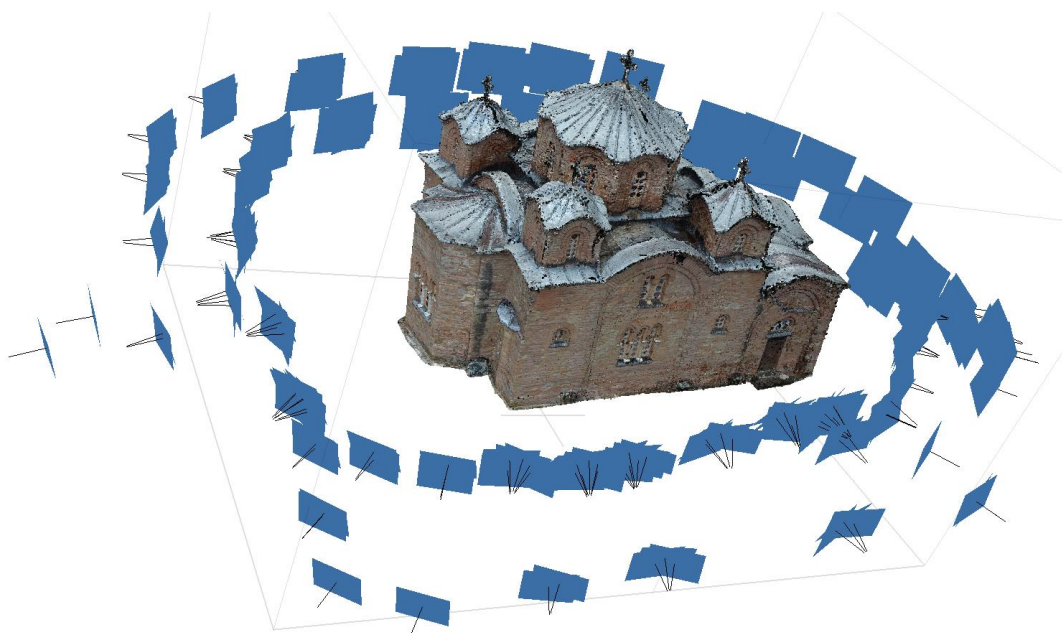


figure 2 - Example of imagery acquisition – terrestrial photogrammetry

cases, the introduction of a known distance in the scene can define a real-world scale.

3.2. Aerial / drone photogrammetry

For terrestrial surveys with close-range photogrammetry, cameras can be directly handled from the ground. Alternatively, cameras can be controlled with wireless technology on air devices; so-called ‘drones’, nowadays they can be found with several abbreviations. The term RPAS is considered as most acceptable for the community that uses this technology for scientific purposes because it defines that the unmanned vehicle actually has a pilot who remotely controls it from the ground unlike the term UAV – unmanned aerial vehicle – flying vehicle only, which associates that the vehicle does not have a pilot. Similar abbreviation is UAS – unmanned aerial system – UAV with a terrestrial segment. However, for the wide society, that connects this technology with entertainment it is commonly known as *drone*. In general, RPAS is a system of flying vehicle, ground-based controller and a system of communications between the two, equipped with a camera and brought together to fulfill a specific task (Colomina, I., Molina, P., 2014).

There is a variety of platforms for aerial photography with different characteristics: manned or unmanned, powered or unpowered and free flying or tethered to the ground. Size and complexity of these platforms vary enormously, ranging from simple kites to substantial manned aircraft. What might be the ideal platform in one situation, could be impractical or impossible in another. The decision for a particular one depends on many aspects. In this section, the mostly used types of RPAS for geomatics purpose will be presented.

RPAS Helicopter is a device having two rotors: the main one lifts the helicopter and allows to tilt, and the secondary rotor provides the ability to rotate around the vertical axis. It is ideal for measuring or monitoring buildings in narrow areas. Because of its ability for vertical taking off and landing, this type of unmanned aircraft is usually used, mostly for documentation in photogrammetry.

Multicopter (Figure 3 - a) got its name because it has multiple rotors (mostly 4, 6 or 8 rotors). It is the type that comes to mind in the society when the term drone is mentioned. It is controlled by changing the angle of the rotors. These devices are supplied with battery, navigation system, antenna for radio connection and, inevitably, a digital camera equipped with gimbal². Quality digital cameras are used for this type of RPAS.

² Gimbal – a 3-axis mechanism for rotation and stabilization of the camera

It is possible to use different sensors e.g. multispectral, thermal or laser scanner. Multirotor systems have in favor the stability in the air given by the multiple rotors and vertical taking off and landing. Moreover, manual, as well as automatic mode is possible according to the predefined flight plan. However, they do not last in the air as much as the fixed-wing drones and are exposed to be more damaged.

Fixed-wing drones (Figure 3 - b) have the ability for a long-range flight and higher endurance in the air. Hence, the rules are similar as for normal manned aircrafts, i.e. these types of drones cannot start vertically, but need certain speed. Also, they have an advantage when it comes to safety – because of the wings and the lightness, it does not fall directly on the ground if unwanted complications happen. Mostly, this type flies in an automatic mode with a predefined flight plan, but with the possibility to be stopped or be interrupted by the controller. Landing is also autonomous with a predefined position, which needs to be in a wider area (some types can land in a spiral way). They are not adequate for documentation or surveying individual buildings based on the flight technology. (Pavelka et al., 2016).

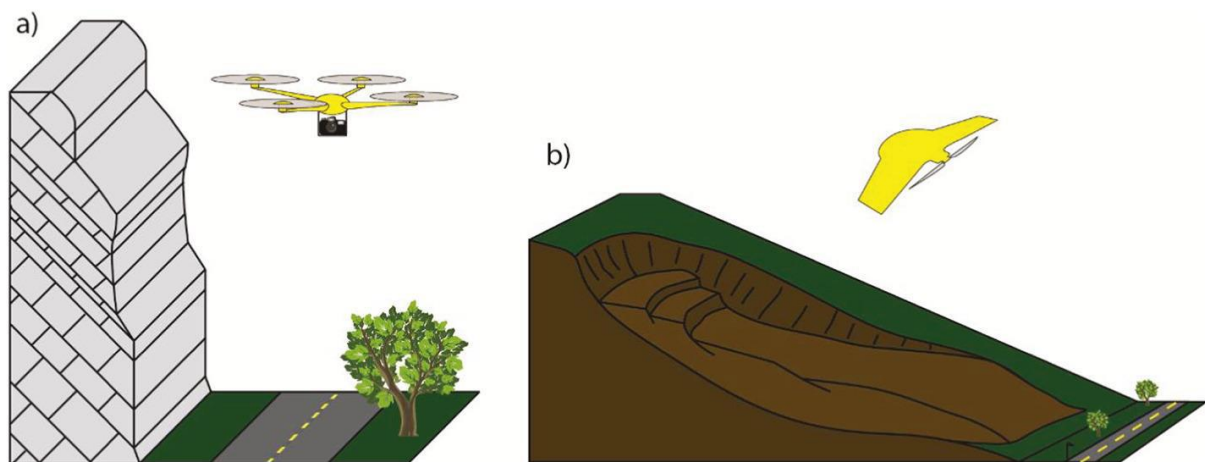


figure 3 - Different RPAS survey options proposed by Giordan et al. (2015) for (a) steep rock slopes and (b) gentle to moderate slopes

Drones are accessible and available nowadays, and almost anyone can buy it. Exactly the acceptable price and the mass availability (even in toy stores) resulted with the unavoidable need for regulation of their use, to ensure both the safety of the air traffic and the privacy of the society and their properties. There are many different drone regulations around the world. While some countries have clear, established drone laws, many others do not, or the existing regulations do not consider how much the RPAS landscape has changed over the last decade. Regulation in EU countries has been in place since 2021; the flight level is limited to 120m and there are clear rules on the use of drones. There are still many countries that lack drone laws and on the contrary, a small group of countries that have completely banned their use.

The fascination of the geomatics industry in the RPAS is mostly due to their ability to collect site data at high resolution, at low cost and with acceptable deployment. Using it in photogrammetry is another tool that opens new possibilities for data acquisition for numerous areas of research. In geomatics, RPAS mainly are applied to fields that benefit from close-range sensing, such as archaeological documentations, cultural heritage, monitoring and imaging of extensive areas, cadaster applications, mapping as well as creating 3D models and digital surface models with accuracy of several centimeters. Within a very limited time and costs, an area can be surveyed and 3D models with up to centimeter accuracy can be created or volumes can be calculated. However, mapping with RPAS and creating a specific output is demanding when it comes to organization and has several phases like creating the project, planning the flight and before flight preparations, on-site flight, data processing and preparing the outputs.

Most RPAS are equipped with a camera and an inertial navigation system – INS (GNSS: real time position of the body + IMU: orientation of the body), where the photo positions and camera tilt angles are registered during the flight. Georeferencing of images is possible according to data from INS or can be used for control or refining suitably distributed control points.

Next, there is a general summary of advantages of using RPAS: cheap transformation, easy manipulation and mobility, high flexibility for deployment to work, possibility to use it in areas difficult to access, possible use in areas dangerous or risky for manned flight, high image resolution etc. (Pavelka et al., 2016)

The use of RPAS has indeed become more popular in cultural heritage surveys, mostly to measure and detect areas that cannot normally be covered using terrestrial photogrammetry or terrestrial laser scanner.

In this project, aerial photogrammetry with RPAS was used for the external, hard-to-reach segments of the object, which was mostly essential to be used for the complicated shape of the roof. In this way, using images captured from different points of view, it was possible to obtain complete images coverage of the whole building. The combination of terrestrial close-range photogrammetry and RPAS allowed the creation of an accurate and reliable 3D model. In order to acquire a complete and quality documentation of the building, images from different high levels and with enough overlap were captured (Figure 4.).

The flight was made in a manual way, remotely piloted from the ground. The building of interest is positioned in an open space, with not many other things around it, so it was possible to lower the high level of the drone and capture images of the lower part of the building as well. As a test, a 3D model was made only with the data acquired by RPAS and was compared with the final 3D model, processed with combination of all methods mentioned in this chapter.

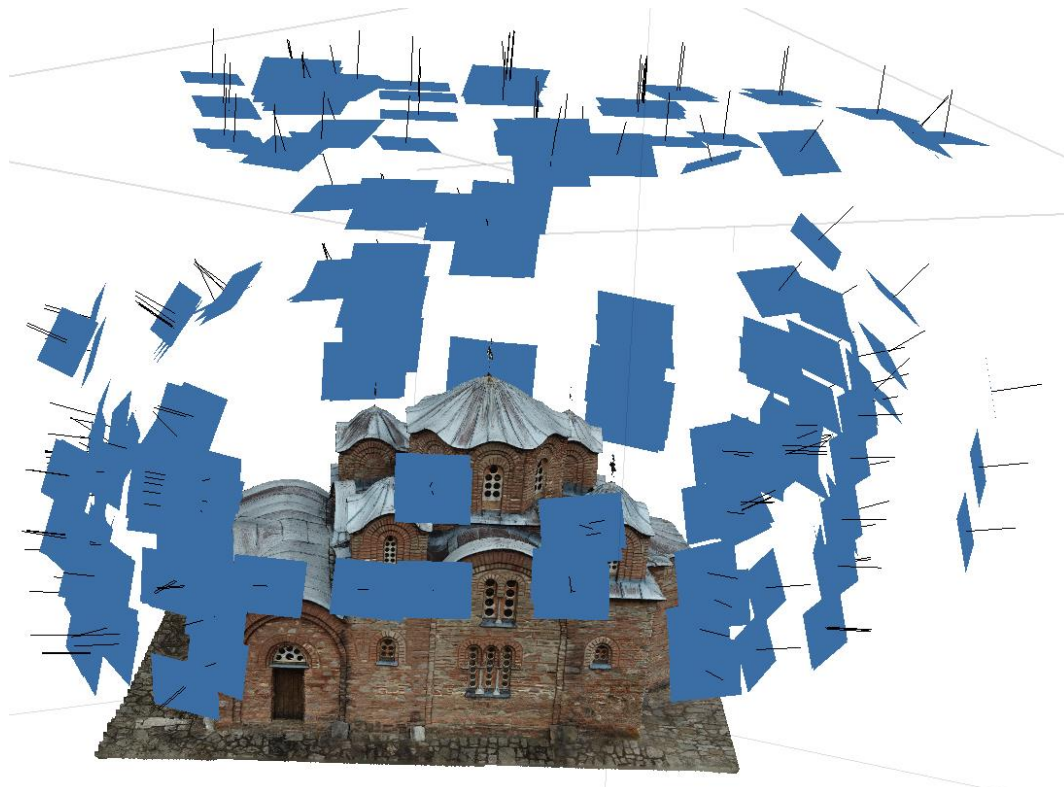


figure 4 - RPAS camera positions

3.3. Terrestrial / mobile laser scanning

Since the early 2000s, terrestrial laser scanning (TLS) has evolved from a research and development topic to a geo-data method that is commercially offered by a multitude of land surveying companies and other service providers all over the world. The technology is primarily used for a least-interactive, rapid acquisition of three-dimensional information and texture of a variety of topographic and industrial objects thanks to its high operation speed, mobility and accessibility. In the field of surveying, laser scanners open a new dimension with data capturing. Moreover, different industrial sectors require precise data of the environment to be able to have an as-build documentation of the facility. This advanced technology becomes a suitable alternative for labor intensive, expensive and unsafe traditional inspection and maintenance methods, which encourage the increased use of the technology in construction industry. It contributes to the protection, conservation and restoration of cultural heritage buildings, as well as in the interpretation and monitoring of their surrounding area.

Terrestrial, as well as mobile laser scanners measure the 3D spatial information of an object within a certain distance, use a laser. The method, in general, is based on calculating XYZ coordinates of numerous points on land by emitting laser pulses toward these points and at the same time, measuring the distance from the device to the target. It is a non-contact mass measurement method that is highly demanded for analysis of historical objects. TLS are already inevitable part of geodesy. The rapid development of this method resulted to appearance of much faster and more accurate devices on the market that have more sophisticated automation and processing programs. Most importantly, it resulted to significant reduction of the time needed for the actual scanning as well as the data processing as much as possible. Devices that are specialized for specific activities appear more frequently. An example can be a total station with an integrated laser scanner that enables a combination of classic geodetic measurement and laser scanning. Its advantage is a more accurate determination of the position of the device and also accurate scanning that results with a point cloud.

The importance of this method is exceptionally significant and even though practically it is used for many complex solutions and models, the theory behind its principles is actually simple. Commonly used 3D scanning systems work on the principle of spatial polar method or spatial intersection method. In both cases, the accuracy of the 3D scanning is affected by many

factors, thereby resulting in cloud comprising errors and thus reducing the quality of the resulting model.

The polar method requires measurement of the horizontal and the vertical angle and digital measurement of the distance to the point. Angle measurements are known to the geodesy since long time ago and are part of the oldest geodetic instruments, but what makes the laser scanners special is the ability to determine the distance with the help of a laser light to millions of points per second. It is done in the way that the scanner emits a beam of infrared laser light onto a rotating mirror that effectively paints the surrounding environment with light. The scanner head rotates, sweeping the laser across the object or area. Objects that are in the path of the laser reflect the beam back to the scanner, providing the geometry that is interpreted into 3D data. In addition to the distance measurement, the scanner also captures measurements on the horizontal and vertical planes, providing a full scope of measurement data for the spatial polar method (Štroner, M. et al., 2013).

A laser scanner typically captures data through two kinds of system:

- Pulse measurement system: works by emitting a single pulse of laser light and determining the distance to the finishing point by measuring the time it takes for the light to be reflected back to a sensor on the scanner;
- Phase-shift system: similarly, this system also uses an emitted laser light, but in this system the intensity of the light is modulated with specific wave forms. The reflection of the intensity patterns is displaced by the impact on the surface of the object. Measuring the displacement between the sent and the received laser signal, the scanner provides precise distance calculation. Generally, laser scanners that use this type of phase-shift systems are accurate, fast and provide high-resolution data.

3D laser scanning technology is particularly well suited for recording different type of landscapes, especially when making detailed inventory records that need to be accomplished rapidly. However, there are some surfaces, which could not be scanned particularly well, like any transparent material such as glass, mirrors, water, crystal, etc. These transparent objects will reflect the light and give false three-dimensional information. Moreover, another problematic situation is when the object is rough and dark, then much of the laser light is absorbed and missing points can be observed.

TLS instruments are commonly divided into three categories based on the distance the laser light can travel to record a point in a field of view: short, medium and long-range scanners. Logically, the TLS devices optimized for a long-range have been applied to measuring spatially larger areas, whereas shorter range scanners measure spatially smaller areas, but in greater detail and accuracy (Heritage, G. & Large, A., 2009).

One of the biggest limitations for this technology in the past was the weight of the instruments (mostly even more than 20kg including the battery) but with the increasement of popularity of the technology and, of course, electronics development, much lighter and smaller devices were developed. Today, we have a hand-held mobile laser device that is very compact and easy to transport.

In general, under the term mobile laser scanning device, it is necessary to imagine a scanner that changes its position during measurement. These devices are used mostly for accurate 3D mapping and the output is a point cloud. Since its position and direction change, these devices must be equipped with an inertial unit INS, which adds the position, direction, and acceleration data to the measurement i.e., they need the signal from the satellites to ensure the correct geo-referenced positioning for the 3D data. It is the principle on which airborne laser scanners or ground mobile laser scanners (often placed on cars or hand-held devices) work.

The level of accuracy of the INS is related to the signal detection quality of the GNSS, especially if it is composed by low-cost sensors. To increase location accuracy and remove MLS errors in GNSS-denied environments, previous developers have made significant improvements on data-driven (Mao et al. 2015) and model-driven techniques. Data-driven methods may be directly used to fix point clouds data starting from ground truths and using multiple available correction algorithms. On the other hand, model-driven approaches set up mathematical models for the MLS systems and analyze the error factors to calibrate the biases (Liu et al. 2019). Furthermore, Simultaneous Localization and Mapping (SLAM) algorithms have been investigated in robotics in the past years.

In the cases where there is no GNSS signal (closed spaces, forests, mines, constructions, etc.) it is important to find another way of determining the location of the device. For these purposes a new technology was developed.

Simultaneous Localization and Mapping is the process of mapping an area whilst keeping track of the location of the device within that area. This is what makes mapping possible. This method allows map construction of an 'unknown' environments using mobile robots, drones or vehicles. SLAM systems simplify data collection and can be used in outdoor or indoor environments. Using SLAM algorithms and software, a device can simultaneously locate itself in the map and create a virtual map of the location. To localize positions with SLAM, it is possible to apply two major strategies: absolute positioning with feature-matching and relative positioning with scan-matching. The first strategy matches feature detected (such as lines, corners, circles, etc.) with a generated feature map which allows to recognize the position. In the second strategy, two or more scan points frames are matched together by various algorithms to obtain the movement done by the MLS. Therefore, the SLAM algorithm performs better when applied indoors, with regular and repetitive features, while it has been shown to perform poorly when applied outdoors due to the complex and irregular features detected by the laser scanner (GeoSLAM, n.d.).

The sensors of this technology may use visual data or non-visual data sources and basic positional data, using an IMU. Using this sensor data, the device calculates the best estimation of the position where it is. As a new position is collected and calculated every few seconds, the already collected features align and the best estimation improves. It is an iterative process – the more iterations a device performs, the more accurate it can position itself in the area.

During the last two decades, the improvement of navigation systems has driven the industrial and scientific community towards the use of several types of sensors which are widely used in the geomatic community. These innovations have contributed to the MLS technologies development, which allows to acquire the surrounding environment in a rapid and efficient way through data localization, with sensors able to perform in all weather conditions (Chang et al. 2019).

SLAM technology can trace its early development back to the robotics industry in the 80s and 90s. Today it is used in many industries. It has opened up opportunities to better map and understand environments whether they are indoor, outdoor, in-air or underground.

In the last decade, a new (updated) version of MLS was developed – Personal Mobile Laser Scanner (PMLS). The conditions to be followed were that it had to be light weight, relatively cheap compared to MLS and ALS and would not need a GNSS signal, as it was primarily

targeted to be used for documentation of interior spaces. This resulted in unique device, carried by human and able to map the immediate surroundings while walking.

These devices are equipped with a rotating head, which usually uses a rotating mirror to spread the beam of light. Depending on the type of the device, up to hundreds of thousands of points per second can be registered. Additionally, the device must be equipped with an inertial measurement unit that records the tilt of the device when measuring acceleration. The modern models are also equipped with a camera that records images during the rotation of the device and as a result of the RGB model, it is possible to assign a real color to the points. This technology includes high-speed portable laser scanners that are able to make a real-time smart 3D surveillance. It is easy-to-use technology, but yet powerful and precise to fulfill the needs of laser scanning professionals.

For the purposes of this project, data acquisition from both terrestrial and personal mobile laser scanning were done in the field survey. However, due to technical reasons, the scanning with the terrestrial mobile laser scanner was not complete for the whole object, so it was decided that only the data acquired with PMLS was going to be used in the 3D model creation. Even though the data from TLS was not used, the method was tested in the field for experimental purposes and as an indication of how it works (Figure 5.).

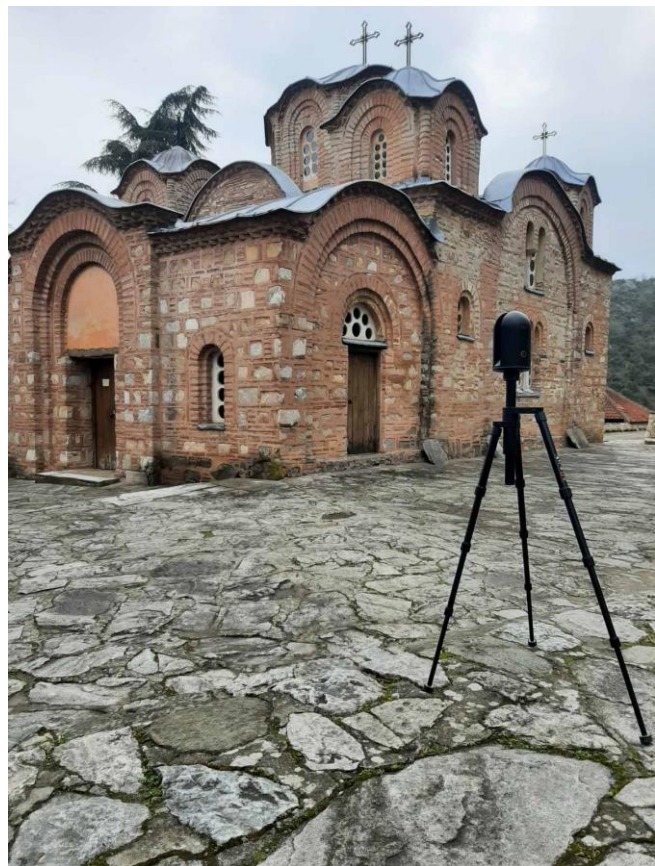


figure 5 - On-site survey - The object of interest scanned with TLS

The facades of the object of interest are quite complex and with a lot of edges and irregular shapes, so it would be interesting to see how this method is dealing with the problematic, but unfortunately it was not possible to finish the survey with the device, so as an alternative, the PMLS was used to scan the object from both outdoors and indoors.

Personal laser scanners have become a famous part of modern geomatics' devices and a great tool for 3D documentation of irregular-shaped objects. In this project, this technology was used for creation of a vector plan of the object and as foundation of the data conversion to BIM. Unlike the external part of the object, where the measurements were made with different methods, the interior was scanned only with PMLS, so it was very important part of the data collection of the project. The acquired data were more complex because of the indoors and outdoors scanning, although it did not contain the higher parts of the building.

Surveying with the PMLS does not require any special expertise in the geodetic world. However, there are certain rules that need to be followed in order to make the measurements as accurate as possible. Each scan should start and end at a fixed point to ensure a closed loop and locate properly the data collected in the unknown environment, registering the whole points cloud obtained without the GNSS signal.

The actual measurement process was simple. The mobile scanner is activated at a pre-selected place and should be left there for a certain time to orientate itself in the environment. The entire measurement route is pre-selected, so from the moment the measurement starts, there should be no stops (the SLAM algorithm does not work when there are stops for a longer intervals) and also, sudden moves with the instrument and different walking pace should be avoided (because of the IMU). The measurement must be finished at the same place where it started (similar to a closed polygon in geodesy) and left again for a certain time as it was at the beginning of the survey.

4 Used devices

Nowadays, there is a wide range of geomatics data acquisition tools for cultural heritage recording and documentation. Accuracy of just few centimeters can be reached with the latest technologies in both indoors and outdoors surveys.

For the purpose of this thesis, three easy-to-use technologies were used. When choosing the technology for the data acquisition, several factors were taken into consideration such as:

- accuracy,
- time consuming,
- financial demands,
- time of evaluation of results,
- data processing time,
- data amount,
- transport.

The area of interest was to make a documentation of a historically important object and process a 3D model with different techniques. The object was abroad, in the Republic of Macedonia, so when the preparations and the plan were made, at the beginning, it was important to choose devices from transport and financial demands point of view, since it was not possible to use classic geodetic total stations or larger laser scanners on tripods. As of accuracy and time consuming, it was essential to be ‘as much accurate as possible (the object has complex shape), but also as efficient as possible’ – finish with all the survey in a limited period of time since it was a several-days trip outside of the country. The rest of the factors are meaningful, but not as decisive as the ones mentioned above.

Finally, for the purpose of data acquisition, four devices were used from the department of geomatics, CTU: Digital camera *NIKON D3200* for terrestrial close-range photogrammetry, *DJI Mavic Pro* for aerial photogrammetry and *Leica BLK360/ZEB REVO GO* for terrestrial/mobile scanning.

4.1. Digital camera NIKON D3200

The 3D data acquisition for this thesis was realized by a photogrammetric – aerial and terrestrial survey, combined with a laser scanning measurement. The external acquisition was realized with the aim of generating whole coverage of the facades with terrestrial photogrammetry, while the aerial was carried out to acquire images of the facades and of the roof (see 4.2.). In this way, using images from different points of view, it was possible to obtain a complete image coverage of the whole object of interest.

As it was planned, the complete coverage of the facade was obtained with the close-range terrestrial photogrammetry method and was carried out using a digital camera Nikon D3200 (Figure 6.).



figure 6 - Camera Nikon D3200

source: www.nikon.com

The used camera is a product of the company *Nikon Corporation*, one of the world's leading suppliers of products and solutions based on advanced opto-electronics and precision technologies. They introduced this model as the successor to the D3100 in 2012.

The extremely portable, compact and lightweight body of the camera D3200 is loaded with the latest (for that time) digital SLR camera functions, allowing a full-scale, flexible photography. It is simply operated and enables to capture images exhibiting a superior image quality.

The D3200 is equipped with a DX-format CMOS image sensor with an effective pixel count of 24.2 million pixels and EXPEED 3 image-processing engine that enables capture of high-quality images and shooting at high sensitivities (Nikon, n.d.).

Technical specifications	
Type	Single-lens reflex digital camera
Effective angle of view	~1.5x lens focal length (35 mm format equivalent)
Effective pixels	24.2 MP
Image sensor	23.2 x 15.4 mm CMOS sensor
Image size (pixels)	6016x4000 [L]; 4512x3000 [M], 3008x2000 [S]
Shutter	1/4000 sec – 30 sec
Image processor	EXPEED 3
ISO sensitivity	100 to 6400

table 1 - Technical specifications Nikon D3200
source: Author's creation, based on data from www.nikon.com

For taking photos, it was used a digital camera Nikon D3200 with photogrammetric adjustments (calibrated and stabilizable focal lengths on the lens).

This technology was used for the SfM method, which was primarily designed for processing images captured by digital cameras. Due to the algorithms of SfM, the time cost of the photogrammetric processing has significantly reduced, and it is possible to create two-dimensional (orthophoto) and three-dimensional (point cloud, textured mesh) results very efficiently.

As a test, the acquired data from the close-range photogrammetry were processed into a 3D Model in Agisoft Metashape. The textured point cloud, processed from images captured only from this method is shown on Figure 7. The point cloud is high quality and accurate in the lower parts of the facade of the object and is a great basis for the 3D model (Figure 8. – a). Nevertheless, since there are not images captured from the roof, on the point cloud could be seen missing parts and holes, meaning there is not data captured (Figure 8. – b).



figure 8 - Textured point cloud from Close-range photogrammetry – north-east view



figure 7 - Textured point cloud from Close-range photogrammetry - details

4.2. RPAS - DJI Mavic Pro

Remotely piloted aerial systems combined with structure from motion photogrammetry has already proven to be very powerful for precise surface reconstructions in a wide range of geoscience applications.

In the last decade, the fast and steady development in the UAS sector brought a wide range of remotely controlled aerial vehicles of different types (fixed-wing, multi-rotor), prices and dimensions to the consumer market (Colomina & Molina, 2014). The mounted cameras (e.g. RGB, thermal, multispectral) and sensor designs (global shutter, rolling shutter) vary widely and so do the corresponding image resolutions.

For the survey of the external hard-to-reach parts of the object of interest for this thesis, a multirotor type of RPAS was used – DJI Mavic Pro. The images were captured manually under almost perfect weather conditions during the flight – cloudy, without any remarkable changes during the survey.

Mavic Pro (Figure 9.) is a multirotor type of RPAS that is a product of the Chinese company DJI, a company that is a world-leading manufacturer of commercial RPAS for aerial photography. Back in 2016 they revolutionized personal flight by introducing Mavic Pro – a portable, powerful and easy-to-use drone featuring the company's most innovative flight technology in a sleek, foldable package, designed to be taken just about anywhere. It is small enough to toss it in a bag and easy enough to launch quickly whenever the time and place are right.

Mavic Pro can fly by predefined plan (autonomously) or manually controlled by a pilot. It is mostly used for documenting smaller areas. No flight plan was used for this project – the drone was navigated by the operator remotely.

For this project Mavic Pro was used for capturing images from different height levels in order to increase the output quality by making more overlapping images. The craft's GPS/GLONASS, IMUs and visual positioning system, make flight performance as stable as possible. Moreover, this RPAS has the ability to fly back to the 'home' point if the pilot loses the visual contact or the battery reaches a critical level.



figure 9 - Quadcopter DJI Mavic Pro
source: www.dji.com

The DJI Mavic system has several parts:

- aircraft with four folding 'arms', containing the important electronic components: camera, gimbal, signal receiver, battery and different sensors.
- remote controller,
- *DJI GO* application for controlling via smart phone,
- optional data processing software.

Technical data	
Sensor	12 MP 1/2.3" CMOS
Field of view	78.8°
Focal length	4.7 mm
Diagonal Size (Propellers Excluded)	33.5 cm
Weight	0.75 kg
Motor	Low noise, electric
Remote controller	Operating frequency 2.4 GHz
Transmission Range	7 km
Battery	Lithium - polymer
Camera	RGB
Software	
Control application	DJI GO
Image processing (optional)	Agisoft Metashape
Operation via controller	
Max. flight time	~ 30 minutes
Operating temperature range	0 – 40 °C
Positioning System	GPS/GLONASS
Takeoff/landing	Vertical
Hover accuracy	
Horizontal	30 - 150 cm
Vertical	10 - 50 cm

*table 2 - Technical specifications of the DJI Mavic system
source: Author's creation, based on data from www.dji.com*

RGB camera was used for capturing with this RPAS, which means it acquires image data in R-red, G-green and B-blue bands. The camera has a resolution of 12 MPix and the captured images have size of 4000 x 2250 pixels. Its position during the flight was manually controlled in the DJI GO application. It is not possible to change the camera of this type of RPAS as it is with the fixed-wing type, where thermal or multispectral camera can be applied.

The acquired data from the survey is processed similarly to terrestrial photogrammetry; SfM technology is used, which generates a point cloud (Figures 10, 11). The advantage of this technology is that has a GNSS device and IMU which adds to all images the necessary information about elements of external orientation and also, because of the GNSS, the generated model has a scale.

Based on the point cloud just from the RPAS images, a 3D model was created in Agisoft Metashape (more in *Case project*). It is shown on the Figure 10. that it is a satisfactory output even without the data from the other methods.

However, the model is not with good quality when checked into details the places where there are not enough images captured; mainly the lower part of the object where there are parts of the point cloud missing (Figure 11. – a). On the other hand, the roof, which was the main focus for this method, has a very good quality and accurate even in the hard-to-reach parts (Figure 11. – b). This model was made only as a test and to compare the details from the point cloud where there is data missing, with details where there is, on the contrary, sufficiency of images.



figure 10 - Textured point cloud from RPAS – south-east view

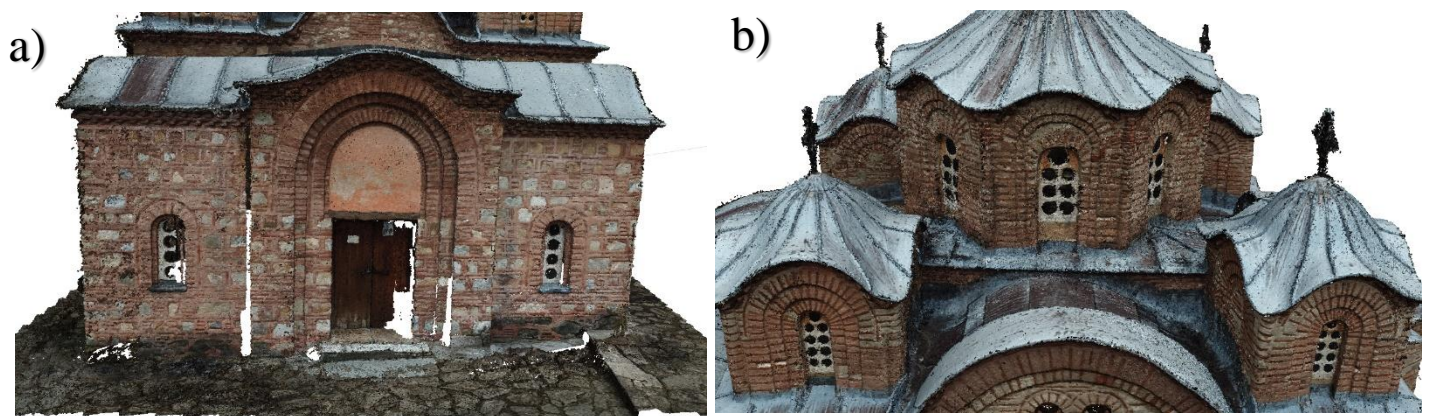


figure 11 - Textured point cloud from RPAS – details

4.3. ZEB REVO GO

We live in a data driven world. Our environments are full of data, and each day we create more. The team at GeoSLAM knew there had to be a way to digitalize 3D data capture, but to make it faster, easier, and to make it possible to scan places that would have been impossible to scan them before. They developed devices that are constructed for ‘walk and scan’ process of scanning. Devices that enable scanning of large areas and buildings in a tremendous, short time without the necessity for static observation and creation of geodetic network points. A device invented from this company was used for the data capturing inside the object of interest in this thesis – personal mobile laser scanner ZEB REVO GO using LiDAR technology (Figure 12.).

The English company GeoSLAM brought mobile 3D data capturing to the market in 2013 with the launch of the ZEB1, the world’s first hand-held mobile mapping system – SLAM scanner powered by a smart algorithm that continues to develop and become more intelligent each time is used. ZEB REVO is the next generation of hand-held mapping, launched in 2015 with many modifications and updates. The GO version of the ZEB REVO scanner was released in 2020, making it the lowest cost hand-held SLAM at the time (GeoSLAM, n.d.).

The used PMLS device is relatively cheap, light, portable and mainly it is used for interior surveys. In this version of the device, the camera is not included in the system, so the processed point cloud is not colored from images, but only by height. It is one of the simplest devices that has a limited range and does not have a direct visualization display. Data is required and stored automatically and can be only checked after exporting to a computer in the GeoSLAM HUB software. The data acquired is not unnecessarily large (as it is for example with TLS) and is suited basis for the spatial component in BIM.



*figure 12 - Personal mobile laser scanner ZEB REVO GO
source: www.geoslam.com*

ZEB-REVO handheld mobile laser scanners combine time-of-flight line scanners with an inertial navigation unit to record the spatial attitude of the scanning plane without the need for satellite navigation systems. The position of walls around the scanner is determined using a simultaneous location and mapping algorithm. SLAM algorithms assume that the scanner's surroundings are static, retain recognizable geometries and do not deform (Bosse et al., 2012).

Technical specification	
Range	30 meters
Field of view	360° x 270°
Frequency	40 Hz
Processing	Post
Datalogger carrier	Backpack
Scanner weight	950 g
Datalogger weight	1.7 kg
Colorized point cloud	X
Intensity	X
Scanner points per second	43 000
Number of sensors	1
Relative accuracy	1-3 cm
Raw data file size	100 MB/minute
Datalogger internal memory	128 GB

table 3 - Technical specifications of ZEB REVO GO
source: Author's creation based on data from www.geoslam.com

Although the ZEB-REVO does not have the millimeter accuracy that the conventional laser scanners have, it excels in speed and mobility of measurements. Just to have a perception, a completely regular covered building with an area of more than one hectare could be documented in about an hour.

During the measurements, the device was slowly carried by the operator, starting and ending at the same place. It has ability to keep the navigation for up to 50 minutes without further intervention or information. The amount of data from this device is around 300 MB from a 40-min survey through an object. Data processing is fully automatic, with accuracy in this case sufficient, reaching 1-3 cm in a position with a range of up to 30 m (scan rate: 43 thousand points per second) (Table 3.).

There were a little over 9 million points in the point cloud scanned and processed by the PMLS in this project, that were filtered and modified after with deleting the surrounding irrelevant points and leaving only the object of interest (Figure 13.).

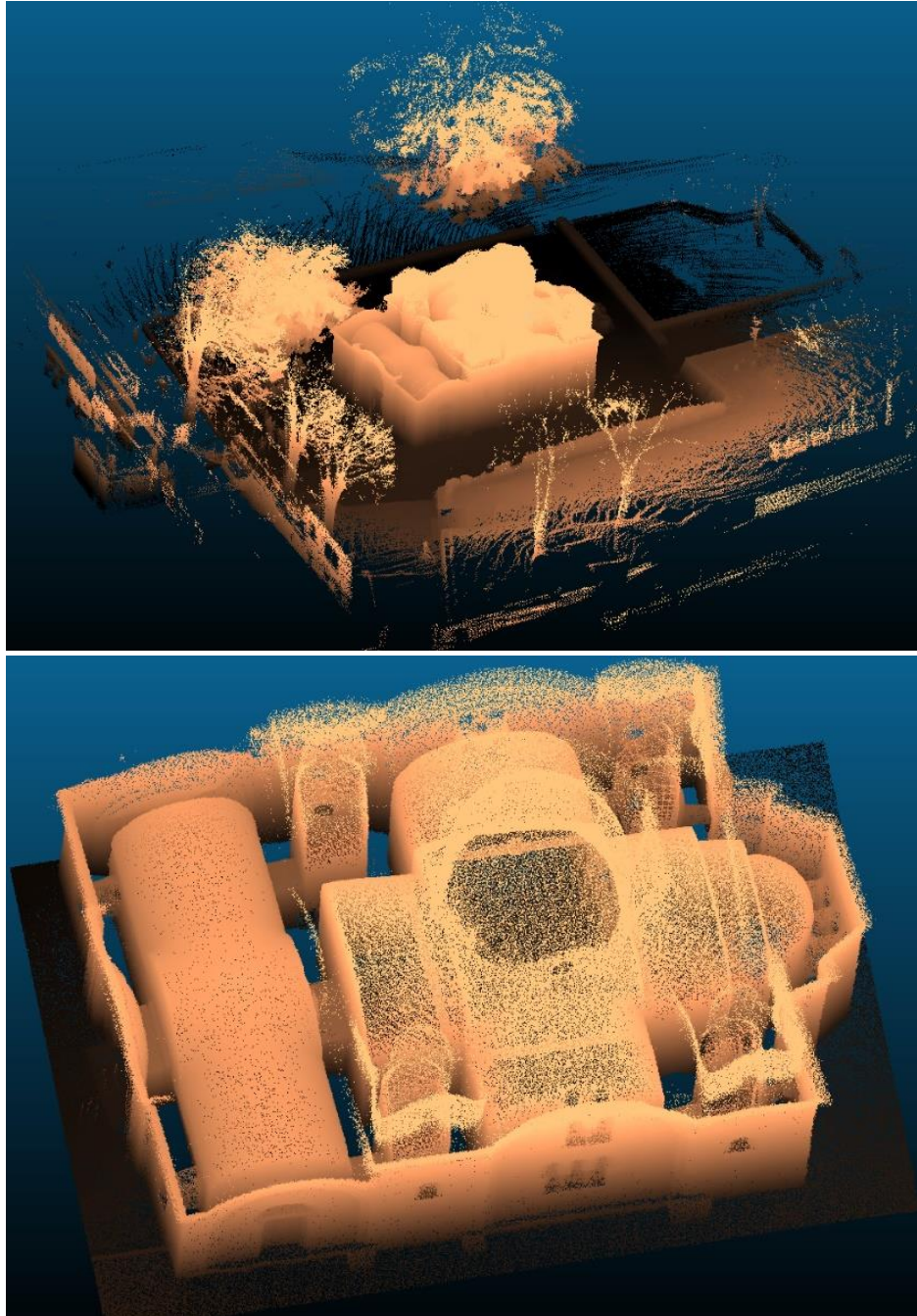


figure 13 - Point cloud from PMLS

4.4. Leica BLK360

In the plan for the field measurements of the building of interest in this thesis, terrestrial laser scanning was put as an important method for data acquisition from the outside and from the inside too. As one of the newest easy-to-use devices in the Laboratory of photogrammetry (Department of geomatics, Faculty of Civil Engineering, CTU), the laser scanner Leica BLK360 was planned to be used for this purpose. However, due to some technical issues with the device, after several scans from different standpoints, it was not possible to capture the whole building and was decided, the scanning to be done just by the PMLS as an alternative.

Nevertheless, since the goal of the thesis is to present different, modern methods and devices used in documentation of historical buildings in cultural heritage, a short overview of this MLS device will be added to this chapter.

BLK 360 is a product of Leica Geosystems, a Swiss company that produces geo-products and complete solutions systems for geodetical surveying.

The Leica BLK360 (Figure 14.) is an advanced precision imaging laser scanner that is extremely simplified to use. It is a one-button device that enables capturing a full scan with spherical images in less than a minute. Part of the system is a *visual inertial system technology*, which automatically combines the scans on-site and speeds up the workflow (Leica Geosystems, n.d.).



figure 14 - Mobile laser scanner - Leica BLK360

Technical specification	
Operational Range	0.6 - 30 meters
Ranging error (at ~10 m)	± 4mm
Field of view (vertical/horizontal)	300°/360°
Embedded camera	3x15 MP + thermal camera
Scanner points per second	up to 360 000
Scanner weight	1 kg
Colorized point cloud	✓

table 4 - Technical specifications of Leica BLK360
source: Author's creation based on data from www.leica-geosystems.com

Controlling the imaging laser scanner is possible with the *Leica Cyclone* mobile-device application (smartphone or a tablet), where the image and point cloud data is streamed via Wi-Fi with full data synchronization between devices.

The enclosed LiDAR sensor and the embedded cameras capture high-quality images/point clouds and all the details even in challenging lighting conditions and environments. The colorized point clouds are outcome of the automatically combined scans and can be exported as different formats – LGS, RCP or E57 files. Also, it is possible for the user to control the imaging laser scanner and to immediately view captured data for on-site feedback and quality control through another application *BLK Live*.

Finally, the newest devices of BLK360 enable sharing the data with others and directly upload to the cloud-based storage as an OBJ file, allowing others to work with or download the data (Leica Geosystems, n.d.).

5 Case project

5.1. Object of interest

A small church of St. Panteleimon, located in a monastery complex in the village of Gorno Nerezi (commonly just Nerezi), on the slope of Vodno Mountain in Skopje, Macedonia, preserves some of the finest examples of fresco from the Byzantine³ period (Figure 15.). The Byzantine Empire is well known for its glittering, gold mosaics, but the medieval artists of Byzantium were also accomplished at a wall painting technique known as *fresco* – a less expensive method than mosaics in which artists applied pigments to wet plaster so that the painting becomes chemically bonded to the wall itself.

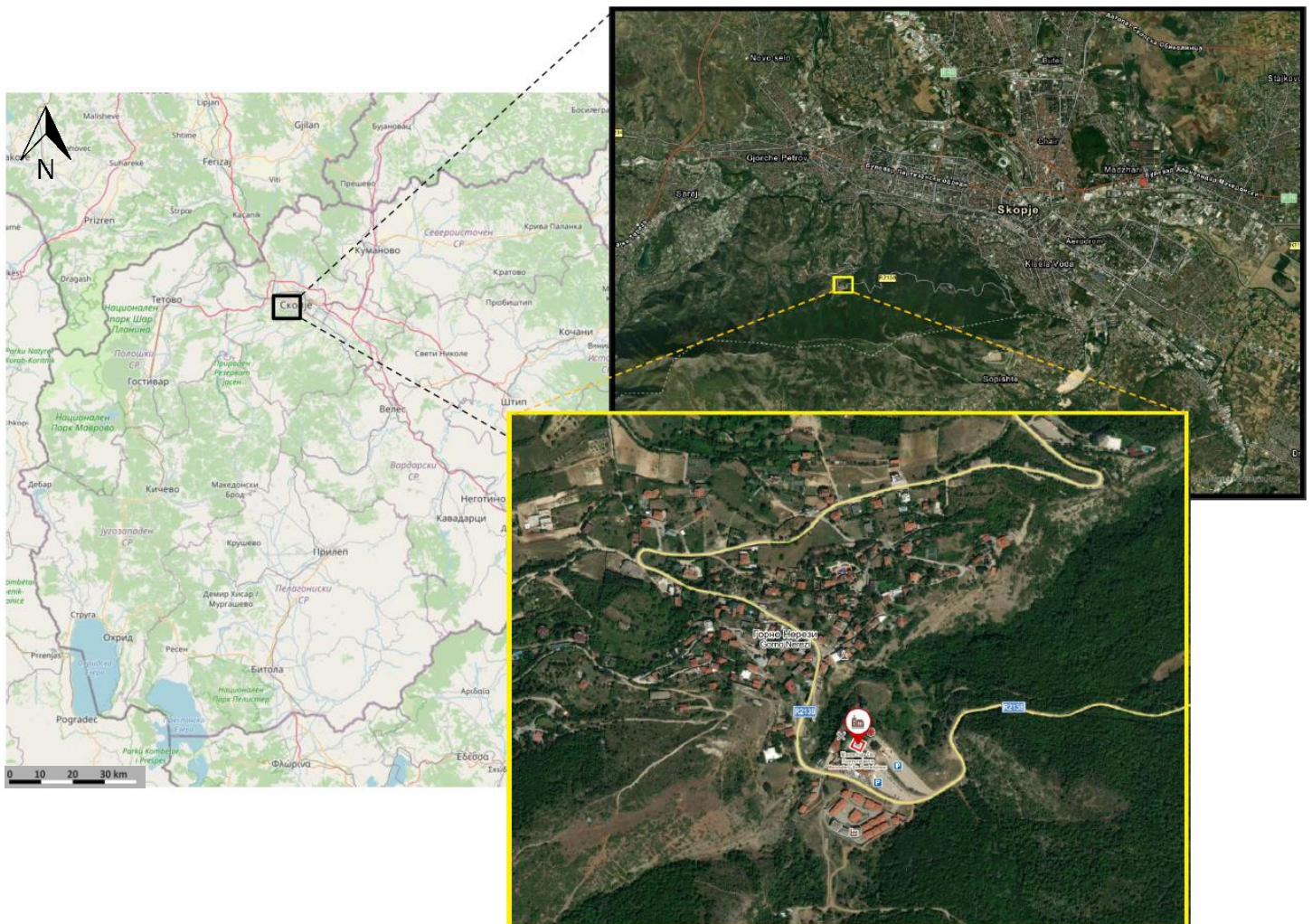


figure 15 - Location of the church St. Panteleimon (WGS84 coordinates – 41°58'36.7"N, 21°22'28.1"E)

³ Byzantine – The eastern half of the Roman Empire; was the continuation of the Roman Empire in its eastern provinces during Late Antiquity and the Middle Ages, when its capital city was Constantinople (today Istanbul)

The church of St. Panteleimon at Nerezi is one of the major surviving monuments of twelfth-century Byzantium. Created by some of the most talented Byzantine artists from the period of the second half of the 12th century and produced by a member of the highest court nobility and the mainstream political elite at that time, the church of Saint Panteleimon in Nerezi stands as a precious reflection of the overall rise of the Empire in the refined medium of supreme artistic creation. Although it is located on the Byzantine periphery, this church stands as an important testimony to twelfth-century Constantinopolitan artistic and architectural trends because of its five domes that emulate the famous buildings of the Byzantine capital, Constantinople (Dimitrova, E., 2015).

According to the painted inscription in the church, it was built in 1164 by *Alexios Komnenos*, a member of the famous Komnenian dynasty that ruled Byzantium during the eleventh and twelfth centuries. The St. Panteleimon church is one of a very few surviving five-domed buildings and so it highlights this important, but rarely preserved architectural type. It was built by a group of talented unknown master-builders, using ordinary blocks of stone and bricks with great artistry that merged into multicolored surface (Sinkevic, I., 2000).

Positioned on the mountain ridge, which offered a beautiful panoramic view of the medieval Skopje, the temple of Nerezi with its specific architectural forms decorated this high geographical position until the year 1555 when a strong earthquake caused cracks in the sensible structure of the central dome. With the commitments of the local builders and some of the skillful painters from the mid-sixteenth century, the church was repaired and the paintings which had been devastated due to the upper part of the building were replaced with a new fresco decoration created by post-Byzantine painters. Thus, with a span of four centuries after its creation, the church has turned into a visual monument of two eras since its lower zones shimmered with the stylish qualities, authentic to Byzantine frescoes, whereas the paintings in the dome and the area under the dome represent the modest features of the artists of the late medieval era (Dimitrova, E., 2015).

From architectural point of view, St. Panteleimon is a modest, cross-domed structure with four smaller domed chapels, making it a five-domed church, very similar to the form of some of the famous imperial churches of the Byzantine capital – also, reflecting the connections with the capital and the imperial family. The presence of the five domes, which crown the church and represent its most distinguished architectural feature, seemingly recall the original intent of its builder.

It is a cruciform church, 15.90 meters long and 9.60 meters wide. Irregular in its layout, the church is of a rhomboidal, rather than a standard rectangular form. The interior is composed of a cruciform naos, a bema, a narthex and four side chapels located between the arms of the cross (Figure 16.). Its exterior, considerably restored since the construction of the church, displays an odd combination of a variety of building techniques which reveal more about the history of the structure than about the initial appearance of the church (Sinkevic, I., 2000).

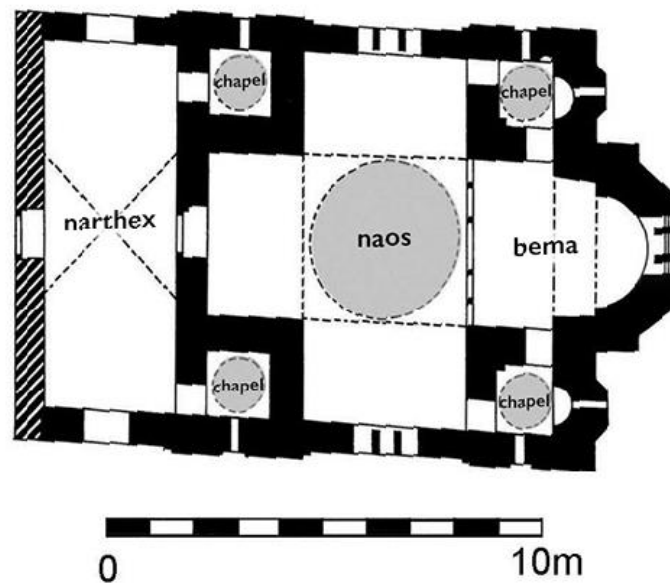


figure 16 - Ground plan – setup of the interior components

The exterior of the church is distinguished by five domes. The central dome is elevated on an octagonal drum and reaches the height of 11.70 meters. The four additional domes are raised on cubical drums, reaching the height of 9 meters. The drums have single-light windows on each of their faces. On both, north and south facade, there are three-light window on the central lower part, topped by a two-light window in the upper part and two single-light windows on the sides. The east facade is distinguished by a three-light window and two single-light windows. The west facade displays the main entry and two single-light windows on the north and south sides.

The exterior of the building exhibits many irregularities. The unconventional shape of the building (diagonally ‘stretched out’ on the south-east and north-west corner) or the lack of alignment of the windows are just some of them. However, the structure details, facade decorations, compositional aspects etc. are topics for a different survey and research and will not be analyzed, as it is not primarily this thesis’ main target.

5.2. Data

The trip to Skopje and the actual field survey of the church was realized in the end of March, 2022. The object of interest was captured and scanned in almost perfect weather condition (cloudy, without Sun), which is a very important factor regarding accuracy and quality when capturing images with close-range/aerial photogrammetry. Since the point cloud acquired from PMLS is not colored, the weather conditions do not affect this method as much.

The complete data acquired from the field survey consists of three easy-to-use, low-cost photogrammetry technologies:

- close-range photogrammetry was used to capture 171 images in total, which are in *.jpg* image format with data size of 1.81 GB;
- with aerial photogrammetry there were 229 images captured and exported in *.dng* image format with total data size of 3.9 GB and also in *.jpg* image format with total size of 834 MB. As the set of images in *.jpg* format is significantly smaller in size than the *.dng* format, in the processing were only used images from this set;
- PMLS was used to scan both the interior and exterior of the building. The point cloud was exported as a *.laz* format file, which has size of 42 MB.

The common thing about all the used technology is that all of them create a point cloud, which is later the base for the 3D model creation, processed by specialized software. All of the point clouds and its outputs are suitable for future building archaeology survey and provide sufficient information for research work.

Following, the most important and time-consuming part of the project was to process all the data that was acquired and to create many different outputs in order to make the documentation of the object 'as rich as possible'.

5.3. Data processing

In the process of making the outputs of this thesis, different civil engineering software and tools were used, in order to create the complex documentation of the building, as planned.

Point clouds from the three data-acquisition methods are used as a base for all the processed outputs afterwards. Unlike the point cloud from PMLS method, which is the actual output from the scanning, the point cloud from the image-based methods needs to be generated in a software from the images captured in the field. Agisoft Metashape was used for that purpose and for the following 3D model creation from close-range photogrammetry and RPAS data. Each point cloud was 'cleaned' using manual and semiautomatic selection tools.

In addition to this chapter, the process of creating all the outputs in different software, together with the processing parameters and the partial results will be presented.

3D Model in Agisoft Metashape Professional

Agisoft Metashape Professional is a multifunctional software for photogrammetric processing of digital images. It is a software developed by Agisoft LCC with the initial version from 2006 named Agisoft PhotoScan.

The main task of this software is a creation of 3D models from imagery data and it is used for both aerial and terrestrial photogrammetry. The resulting outputs could be in different forms. It can be a *Dense point cloud*, a textured and colored *Mesh*, or a *Digital surface model* and *Orthophoto* if it comes to aerial images. The software is multifunctional not only for generating spatial data from classic RGM images, but also for processing e.g., multispectral or thermal data on which different analyzes can be done. Almost all the calculations performed in Agisoft are semiautomatic. With the correct setting of the parameters in the individual steps, it is possible to obtain results with millimeter accuracy. However, what matters the most is the quality and resolution of the input data. There are some recommended requirements for the minimum parameters of the computer's processing performance and usually the duration of the calculation process depends mostly on it.

In this thesis, Agisoft was used for generating a 3D model from the set of images from close-range and aerial photogrammetry.

After importing the images in the software, the data processing was made in several steps that follow consecutively to complete the whole workflow. Every step is started manually with defining required parameters:

- Load camera positions and check camera calibration – all 400 acquired images were imported and image quality was estimated and inspected for inappropriate (less quality) images. The software performs a self-calibration, but it is also possible to import calibrated internal orientation elements in this step
- Align photos – at this stage the software finds matching points between overlapping images, estimates camera position and orientation for each photo and builds a sparse point cloud model. Important parameters in this calculation are: *accuracy*, with which the system will estimate the internal orientation elements, *pair selection*, which defines how will the pairs (connection points) be calculated, *key point limit*, sets the maximum number of feature points on every image to be taken into account during current processing stage and *tie point limit* defines the maximum number of matching points for every image. On Figure 17. the set parameters are shown for the calculation of the sparse point cloud

Property	Value
Tie Points	
Points	153,907 of 920,936
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	4.31734
Alignment parameters	
Accuracy	High
Generic preselection	Yes
Reference preselection	No
Key point limit	40,000
Tie point limit	10,000
Guided image matching	No
Adaptive camera model fitting	No
Matching time	19 minutes 37 seconds
Matching memory usage	436.10 MB
Alignment time	15 minutes 40 seconds
Alignment memory usage	361.80 MB
Optimization parameters	
Parameters	f, cx, cy, k1-k3, p1, p2
Adaptive camera model fitting	No
Optimization time	7 seconds

figure 17 - Align photos - calculation parameters

- After the sparse point cloud was calculated, a camera optimization and filtration of the points were done. Important parameters in this step are: *reprojection error*, *reconstruction uncertainty*, *image count* and *projection accuracy*. Only one parameter at a time is set and the selected points are deleted.

After each selection, a *cameras optimization* should follow for bundle adjustment. The resulting, filtered sparse point cloud is shown on Figure 18.



figure 18 - Cleaned' sparse point cloud

- Build dense point cloud – based on the estimated camera positions, the program calculates depth information for each camera to be combined into a single dense point cloud. The dense point cloud can be edited and classified within Metashape environment and used as a basis for such processing stages as *Build mesh*, *Build DEM*, *Build tiled model*. Alternatively, the point cloud can be exported to an external tool for further analysis. Parameters that can be modified at this stage are *quality* and *depth filtering*. *Quality* specifies the desired reconstruction quality and defines if the system should work with full image resolution (*ultra-high* – obtains more detailed and accurate geometry, but require longer time for processing), or with lower image resolution in the processing. *Depth filtering* is the stage when Metashape calculates depth maps for every image and filters the cloud for outliers.

On Figure 19., the parameters that were set for the dense point calculation and information about its generation are shown.

Property	Value
Dense Cloud	
Points	35,385,348
Point colors	3 bands, uint8
Depth maps generation parameters	
Quality	High
Filtering mode	Moderate
Processing time	5 hours 18 minutes
Dense cloud generation parameters	
Processing time	3 hours 10 minutes

figure 19 - Build dense cloud - calculation parameters



figure 20 - Dense point cloud

Even though for the calculation of the dense cloud the source data was a ‘cleaned’ and filtered sparse cloud, the generated dense point cloud needs to go through another filtration and editing. It was done manually with the selection tools in Metashape and errors like *noise* and points outside the area of interest were deleted. On Figure 20. the final dense cloud is shown, which was transformed into 3D model in the next step.

- Build mesh – polygonal, colored, mesh 3D model based on the dense cloud data. *Arbitrary* surface type was chosen in the reconstruction parameters, since it can be used for modeling of any kind of object (statues, buildings etc.). On the contrary, *heightfield* surface type is optimized for modeling of planar surfaces such as terrains or reliefs. Dense cloud was set as a source data and *high* option was specified for the quality of the depth maps, which is more detailed and accurate, but require longer time for processing. Entry values and other parameters for the calculation of the Mesh 3D model are shown on Figure 21.

Property	Value
Model	
Faces	7,077,069
Vertices	3,540,579
Vertex colors	3 bands, uint8
Texture	4,096 x 4,096, 4 bands, uint8
Depth maps generation parameters	
Quality	High
Filtering mode	Moderate
Processing time	5 hours 18 minutes
Reconstruction parameters	
Surface type	Arbitrary
Source data	Dense cloud
Interpolation	Enabled
Strict volumetric masks	No
Processing time	22 minutes 2 seconds
Texturing parameters	
Mapping mode	Generic
Blending mode	Mosaic
Texture size	4,096
Enable hole filling	Yes
Enable ghosting filter	Yes
UV mapping time	6 minutes 7 seconds
Blending time	37 minutes 54 seconds

figure 21 - Build mesh - calculation parameters

- The resulting 3D model was textured, which helps to obtain optimal texture packing and consequently, better visual quality of the final model. On Figure 22. is shown a detail from the textured model (left) and from the meshed model (right). The improvement in the visual quality is noticeable on the textured model, which is the final 3D model and the first output from this thesis (see 5.5.).



figure 22 - 3D model in detail - textured (left), mesh (right)

BIM – Model in Revit

Building Information Modelling has the potential to become the biggest step change in the way that the construction industry operates within the built environment, since the industrial revolution promising major benefits in terms of cost, accuracy and time to build. Since the concept of BIM emerged, the debate has continued around the value and application, but as more countries make BIM a legislated requirement, the debate is no longer whether BIM should be adopted, but rather how it can be successfully implemented, and how its full value can be unlocked.

Revit is a BIM software that helps architecture, engineering and construction fields to create a high-quality buildings and infrastructure. Since 2002 it is a product of the company Autodesk, which developed and significantly improved it as one of the most popular software for BIM.

For the purpose of this thesis, Revit software was used for creating a model, based on the combined point cloud from all the acquired data. For combining and aligning the different point clouds, Cloud Compare was used – an open-source software specialized for operation with point clouds. Since the dense cloud from Metashape is over 35 million points and in addition, there are over 9 million points in the point cloud from the PMLS, certain modifications to the combined cloud needed to be done in order to import it in Revit.

Firstly, a rough, general cleaning of the point cloud from PMLS was done i.e., the surrounding building, trees, bushes and other objects that are not important for the creation of the model were removed.

The alignment of the point clouds in Cloud Compare was done by picking equivalent point pairs on both point clouds. The final, homogenous point cloud was unnecessarily too big (~45 million points) for this purpose, so the spatial subsample function in Cloud Compare was used. In modeling, point clouds are used as a reference, so for the object of interest in this thesis, since it was not crucial to have the model with high precision, having that big point cloud would only slow down the processing. In the spatial subsampling, a minimum distance of 2 cm between points was set. This resulted in a filtered point cloud containing a little over 2 million points, which was optimal solution.

After all the previous adjustments and processing, it was necessary to prepare the final point cloud in a format that the software Revit could recognize to import. It was done in another software Autodesk ReCap where the *.las* point cloud was transferred to a *.rcp* format file.

The reduced point cloud was exported as a *.rcp* file so it can be recognizable for Revit and was imported in the program for the modelling part.

In Revit, it was started with defining the drawing setup i.e., creating the floor plans (levels) and building sections for a better orientation in the model (Figure 23.). The first level is defined so it is the lowest point of the building (zero point) and the heights of the rest of the levels are measured from it.

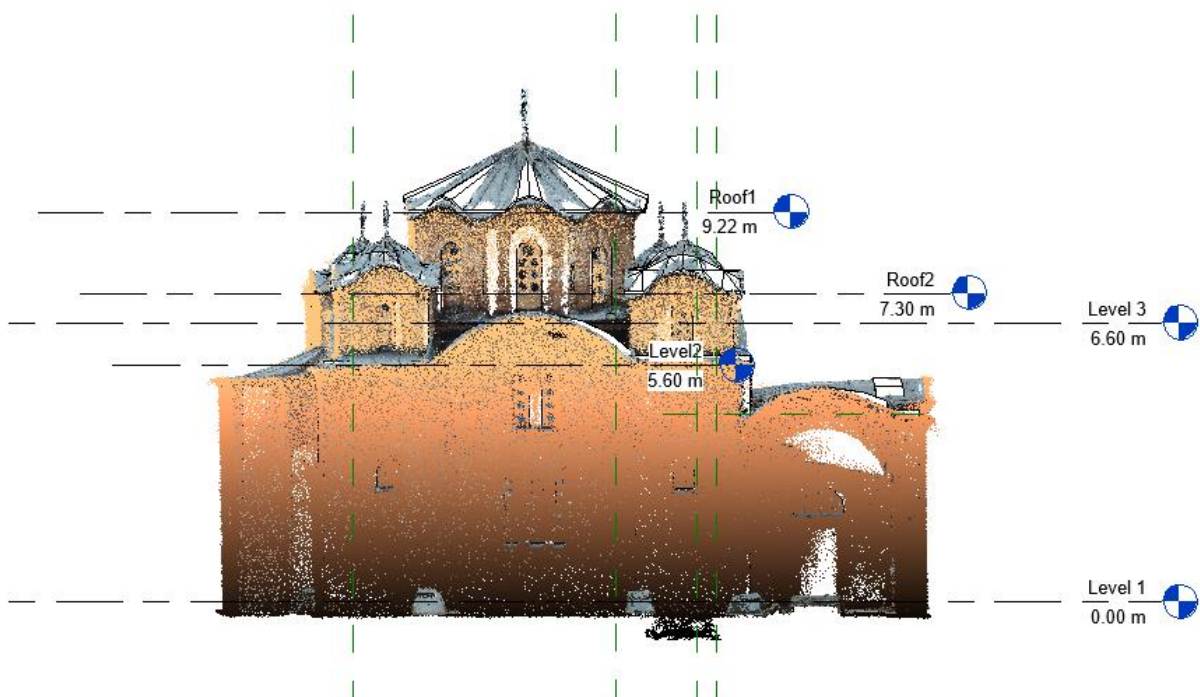


figure 23 - Setup of the floor plans (levels)

The modeling process was based mainly on the point cloud. In the section of the Level 1, the modeling was started with creating the bearing walls (Figure 24.).

Almost all of the modeling was done with the functions in the *Architecture* panel. The workflow was done by the 'rule' that the rough modeling is done first and then the details are modeled afterwards. The creation of the 3D model in the software Revit was the action that probably took most of the time in the process of making this documentation of the historical object.

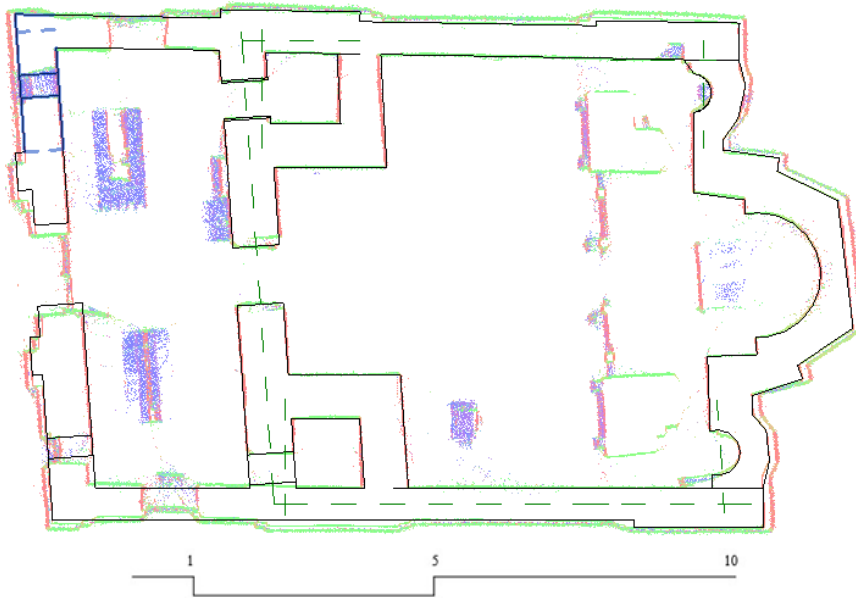


figure 24 - Floor plan (Level 1) - modeling the walls using the point cloud as a reference

After modeling the basis in Revit (Figure 25.), the actual version of the model was exported and the knowledge in the software SketchUp was used to model the more complicated shapes and details. This included the windows, the doors, part of the roof, the cross-shaped ceiling, the crosses on the roofs and other facade details.

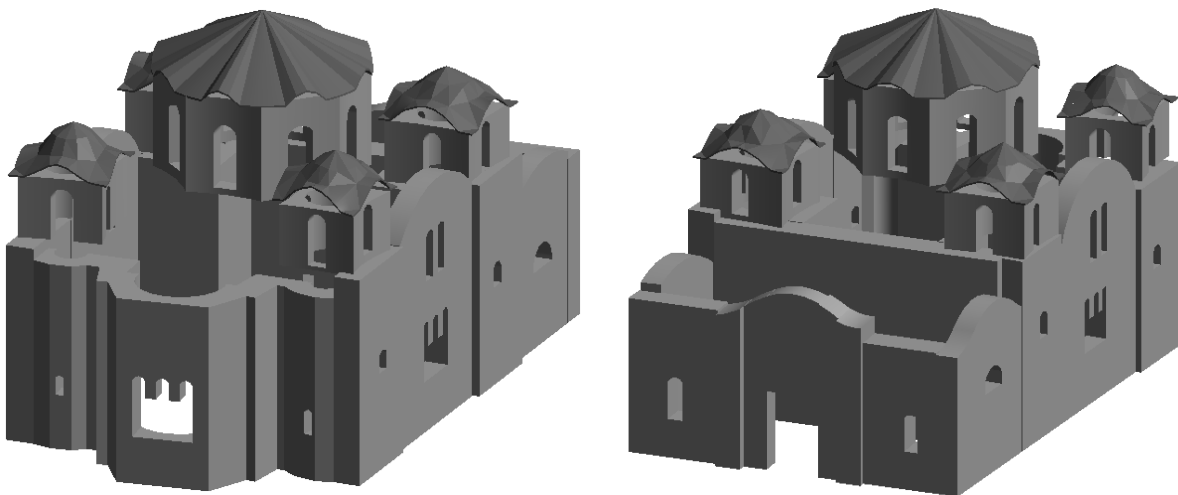


figure 25 - 3D Model exported from Revit

SketchUp is a product of Trimble, which is a great tool in geomatics and architecture for 3D modelling. It works on the sketch-based modelling approach and supports 2D and 3D model export functions among other features.

This software was used to finish the model from Revit i.e., to model the details on the building as well as the surrounding for better visualization.

The model was imported into SketchUp as a *.dwg* format file. The windows and the doors were created as groups, or for the ones that were repeating – as components. For the profiles of the missing roofs, the *Follow me* tool was used, where it was drawn and then extruded. Useful tools for modelling in this software are the *Offset* and *Push/Pull* tools. It was used to create the levels on the facades and also for the crosses as the final detail on the building. Additionally, some of the walls needed to be corrected, so the option for *Face intersection* helped with cutting and removing unnecessary parts of the modelled walls.

In the interior, the ceiling has quite complicated shape, so for the irregular parts of the ceiling it was necessary to create different small surfaces and combine them into bigger one.

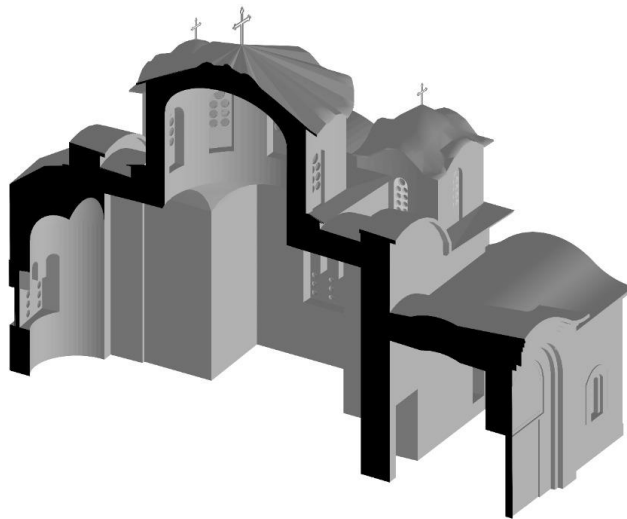


figure 26 - Horizontal section in the 3D BIM model

Finally, some textures were applied to the model and it was exported as a 3D model (.fbx format file) for the transfer to virtual reality. On Figure 27. below, the finished model is shown without any texture.

This software offers a lot of design options, so the final 3D output for the BIM model was ‘decorated’ with texture and surroundings for better visualization (see 5.5).

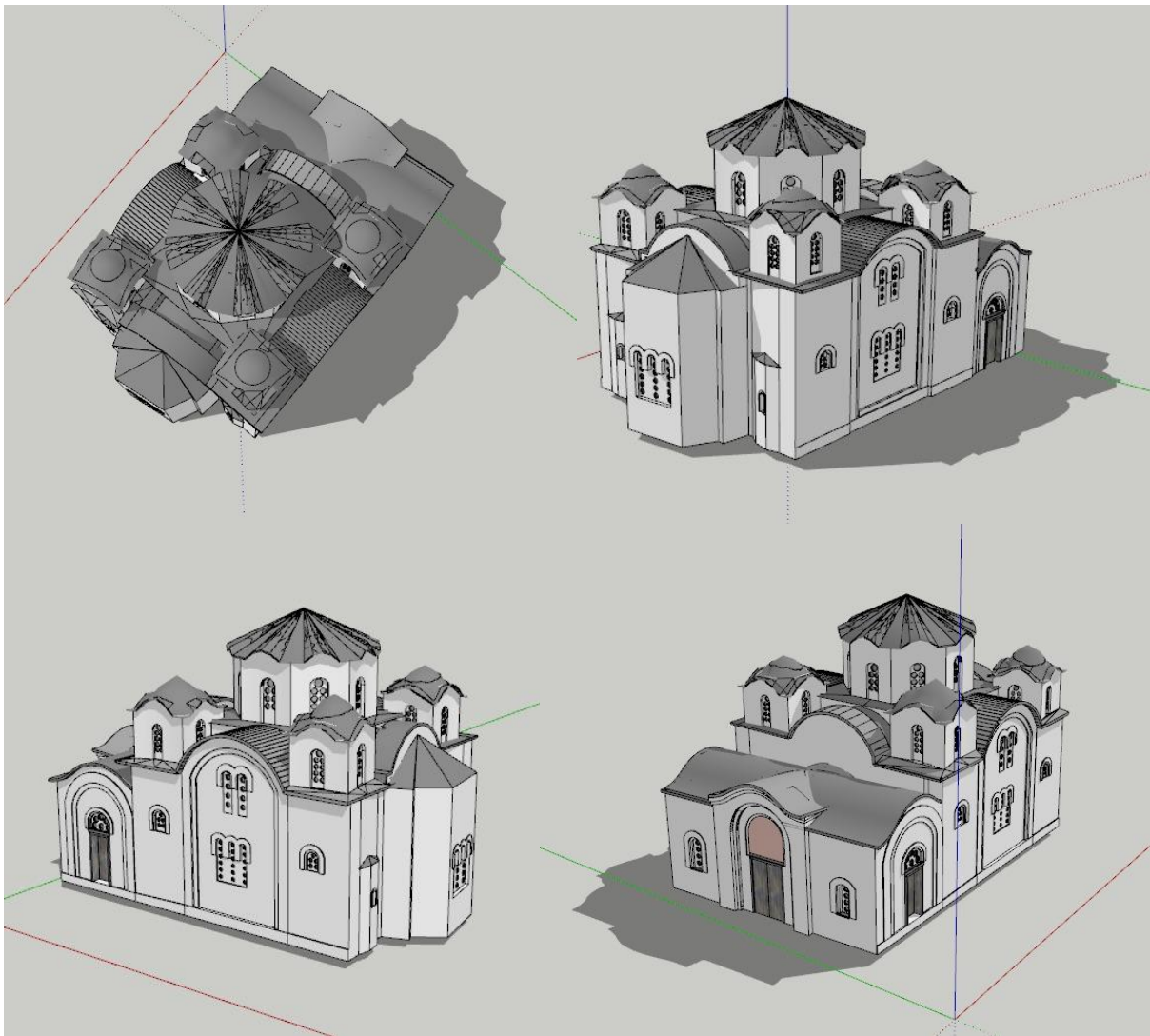


figure 27 - 3D BIM model not textured

GeoSLAM Hub – point cloud sections

GeoSLAM Hub software is a licensed processing platform from GeoSLAM for the data acquired with their personal laser scanners. The Hub software is a powerful tool for the SLAM technology that offers fast and quality post-processing in order to deliver complete end-to-end solutions. The main processing that can be done in the software are (GeoSLAM, n.d.):

- SLAM processing to generate accurate 3D point clouds from the acquired data
- Import, view and interrogate data captured from all GeoSLAM devices
- Geo-referencing of datasets to control
- Provides survey-grade data accuracy without the surveyor
- Quick and easy workflows with drag and drop functionality; produces results in minutes

The acquired data for this project was imported in the software and inspected for any errors. The point cloud was satisfactory, so the next step was cleaning the point cloud from the surrounding environment that was unnecessary for the project and preparing it for the next operations. On Figure 28. the imported point cloud from the PMLS is shown and the scanning trajectory from the operator (red line).

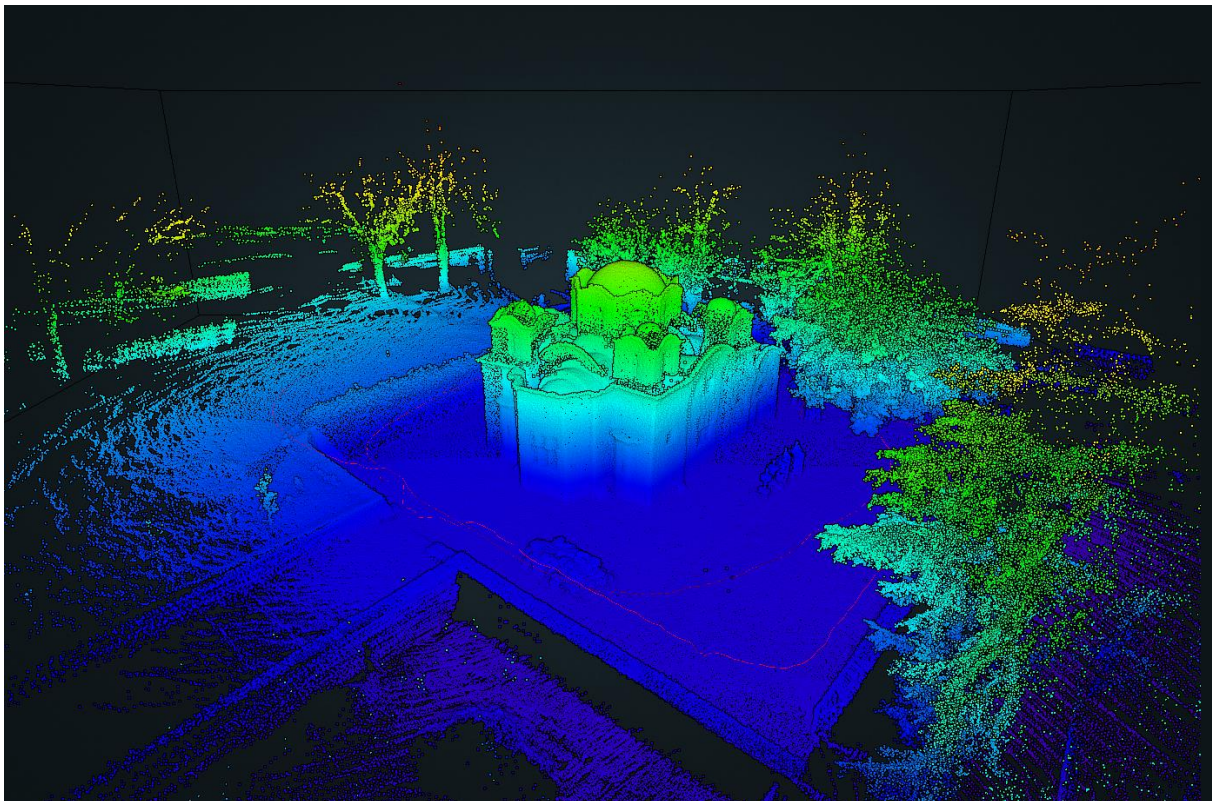


figure 28 - GeoSLAM Hub - Point cloud from PMLS

The software GeoSLAM Hub offers an automatic vectorization and creation of a floor plan, which was tested as well, but although the resulting drawing was satisfactory, it was also vectorized manually and exported to AutoCAD for making the whole output composition (see 5.4.).

Different horizontal and vertical sections of the point cloud (Figure 29.) were also made in Hub, with which the workflow in this software for the purpose of this thesis was completed.

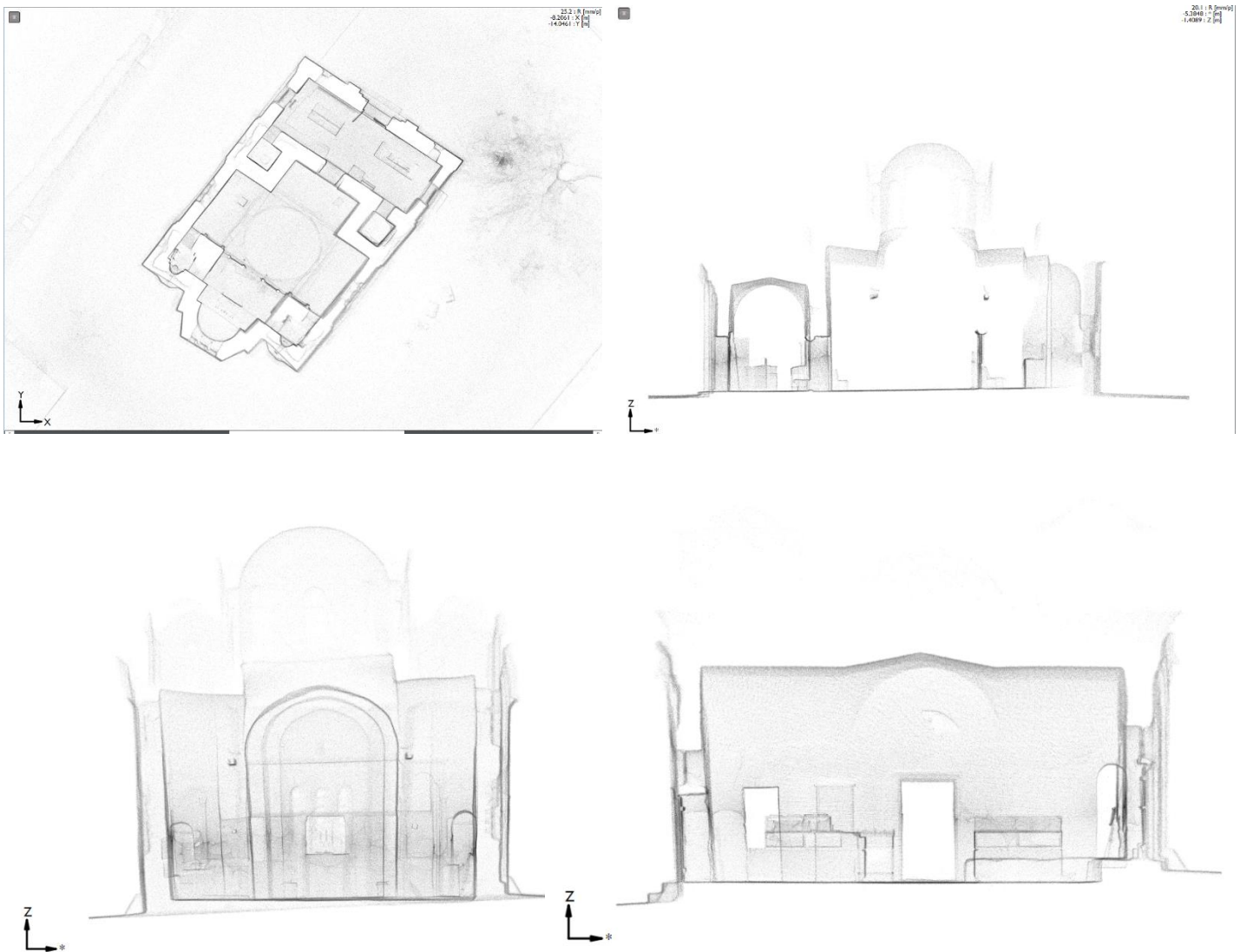


figure 29 - Point cloud sections in GeoSLAM Hub

VR Model in Unreal Engine

A different and quite popular approach nowadays to visualization of historical objects in a different way, is the virtual reality technology. It generates a visual experience that gives an impression of the reality using stereoscopic imaging device, usually in the form of special glasses.

In this project, the BIM model that was created in Revit/SketchUp was transferred to the VR game environment Unreal Engine. It is an open-source engine for advanced real-time 3D creation and experiences.

Before the import of the model into the virtual environment, it was necessary to make some adjustments to the model to ensure a correct visualization.

The input for this technology was the non-textured BIM model. The advantage of having created another 3D model from the imagery data in Agisoft was helpful for orientation of the BIM model and giving a texture from the images. For this purpose, in Agisoft the BIM model was imported and positioned on the same place as the model from combined close-range terrestrial and aerial photos and was projected a texture from the photos.



figure 30 - Final BIM model with projected texture

The BIM model was better to transfer to the VR engine in comparison to the photogrammetric model mainly because it consisted of considerably less polygons (low - poly) which is very important for the VR in terms of performance of the machine as well as storage and manipulation with it (Figures 31. and 32.).



figure 31 - BIM model - Wireframe 108 thousand polygons

The photogrammetric model when presented as a wireframe model has a little over 4.5 million polygons (high – poly). In order to import it to the game engine, it would be necessary to decimate and edit it to reduce the number of these faces.

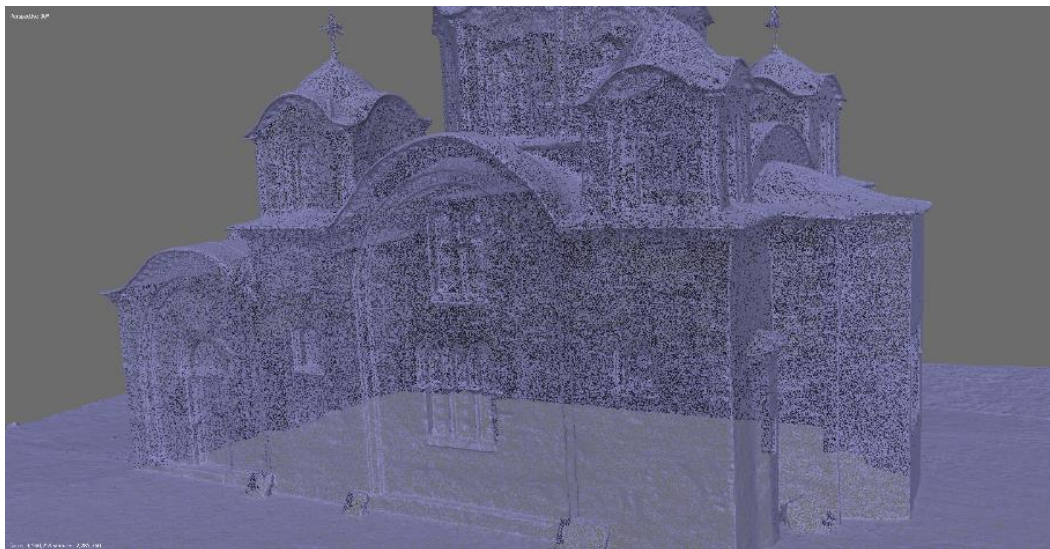


figure 32 - Wireframe close-range photogrammetry model - 4.5 million polygons

When importing the model into Unreal Engine, an already existing template was chosen that has programmed different functions helping to create the virtual environment easily. Furthermore, the output from this technology was prepared by adding the surroundings of the building like grass, bricks etc. (see 5.5)

5.4. 2D Documentation

Nowadays, surveying with laser scanners and close-range photogrammetry technologies is generally focused to obtain 3D outputs. However, two-dimensional data is an essential part of a complete documentation in the cultural heritage field. For architectural analysis and restoration work, that could follow in the future, 2D representations are used as a resource for other experts, which can be involved in such a multidisciplinary project.

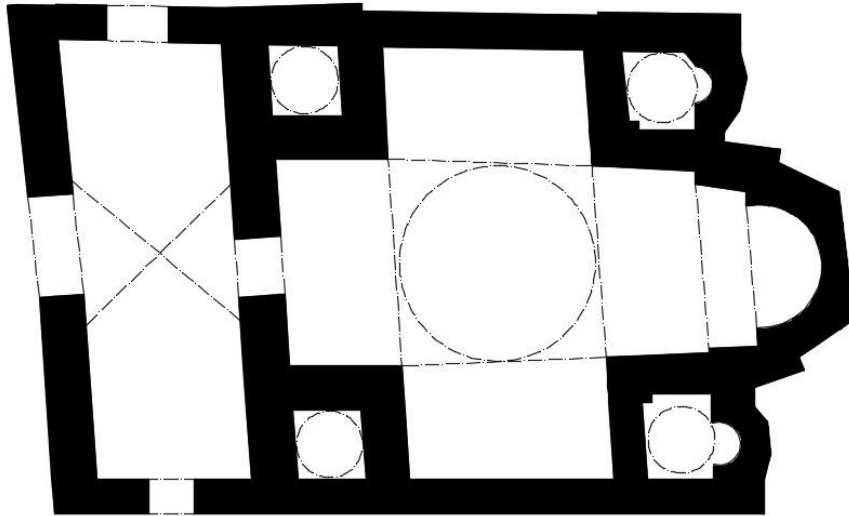
In order to document the architectural complex, for a complete and reliable knowledge of the monument and for a possible future restoration project, different 2D drawings of the building were processed to get the 2D information.

Apart from the sections of the 3D point cloud that were shown previously in the GeoSLAM Hub workflow, other different 2D drawings were created. A vectorized floorplan was made, based on the data from the PMLS and as a vertical section, derived from the BIM model.

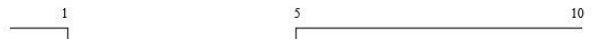
Another output that could be included in the 2D documentation is the orthophoto of the roof of the building. It was processed in Agisoft Metashape with a resolution of 5 millimeters as the last step in the previously presented workflow and together with the 3D textured model are the final outputs from this software.

Finally, this 2D documentation is completed by drawings of all the facades of the building, which are considered as outputs of the thesis and together with the previously mentioned ones, are shown in continuation of this chapter.

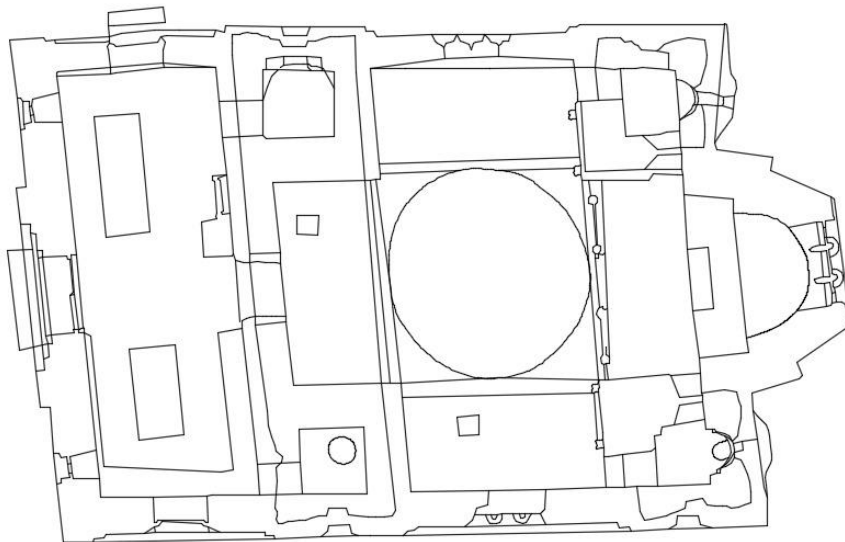
The intention of the author with this part of the chapter is to represent all the 2D outputs of the thesis, as a whole, in one place. The rest of the outputs, the 3D models, are going to be shown in the next chapter (see 5.5).



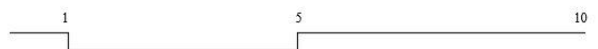
FLOOR PLAN - BIMMODEL



Created by Kuzmanov Pane
 within the Master thesis
 at the Faculty of Civil Engineering -
 Czech Technical University in Prague
 December 2022



FLOOR PLAN - P.M.S



Created by Kuzmanov Pane
 within the Master thesis
 at the Faculty of Civil Engineering -
 Czech Technical University in Prague
 December 2022

Church St. Panteleimon - roof

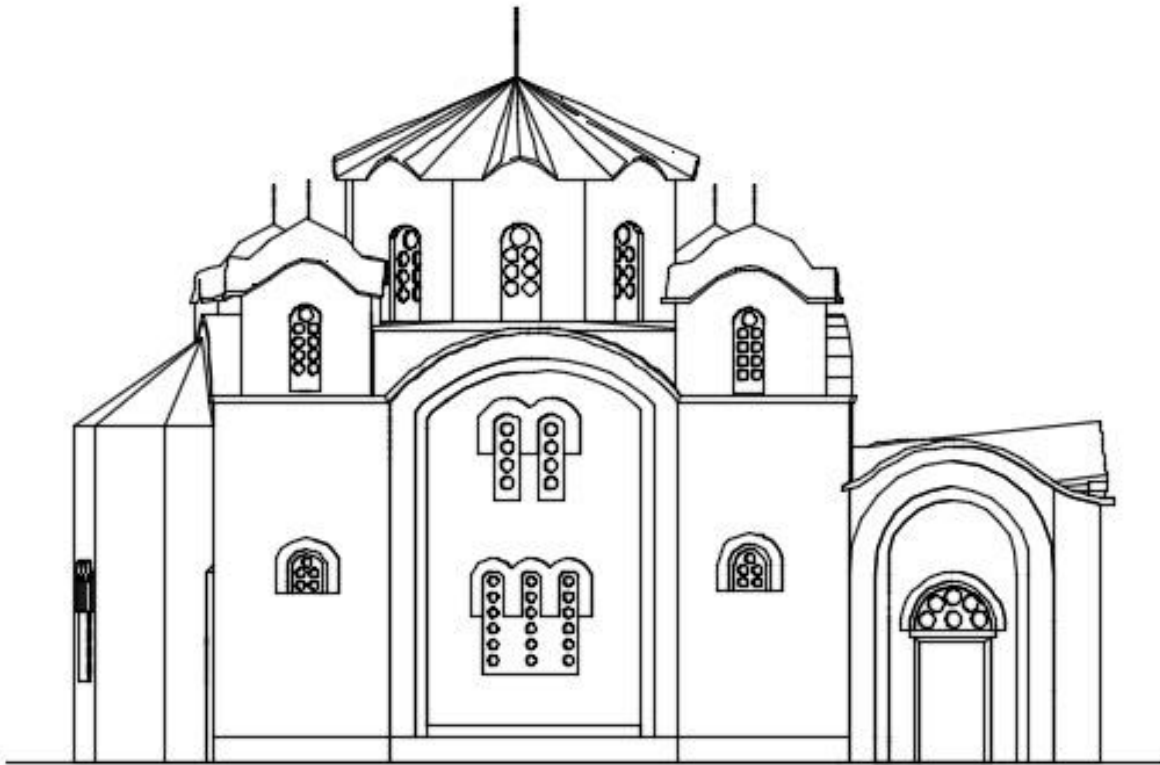


0 2,5 5 10 m

Created by Kuzmanov Pane
within the Master thesis
at the Faculty of Civil Engineering -
Czech Technical University in Prague
December 2022

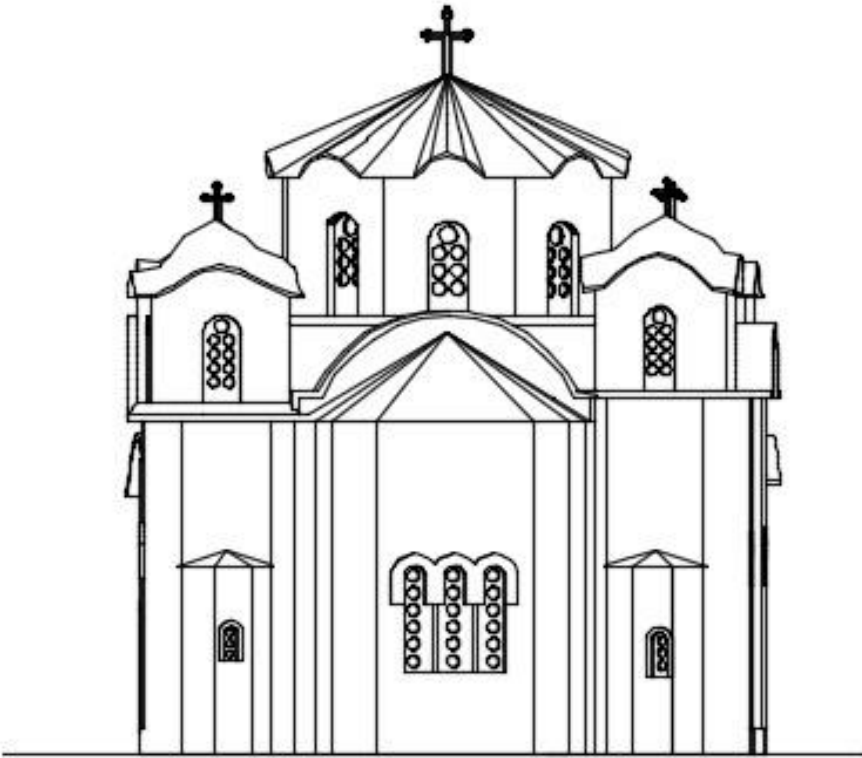


WEST FACADE



NORTH FACADE

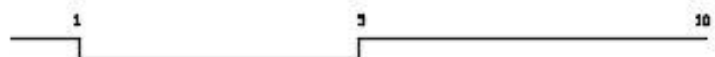




EAST FAÇADE



SOUTH FAÇADE



5.5. 3D Visualizations

In the process of creating the outputs, different software were used to process the set of 3D models and documenting the monitored historical building. The final 3D visualizations, as the most important outputs from this thesis, will be presented in this chapter.

Processing the data from this project resulted with three 3D models:

- 3D model generated in Agisoft Metashape,
- BIM model and
- 3D model transferred to virtual reality.

The models were done consecutively, meaning that the point cloud from the 3D model generated from all the acquired data, was used as a base for the production of the BIM model; following, the BIM model was given a texture from the aerial and terrestrial photos and transferred to the engine for virtual reality.

As an additional visualization, the final generated 3D models were published on the platform Goggle Earth and also, after making some essential preparations on the BIM model, it will be physically printed in 3D in the laboratory of photogrammetry, FCE, CTU.

Finally, a 3D rendering software Lumion was used to bring the 3D model ‘to life’ with surroundings like trees, grass, bricks etc.

All the 3D models are going to be available to browse at the webpage of the laboratory of photogrammetry⁴.

These outputs (2D and 3D) can be used to facilitate further recording management, research and interpretations of historical buildings for the Macedonian national cultural heritage.

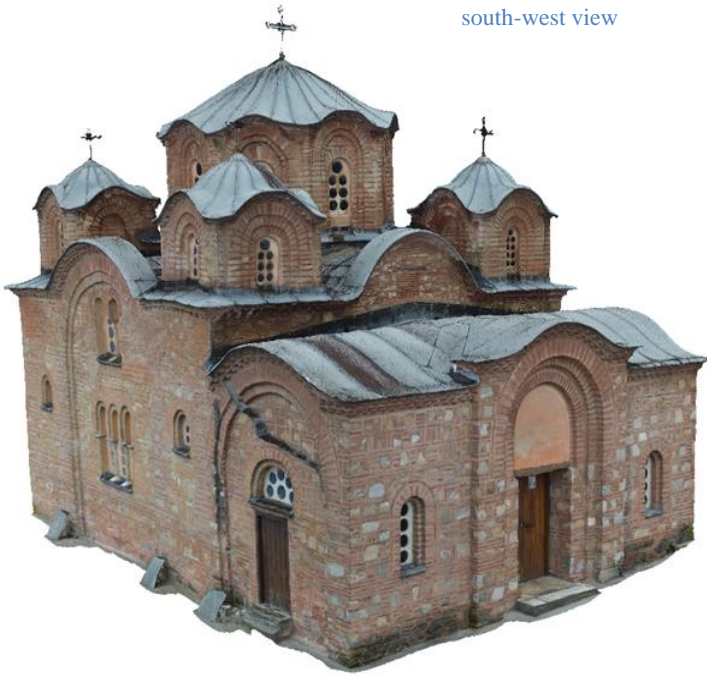
⁴ <https://lfgm.fsv.evut.cz/projekty.html>

Textured 3D Model generated in Agisoft Metashape

north-west view



south-west view



south-east view



north-east view



Textured 3D BIM Model

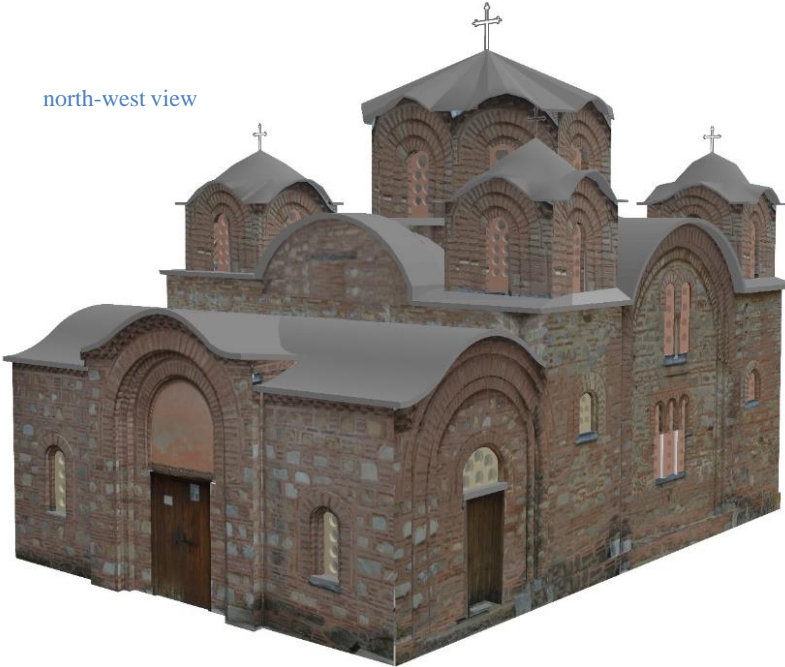
south-east view



north-east view



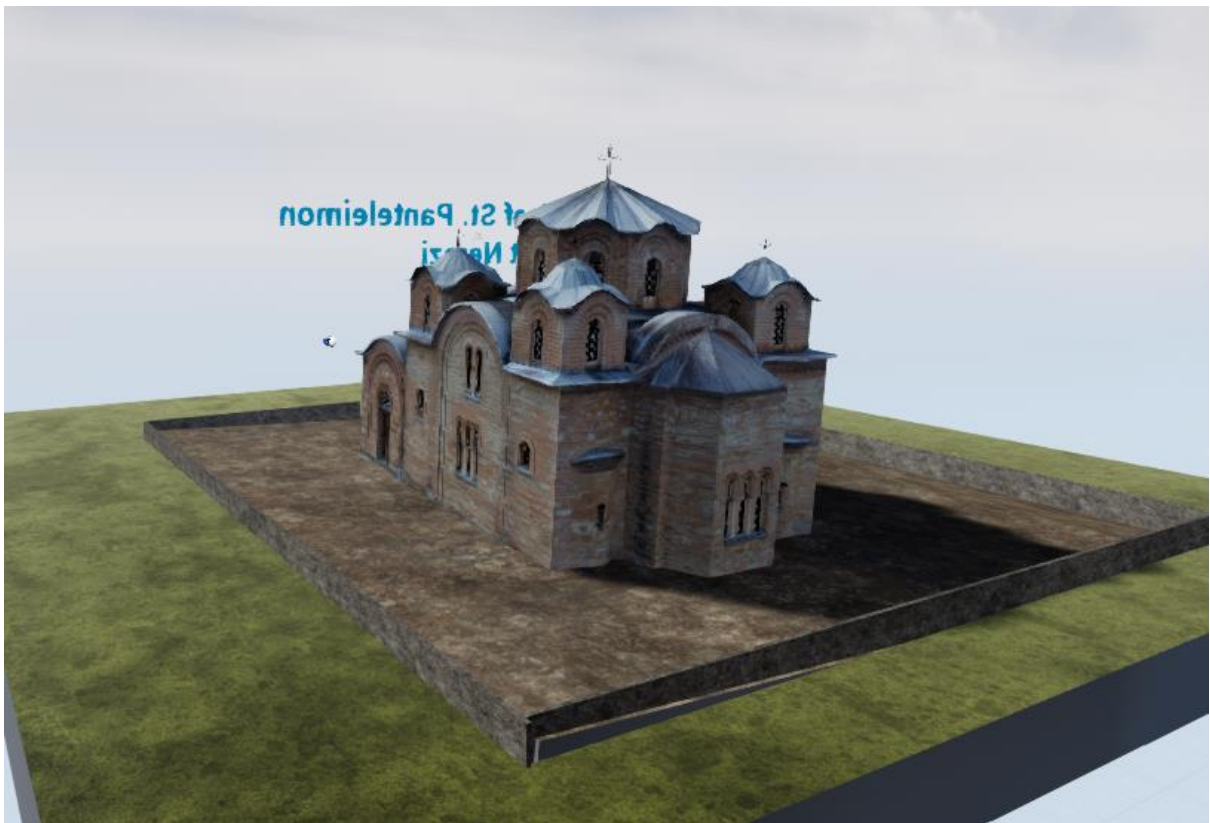
north-west view



south-west view



3D Model in VR





Renders - Lumion





5.6. Discussion

In this project, pairing laser scanning with photogrammetric 2D imagery methods enabled a detailed and comprehensive picture of the surveyed historical object of interest to be created. The visual outputs generated through these techniques have contributed for a better interpretation and documentation of the building and for a theoretical future management of it.

Having data from different technologies allowed the author to understand better the problematic situations that could occur during the process of making the final outputs. Combining technologies like laser scanning and close-range photogrammetry certainly has advantages and benefits. In addition, in reality, the close-range photogrammetry method for this thesis was also a combination of terrestrial and aerial images.

In order to get the scaled model when capturing with photogrammetry methods, it is necessary to have control points or measured distances on the surveying object in reality. Neither of these were done for this project, but laser scanning was used as a substitute for this purpose, which defined the dimensions.

Photogrammetry, specifically structure from motion method, coupled with RPAS, expands the best-use application of 3D reality modeling technologies for many scenarios. However, it also has some problems. From one point of view, different cameras are used, so in order to combine the data afterwards, it is necessary to follow some requirements. There cannot be very big differences in the distance from the object, or the height angle between ground image axes and aerial images axes cannot be greater than approximately 30 degrees. It means that is not possible to capture aerial images with drone only from the upper part of the object and the lower part with terrestrial photogrammetry. This could lead to difficulties in the processing afterwards when combining images from both systems. A solution would be capturing overlapping (connecting) images, so a data joining can be done, or combining the sub-models from different sources additionally, which is more time consuming. For this thesis, the joined model from both aerial and terrestrial images was generated in Agisoft Metashape with satisfactory quality.

Having a personal mobile laser scanner would be probably the easiest way to make a 3D model of an object. Data is acquired without many difficulties and the processing is fully automatic. Another advantage is that it is possible to make the vectorization of the ground floor semi-

automatically. Nevertheless, there are many disadvantages in comparison to the terrestrial laser scanners. The data amount and the precision from ZEB-REVO compared to TLS are not as high and the automation with the vectorization is effective only for simple-shaped objects. In addition, ZEB-REVO does not have a camera included, so the point cloud is classified according to the height of the points. Anyway, for the purpose of documenting in cultural heritage this mobile scanner was adequate. Some parameters of the used technology are compared in Table 5.

Device	Accuracy [mm] on 10 m	Range [m]	Acquiring points/sec	Data size [MB]	Time [minutes]
Nikon D3200	5-20	10	~30 photos/minute	~10/photo	~30 photos/minute
DJI Mavic Pro	5-30	30	~20 photos/minute	~4/photo	~20 photos/minute
ZEB-REVO	10-30	30	43000	100/min	slow walking
BLK360	4	30	360000	600/scan	6/scan

table 5 - Comparing the used technology

The common thing for all the used technologies in this project is that they all produce a point cloud that is further processed. The differences are the density of points and if the points are colorized or not – the point cloud from PMLS is least accurate and unlike the others, does not have colorized points.

Because multiple data types were obtained from a single site, they were compared in the software CloudCompare to detect differences (Figure 33.).

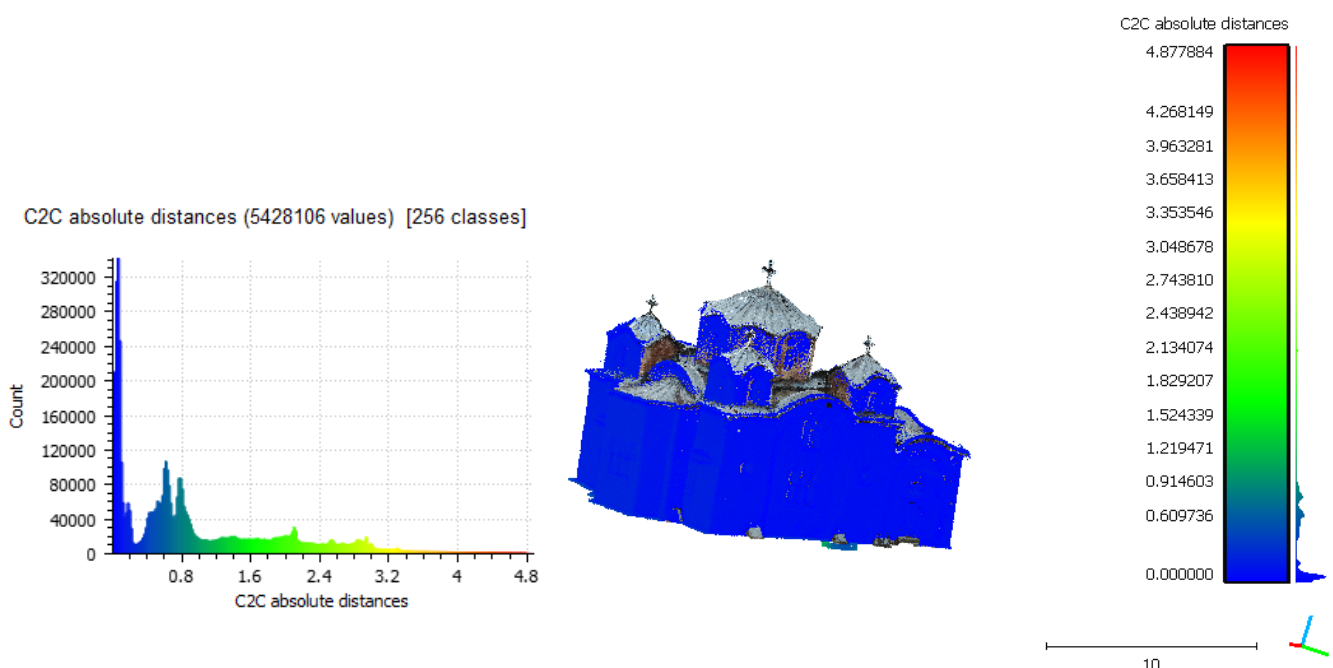


figure 33 - Differences between point cloud from combined terrestrial and aerial photogrammetry (reference) and point cloud from ZEB-REVO (blue)

From the result, it is noticeable that the point clouds are almost identical (most of the points are within 10 cm distance). The biggest absolute distance is probably in the interior points, which is logical, since the reference point cloud from combined photogrammetry methods is only representing the external part of the building.

Another comparison was done in another software – Geo Magic, now between the two 3D models, where again, quite satisfactory results were reached (Figure 34.).

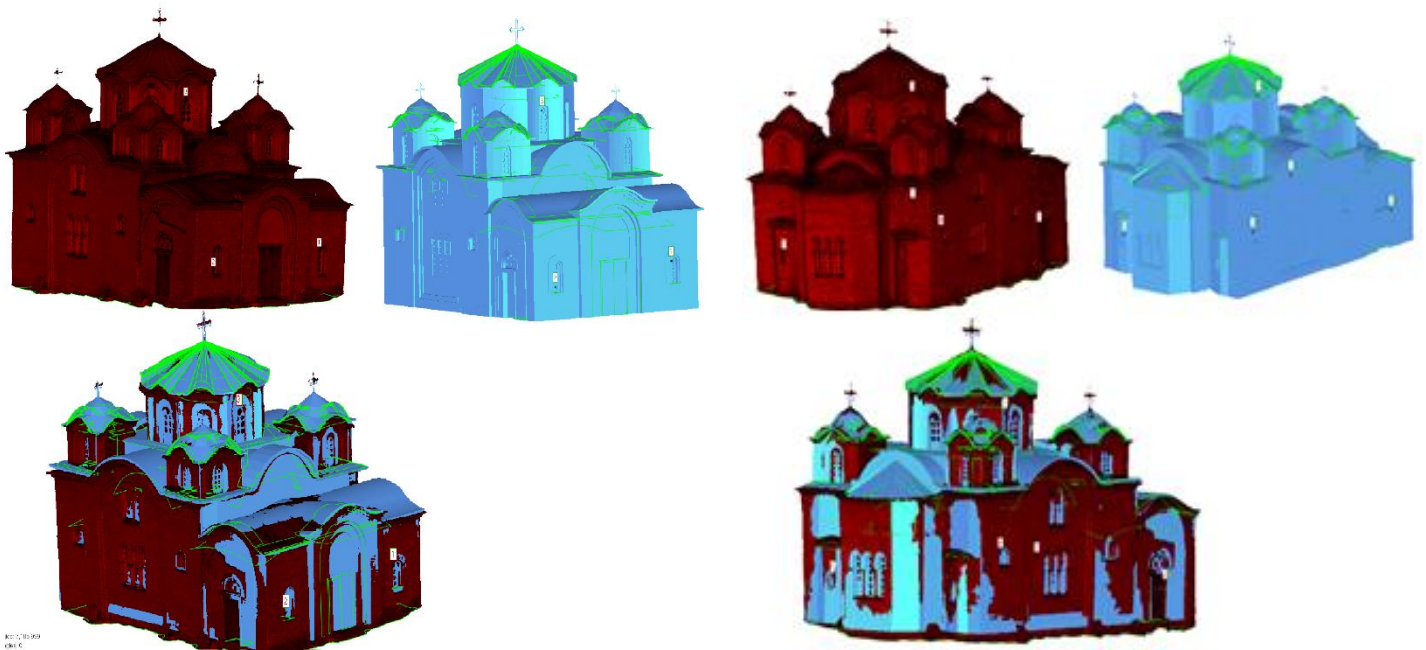


figure 34 - Differences between the 3D model from combined terrestrial and aerial photogrammetry (reference, red) and the BIM model (blue)

Geo Magic software was used to evaluate the precision with which the BIM model was modelled compared to the model generated from aerial and terrestrial photos, which was considered as a reference.

On Figure 35. evidently noticeable are the parts of the model where there are inaccuracies. Those are mostly the windows and of course, the roof, which has very irregular shape in reality and is hard to model it exactly the same as it is. However, the BIM model has quite well accuracy compared to the reference model and is considered sufficient for the purpose of this thesis.



figure 35 - Comparison of the 3D models - BIM model (grey), reference photogrammetry model (blue)

As it was already presented before, many programs were used in order to process all the data and prepare all the outputs for this thesis. Employing different software definitely has an advantage, in a way that some functions are more prominent or have better visualization in one and more complicated in another program. However, during the processing of the BIM, there were some difficulties when it was transferred to the environment for virtual reality. Since the basics of the BIM model were done in Revit and afterwards it was finished in SketchUp, problems like different scaled features and irregular shapes occurred.

Other than not being able to scan the whole building with the TLS Leica BLK because of technical problems, the surveying was done without any problems in one day.

6 Conclusion

Documenting cultural heritage sites mean acquiring detailed and accurate data and the most popular method of storing this 3D information about historical structure is using 3D models. Aside from providing a record for future generations, photogrammetry can contribute to more practical and quantitative planning of conservation and restoration. Thus, with these precise and realistic 3D models of the site, both aesthetic and practical implications of restoration and conservation work can be evaluated even before work commences.

The use of three-dimensional coordinate data for building analyses has increased in the cultural heritage field. In particular, the precise investigation and monitoring of historical sites in terms of preventive conservation has gained attention, and digital documentation processes have been recognized as an essential element in conservation, rather than the active repair of cultural heritage.

Low-cost and easy-to-use photogrammetric methods like close-range aerial/terrestrial photogrammetry and mobile laser scanners are technologies that reach high satisfactory results for the needs of documenting these historical sites. The integration of these different photogrammetric approaches has proved its indisputable potential as the best way to the cultural heritage documentation and monitoring.

This was also the goal of this thesis, to document a historical object with quality 2D and 3D results using the modern technologies of geomatics. For this purpose, the object was surveyed with terrestrial and aerial close-range photogrammetry method and with a personal mobile laser scanner.

Terrestrial imaging could not provide complete 3D reconstruction because the lack of visibility in floor and roof structure. With the aid from aerial images, the roof and the hard-to-reach parts were able to be modeled, forming complete 3D model with its surrounding environment. The laser scanner was employed primarily for surveying the interior, and since the model from photogrammetry is not scaled, it was used to define the dimensions as well.

In total, three models were created as main outputs from this thesis.

3D model was generated from the exterior data from the photogrammetry methods which was later also used as reference to evaluate the precision and accuracy of the other BIM model. Moreover, the photos were also helpful for projecting the texture for the BIM model before importing it to the engine for VR.

Turning the captured data into digital model that can be used for planning, monitoring or managing an object is shortly what BIM is about. The acquired data from the PMLS combined with the point cloud generated from the images for additional precision, was the reference in the process of creating the BIM model.

Finally, the BIM model was given a texture and imported in the game engine for transferring it to VR.

Sufficient results were achieved in the process of documenting the object of interest for the means of cultural heritage. Hopefully the outputs will help for a better interpretation and management of the object.

Being able to do this project for a historical object in Macedonia and moreover getting to apply these modern approaches to conservation of the cultural sites in this country, has a special meaning for the author. In discussion with the people working in archaeology and cultural heritage in the country, it is not that common to have a complex digital documentation of monuments and historical objects. Indeed, these modern geomatic technologies are needed for creating more detailed and comprehensive image of the historical sites and conserve it for the future generations.

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