CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF CIVIL ENGINEERING

STUDY PROGRAM: GEODESY AND CARTOGRAPHY

STUDY FIELD: GEODESY, CARTOGRAPHY AND GEOINFORMATICS

BACHELOR THESIS

USING MODERN METHODS OF GEOMATICS FOR DOCUMENTATION OF HISTORICAL OBJECTS

Thesis supervisor: prof. Dr. Ing. Karel Pavelka
Department of Geomatics

2020

Pane Kuzmanov

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

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: Kuzmanov Jméno: Pane Osobní číslo: 477270

Zadávající katedra: Geomatiky

Studijní program: Geodézie a kartografie

Studijní obor: Geodézie a kartografie

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce: Využití moderních metod geomatiky pro dokumentaci historických objektů

Název bakalářské práce anglicky: Using of modern geomatics methods for documentation of historical objects

Pokyny pro vypracování:
Vypracujte rešerši využití RPAS - remoteli piloted aircraft systém (UAV) pro dokumentaci historických a archeologických objektů v rozsahu min. 5 stran a uveďde, jak je možno objekty, nalezené pomocí RPAS verifikovat v terénu. Zaměřte se i na digitální model reliéfu z leteckého laserového skenování (DMR5) Na vhodném příkladě proveďte měření (snímkování) a pokuste se objekt verifikovat v terénu např. geofyzikálními metodami.Zhodnoťte výsledky.

Seznam doporučené literatury:
Pavelka, K. RPAS. 2016. ČVUT v Praze, ISBN 978-80-01-05648-6
Aber., J., Marzolff, I.2010. Small-format aerial photography. ISBN: 9780444532602
Gojda, M. – John, J. et al.: 2013. Archeologie a letecké laserové skenování krajiny,ISBN 978-80-261-0194-9

Jméno vedoucího bakalářské práce: prof.Dr.Ing.Karel Pavelka

Datum zadání bakalářské práce: 17.2.2020 Termín odevzdání bakalářské práce: 17.5.2020
Údaj uveďte v souladu s datem v časovém plánu příslušného ak. roku

Podpis vedoucího práce Podpis vedoucího katedry

III. PŘEVZETÍ ZADÁNÍ

Beru na vědomí, že jsem povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je nutné uvést v bakalářské práci a při citování postupovat v souladu s metodickou příručkou ČVUT „Jak psát vysokoškolské závěrečné práce" a metodickým pokynem ČVUT „O dodržování etických principů při přípravě vysokoškolských závěrečných prací".

17. 2. 2020
Datum převzetí zadání

Podpis studenta(ky)

ABSTRACT

This bachelor thesis represents a modern method of geomatics, in this case the remotely piloted aircraft system (RPAS), and its usage for documenting historical objects. This thesis is divided in two main thematic parts. In the first one, a short literature review connected with this subject is presented, as well as the basics of RPAS, types, its usage and legislation. The second part is a case study, where practically a documentation of a particular archaeological site is made. The case study is divided in two parts, since two different RPAS were used and two different data processing software.

KEY WORDS

RPAS, archaeological survey, orthophoto, digital surface model

ABSTRAKT

Bakalářská práce představuje moderní metodu geomatiky, v tomto případě dálkově řízené letecké systémy (RPAS), a jejich využití pro dokumentace historických objektů. Práce je rozdělena do dvou hlavních tematických částí. V první části je uveden stručný přehled literatury vztahující se k tomuto tématu, dále základy RPAS, typy, jejich využití a legislativa. Druhou částí je případová studie, kde je prakticky zpracována dokumentace konkrétního archeologického naleziště. Případová studie je také rozdělena do dvou částí, protože byly použity dva různé RPAS a dva různé programy pro zpracování dat.

KLÍČOVÁ SLOVA

RPAS, archeologický průzkum, orthophoto, digitální model povrchu

DECLARATION

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

Prague, 2020 **Pane Kuzmanov**

………………...

ACKNOWLEDGEMENT

A sincere thanks to my thesis supervisor prof. Dr. Ing. Karel Pavelka for sharing his professional expertise and for providing his valuable suggestions and guidance. I am also grateful to my close friends and family for the support they have expressed during the entire period of my studies.

LIST OF ABBREVIATIONS

ALS	Airborne Laser Scanning
COSMC	Czech Office for Surveying, Mapping and Cadaster
CTU	Czech Technical University
ČÚZK	Český Úřad Zeměměřický a Katastrální
DEM	Digital Elevation Model
DMP	Digitální Model Povrchu
DMR	Digitální Model Reliéfu
DSM	Digital Surface Model
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSD	Ground Sample Distance
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LiDAR	Light Detection and Ranging
NDVI	Normalized Difference Vegetation Index
RPAS	Remotely Piloted Aircraft System
SFAP	Small format Aerial Photography
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle

TABLE OF CONTENTS

Preface

The inspiration to do this research was the new, modern technology of geomatics that has been implemented in different areas during the last two decades. This thesis presents the usage of the remotely controlled aerial vehicles in order to document the already known archaeological site near Březno in the Czech Republic. The main goal of the thesis was to generate orthophotos and 3D DSM based on the acquired data from two different types of RPAS.

The aerial images used for this research are self-made which in comparison to images from external sources enables deeper understanding for the process of implementing the RPAS technology in the area of archaeology.

1 Literature review

Several books from the library of the Czech Technical University (CTU) in Prague and many articles online were used in the process of making the literature review regarding this topic. This chapter is very important because it allows the researcher to become more familiar with the subject and get to know about the major theories and evidences that have already been done. Also, it is very interesting to analyze how a specific field has been upgrading over the years and to make a comparison with the latest ways of approaching to a particular problem. This thesis is mainly focused on the application of remote sensing in the field of archaeology and therefore, the literature review is primarily focused on this area of interest, but also, in general the importance of RPAS and its applications in different areas.

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.

An important book from the area of interest of this thesis is *Non-destructive archaeology* (Kuna, M. et al, 2004). This book is a product of a ten-year research devoted to archaeology by the authors and one of the outputs of a six-year grant-assisted research project. It is representing the theories, methods and goals of non-destructive archaeology. In this book, aerial archaeology is explained as one of the most important methods for access to new archaeological data. None of the other methods have that wide of a range of exploring new archaeological locations and new types of objects.

Martin Gojda has had a big influence on the development of aerial archaeology in the Czech Republic. The possibility of usage and application of airborne laser scanning (ALS) in the area of archaeology in the Czech Republic was presented at the international exhibition *Lety do minulosti – Flights into the past* (Gojda, 2007). In the article *Archaeological remote sensing by means of ALS* (Gojda et al., 2011) he 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.

In 2008, the project of creating a new altimetry of the Czech Republic was introduced by the Czech Office for Surveying, Mapping and Cadaster (COSMC, ČÚZK), the Ministry of Defense and the Ministry of Agriculture. The project’s basic characteristics were described by Brázdil, K. (2010). Method of airborne laser scanning was selected as main source of data acquisition, which allowed the creation of the Digital Elevation Model (DEM) and Digital Relief Model (DMR) of a new generation, having the precision up to a decimeter. About this project and generally about the technologies of processing airborne laser data, Dušánek, P. (2014) writes in his work. This article is published in the time when DEM of 4th generation (DMR 4G), DMR of 5th generation (DMR 5G) and Digital Surface Model (DSM) of 1st generation (DMP 1G) were introduced in the Czech Republic, now all available for the public on the website of ČÚZK. Hubáček, M. et al. (2016) is also writing about these triangulated irregular network (TIN) models. He is testing and proving the high accuracy and quality of the elevation models of the new generation - DMR 4G and DMR 5G.

In their projects, researchers often combine data acquisition from unmanned aerial vehicle (UAV) with terrestrial photogrammetry and laser scanning (Lambers et al., 2007). Digital photogrammetry and laser scanning efficiently record the archaeological 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 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 basics of small-format aerial photography (SFAP) are described in the well-known work *Small-Format Aerial Photography – Principles, Techniques and Geoscience application* (Aber, J., Marrzolff, I., Ries, J., 2010). The book presents both the basic and advanced principles and techniques of SFAP with an emphasis on digital cameras. It is the only comprehensive and up-to-date book on this subject. The authors are giving a user-oriented introduction to all SFAP-related applications.

In the dissertation thesis *UAV photogrammetry* (Eisenbeiss, H., 2009) the author is presenting his long-term research in this area. He is introducing new terminology, for that time, UAV Photogrammetry and demonstrating how UAVs can be applied for photogrammetric data acquisition and processing. It is focused particularly on archaeology and environmental application. Also, the author is combining the various classes of UAVs into three new categories, separating Open-source and Manual controlled UAVs (OM-class), Micro and Mini UAVs (M-class) and Large payload UAVs (L-class). According to him, this classification allows a selection of an UAV system for a photogrammetric application depending on the project budget, the endurance, range, maneuverability, payload capacity and the type of motorization.

In the article *UAVs for the documentation of archaeological excavations* (Saurbier, Eisenbeiss, 2010), the authors are dealing with the investigations of UAV application in archaeology. The capabilities of photogrammetric methods using UAVs as a sensor platform are demonstrated in three case studies in the work: documentation of a large archaeological site in Bhutan, an excavation of smaller site in the area Pernil Alto near Palpa (Peru) and the Maya site in Honduras.

RPAS platforms are a valuable source of data for mapping and 3D modeling issues. The main outputs, DSM generation and orthophoto production, can be produced in an automated way. The developments 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).

The evolution and the use of Unmanned Aerial Systems (UAS) are as well discussed in the technical article *Unmanned aerial systems for photogrammetry and remote sensing: A review* in an international magazine (Colomina, I., Molina, P., 2014). The authors are describing UAS as a set of complementary technologies brought together to fulfill a specific task. 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 presenting 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 in detail the 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 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.

Particular example of the usage of RPAS for detecting archaeological objects is presented in the article (Šedina et al., 2019), which is about a location near the village Ctiněves in the Czech Republic that has been studied for several years. It is about urn graves of the Knovíz culture (1200 – 1000 BC). In this project, urn graves and tumulus are detected based on the vegetation symptoms caused by favorable meteorological conditions that year. Vegetation signs on the ground from the subsurface structures are one of the most widely known and studied technics in the non-destructive archaeology. The monitoring of vegetation must be done under suitable light and vegetation conditions and using adequate instruments with infrared or multispectral/hyperspectral systems (John, J.-Gojda, M. et al., 2013).

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, 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 in order to document sites and process the acquired data to an orthophoto and a DSM.

The increasing of the remote sensing platforms 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., Marrzolff, I., Ries, J., 2010). Software for generation of a fine quality orthophoto of the acquired image series are examined in the study for accuracy assessment of different software for processing UAV data (Brach et al., 2019). Six of the most frequently used photogrammetric software are described and a comparation of the final results between them is presented.

The growing of RPAS in civilian applications has significantly increased in the USA in the last years and has gained tremendous interest for experienced operators and pilots (Raid Al-Tahir, 2015). This is discussed in the paper *Integrating UAV into geomatics*, where the author argues that universities should expand their educations and training programs to include UAV-based geomatics operations and application development.

The purpose of this review was to go through some of the works and researches in composition studies, done about remote sensing and its application. It is clear from these researches that modern methods of geomatics, as RPAS and ALS are popular around the world for documentation and 3D models generation. RPAS 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 a long-term ongoing research.

2 Introduction

Aerial photography is one of the most widely used and cost-effective methods of remote sensing. Since its inceptions, aerial photography has gone from balloons and kites to airplanes and satellites and now drones.

Historically, the beginnings of aerial photography are going back to the nineteenth century when people desired to see the landscape "as birds do". The first documented aerial photography was taken from a balloon in 1858 in France (Colwell, 1997) when it was with a rather limited use, high costs and risks. The early 20th century, is considered the golden age of aerial photography when kites were the most widely available for lifting a camera into the sky. In the following years, aerial photography was mostly used for military reconnaissance and operations during the First, the Second World War and the Cold War. Photographic methods were developed rapidly, culminating early in the 21st century with transition to digital technology in general.

This thesis is divided into several chapters with each chapter providing deeper understanding for the application of RPAS in the field of archaeology. The first chapter distinguishes the different types of RPAS including the ones that have become commercially available due to which certain regulations by governments has become inevitable. Therefore, the chapter then proceeds to introduce the norms and regulations currently applicable. The following chapter is about the usage of RPAS and the advantages it offers when applied in different areas.

The incipient chapter of the second thematic part is the case project during which a survey was conducted in the archaeological site Březno with the main purpose of testing two different types of RPAS for data acquisition. The data was then further processed in two different software with the common aim, to generate an orthophoto and DSM where based on the vegetation indices, the existence of a subsurface object would be proven.

The primary sources that were used in this thesis are professional literature and the acquired data from the execution of the case project. Further on, the RPAS suppliers' websites were the source for the technical specifications stated henceforward.

3 RPAS

There are several abbreviations used for so-called drones. 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 – it means the UAV with terrestrial segment. However, for the wide society, that connects unmanned aerial vehicles with entertainment it is commonly known as *drone*. 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).

3.1 Types of RPAS

Variety of platforms for aerial photography with different characteristics exist: 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 numerous aspects. In this section, the mostly used types of RPAS for geomatics purpose will be presented.

RPAS Helicopter (Figure 1) 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.

Figure 1 - RPAS Helicopter
source: www.survey-copter.com

Multirotor (Figure 2 - a) got its name because of the multiple rotors it has (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 gimbal[1]. Quality digital cameras are used for this type of RPAS. It is possible to use different sensors e.g. multispectral, thermal or laser scanner. What multirotors have in favor is 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 2 - b) have the ability for a long-range flight and higher endurance in the air. Here, 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, since they are using cheaper compact digital cameras with resolution of 10-20 MP. (Pavelka et al. 2016).

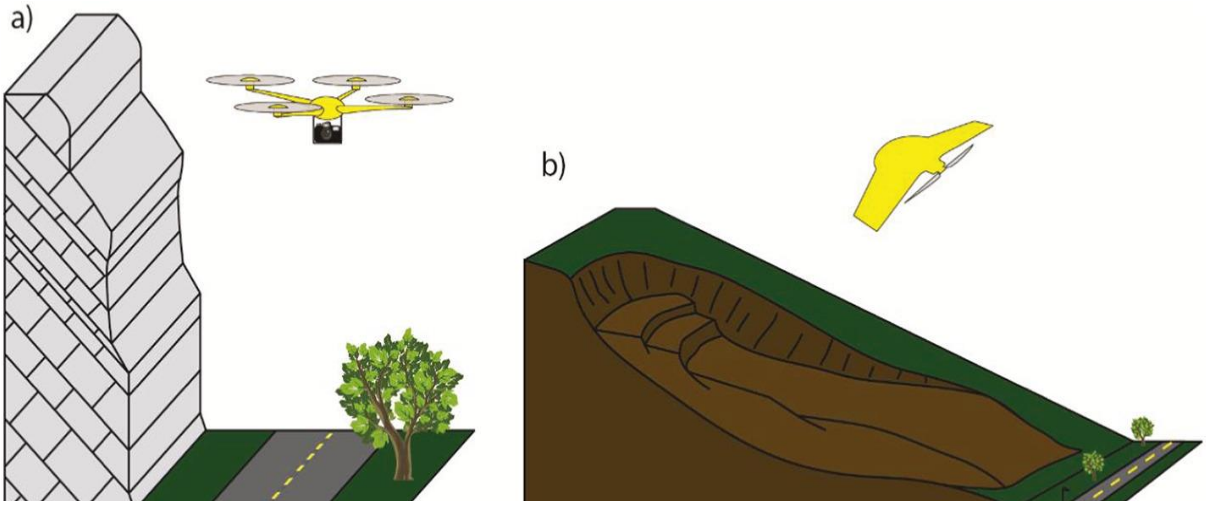


Figure 2 - Different RPAS survey options proposed by Giordan et al. (2015) for (a) steep rock slopes and (b) gentle to moderate slopes.

---

[1] Gimbal – a 3-axis mechanism for rotation and stabilization of the camera

3.2 Legislation

Nowadays, drones are accessible and are available to be bought by almost anyone. The acceptable price and mass availability (even in toy stores) on the internet 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.

The civil usage of the airspace and unmanned aircraft operations over the territory of the Czech Republic is regulated in the *Czech Aviation Law - Act No 49/1997 for civil aviation*. It is important that for all unmanned aircraft, regardless of the purpose of use (recreational and sport flying/aerial work/corporate flights), the rules of the air apply, laid down by the aviation rules, especially by the *Attachment X of the applicable Czech Regulation L 2, Rules of the Air (Doplněk X předpisu L2).* The terms UAS and UAV often appear in this official document.

The Attachment X contains the categorization of unmanned aircrafts, their area of use, the ability to control them during the flight etc. It defines the terms UAV and UAS. The flight of the drone must be controlled by the pilot, responsible for any consequences. The pilot must maintain permanent visual contact with the aircraft. The flight itself should be recorded in the flight log so that the record always contains the date of the flight, the name of the pilot, the identification of the device, the time of the flight and similar information (Civil Aviation Authority, 2014).

The new rules and procedures for the operation of unmanned aircraft, which are set to be applicable from 1st of July 2020 in Europe, have already been published from the European Union Aviation Safety Agency (EASA). The published article covers the *Commission Implementing Regulation (EU) 2019/947*, the related acceptable means of compliance and guidance material, as well as the *Commission Delegated Regulation (EU) 2019/945* on UAS and on third-country operators of UAS. In the Implementing Regulation, there are three key elements relevant to the registration as an operator, the registration of the drone and the competency of the drone pilot (European Commission, 2019).

Around the world there are different drone regulations. While some countries have clear, established drone laws, many others do not, or the existing regulations do not consider how much the UAV landscape has changed over the last several years. There are still many countries that lack drone laws and on the contrary, a small group of countries that have completely banned them.

4 Use of RPAS

Drones have been used increasingly for aerial photography in scientific researches during the last two decades. In this chapter, the wide usage of the RPAS technology and its applications in different areas will be presented. The fascination of the geomatics industry in the RPAS is mostly due to their ability to collect site specific images at high spatial resolution, at low cost and with acceptable deployment. Using RPAS in photogrammetry is another tool that opens new possibilities for data acquisition for numerous areas of research.

Generally, using the RPAS could depend on the flying purpose, type of the monitored construction, the surface or on the legal norms. Multirotors are ideal for monitoring or documentation of smaller areas and civil engineering structures. Their advantage in comparison to fixed-wing drones is that taking of, as well as landing is vertical and can be used in relatively narrow locations. Controlling with these types of unmanned aircraft is more complicated and requires more experience. On the other hand, fixed-wing RPAS need certain speed and open space for taking off and landing. Mostly, they are used for documentation, monitoring and surveying flat surfaces and bigger areas (up to 1km^2 with one flight) e.g. in archaeology, wider transportation or water areas.

In geomatics, mainly, RPAS are applied to fields that benefit from close-range sensing such as, archaeological documentation and cultural heritage, monitoring and imaging of extensive areas, land registry applications, mapping as well as creating 3D models and DSM in the order of several cm.

Summary of advantages of using RPAS (Pavelka et al., 2016):

- cheap transportation;
- easy manipulation and mobility;
- high flexibility for deployment to work;
- possibility to use them in areas difficult to access;
- using in areas dangerous or risky for manned flight;
- high image resolution.

Using the RPAS in archaeology is a modern method and a useful tool for documentation and reconnaissance of the archaeological locations. The main purpose of applicating the RPAS in archaeology is to find and evaluate archaeological resources without destructive interventions in the field. RPAS can be used for identification of new archaeological locations according to the vegetation, soil or terrestrial symptoms, or simply for documentation of an already existing one.

For the purpose of identifying new archaeological sites, professional systems equipped with specialized instruments as infrared or multispectral cameras are applied. When it comes to small archaeological locations that are already monitored, preparing a documentation using even small RPAS can be economical and quick. Application of RPAS in archaeology has an economical dimension and makes possible a more far-sighted and sparing approach to the archaeological heritage. After a new archaeological object is identified with the RPAS technology, often a verification with geophysical measurements is made on the field. Usually, magnetometers and ground-penetrating radars are used for verification (Kuna, M. et al, 2004).

As the authors Šedina et al. (2019) are explaining, first the sites for measurement in the explored area are selected. Before the RPAS flight, a basic map is created by measuring the existing sites with some of the GNSS methods and the ground control points are signalized in adequate way. During the flight, the platform is observed with a control station which shows real time flight data such as position, speed, GNSS observations, battery status etc. Following the autonomous RPAS flight, data processing, which results usually with orthophoto and digital surface model, is operated in some of the wide range of software.

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 an orthophoto is pretty demanding when it comes to organization and has several phases. Pavelka et al. (2016) are giving a preview of the main phases, which are essential for mapping and generating an orthophoto and DSM:

1) *Creating the project*

The first phase is undertaking the needed documents from the client, specification of the characteristic for the resulting accuracy and content of mapping area. Following is the flight plan with specified ground sample distance (GSD) and the signalization and preservation of the starting points.

2) *Formation of the ground starting points in the field*

The physical stabilization and signalization of the ground starting and control points are made in a way, so there will be starting points inside and outside the monitored location. Also, the coordinates of all the starting and control points are measured with one of the GNSS methods.

3) *Planning the RPAS flight*

The plan for the flight is made based on the already known area, time period, GSD and meteorological condition. Digital maps from WMS service or applications from Google Earth are used as a base for making the flight plan.

4) *Before the flight preparations*

After finishing all the administrative parts and registration of the controls and procedures in the adequate documents, a preparation of the aircraft and the cameras is made e.g. battery status and other recommended tasks.

5) *RPAS flight*

The aircraft is remotely controlled by a pilot, who makes the flight as effective as could be. During the flight, different notes of the aspects that can possibly affect the scanning quality are listed.

6) *Data processing after the RPAS flight*

The records are described with location, date and other information in order to be identified. The operator downloads the essential data from the cameras for the calculations of the camera parameters.

7) *Preparing the data for the orthophoto and mapping outputs*

Some quality controls of images and registrations are done before the photogrammetric processing. After that, the coordinates of all the signalized starting and control points are measured on every image. This phase is quite demanding and usually supported by software that helps to identify the points.

8) Orthophoto generation and mapping process

Orthophoto generation requires georeferenced photos and a DSM. The procedure is based on the determination of the parameters for the collinearity equations i.e. the spatial position of the projection center (X, Y, Z) and the camera orientation angles. Some limit deviations and intervals that should be fulfilled in order to proceed with the generations are given and if not, then other analyses of the calculation should be made or eventually an additional measurement from another operator.

Most RPAS are equipped with a camera and inertial navigation system - INS (GNSS + IMU), where the photo positions and camera tilt angles are registered during flight. The bundle adjustment solution[2] is used to calculate the exact parameters of the camera internal and external orientation (aerotriangulation technology). Georeferencing of images (or orthophotos) is possible according to data from INS or can be used for control or refining suitably distributed control points.

4.1 Using of RPAS's products

Generated orthophotos can be used as base maps on which accurate measurements can be made. It should serve as the input for any further processing, e.g. 3D modelling. The orthophoto is a very useful product for cultural heritage documentation since in this metric product is possible to combine radiometric information with real measurements allowing a complete representation from every point of view (both terrestrial and aerial) of the analyzed object.

Using RPAS for Cadaster surveying definitely has advantages and potential for further application in this area. However, there are some shortcomings and limitations of this technology e.g. vegetation shades, roofs of the buildings and not visible land borderlines. Because of these unresolved limits, currently it is not possible to replace totally the classical methods of geodesy. Nevertheless, the predictions are that RPAS are going to be used as an additional method for surveying in the Cadaster.

---

[2] Bundle adjustment is the problem of refining a visual reconstruction to produce jointly optimal 3D structure and viewing parameter (camera pose and/or calibration) estimates.

Worth mentioning are also areas other than geomatics which are using remotely controlled models for different functions. Civil engineering and architecture use the RPAS technology for surveying building sites, inspecting buildings, collecting useful data and creating visuals for marketing purposes.

In the film industry and television, using of this technology has become a “game-changer”. Filmmakers are using it to capture aerial footage and images without having to get a cameraman on an actual helicopter.

Remote sensing is a well-known platform for agriculture and environment analysis too. However, it is resulting with high expenses when fine resolution is requested. There are agricultural drones that help to achieve and improve what is known as *precision agriculture*. Multiple uses of agricultural drones exist, including scouting land and crops, spotting treating plants, monitoring overall crop health and many more. The use of RPAS in agriculture is the technology that will help this business meet the changing and growing demands of the future.

Nevertheless, the police and military are the fields that use RPAS the most. They possess different types and sizes and use them for different purposes, e.g. situations where manned flights are considered too risky or difficult, tracking, monitoring activities on the ground etc. The technology has been put to use by federal, state, and local law enforcement agencies throughout the country, primarily for surveillance purposes. Although these police drones are not equipped with any type of weapon, many are capable of being armed with such technology and several weaponized police drones have been developed.

5 Case study

The project creation was divided in two parts, outside practical aerial measurements and data processing and analyzing for orthophoto and DSM generation. The measurements were made on a cloudy weather, ideal for aerial photography, because of the unwanted shadows that can affect the image quality. Two flights were made with different types of RPAS, using different cameras. As for the data processing, also two different software were used for the orthophoto generation. In addition to this chapter, a detailed illustration of the used tools and software will be presented, as well as a comparation between the different RPAS, cameras and programs. However, both of them are aiming at the main goal – an orthophoto on which the vegetation symptoms evidencing the subsurface archaeological object would be clearly seen.

5.1 Area of interest

The subject of analyses for this thesis was an already known archaeological location in the Czech Republic. The site is located in the village Březno, district Louny, in the Ústecký region.

Figure 3 - Location of the case project. Near Březno, meander of the river Ohře
source: www.mapy.cz

The flow of the nearby river Ohře is specific for its meanders which have been historically proven as useful for defense and safety purposes of human settlement within them. The location in question elaborated in this case project is within one of the numerous meanders of the river Ohře, a site that has been monitored for many years now. (Figure 3)

Relatively close to the location of study is the archaeological open-air museum *Archeoskanzen Březno u Loun*, where replicas of prehistorical little houses, built on the basis of local finds are presented (Figure 4.). It was established in 1981 as a part of an experiment following a largescale research carried out by the Archaeological Institute in Prague. Long-term archaeological researches made for this specific area have documented the development of human settlement, that is predicted from the Neolithic Period to the early Middle Ages (Kuna et al., 2015).

Figure 4- Archaeological Open-air museum
source: www.archeologickyatlas.cz

5.2 Used technology

For the purpose of realization of this project, two different types of RPAS were used (fixed wing drone – autonomous flight and multirotor – manual flight):

5.2.1 RPAS eBee

The fixed wing RPAS eBee is a product from the Swiss company senseFly, which is an association that since 2009 provides hardware and software for the purpose of geodesy, geomatics, agriculture etc. The senseFly eBee (Figure 5.) is a fully autonomous and easy-to-use mapping RPAS, that is used to capture high-resolution aerial photos, later transformed and generated into accurate orthophotos (with pixel size of around 3 cm) and 3D models.

Figure 5 - eBee mapping RPAS from senseFly
source: www.sensefly.com

No special piloting skills are required for this RPAS, since it flies, captures images and lands itself according to the predefined flight plan that is made in the software eMotion, also provided from the company senseFly. However, there is always a possibility to alter its flight plan or land manually if required. The eBee construction is made of ultra-light materials, because of which it weights less than one kilo (around 700 g), vastly minimizing its impact energy.

The whole eBee system consists of several components:

- *Winged drone,* also composed of several parts that can be replaced in the event of damage. The most important component is the body that includes the main parts of the drone, such as the motor, powered by a lithium-polymer battery, signal receiver, INS and camera. The other components are two attachable wings and a rotor on the rear part of the body, allowing the drone to move;
- Software for planning flight missions, in this case *eMotion*;
- Data processing software, *Pix4D.*

Hardware	
Wingspan	96 cm
Weight	0.70 kg
Motor	Low noise, electric, 160W
Radio link range	3 km
Battery	Lithium - polymer
Camera (optional)	S110 NIR/RE, Sequoia, thermoMAP
Software	
Flight planning and control	eMotion
Image processing	Pix4D Mapper
Operation	
Max. flight time	50 minutes
Speed	40 - 90 km/h (11 - 25 m/s)
Wind resistance	up to 45 km/h (12 m/s)
Max. Coverage	12 km^2
Automatic landing	~ 5 m accuracy
Results	
Ground sampling distance	~ 1.5 cm
Horizontal accuracy, with GCP	~ 3 cm
Vertical accuracy, with GCP	~ 5 cm
Horizontal/vertical accuracy, no GCP	1 - 5 m

Table 1 - Technical specifications of the eBee system
source: Author's creation, based on data from www.sensefly.com

Canon PowerShot S110 infrared camera was used with this type of RPAS which also belongs to the package equipment of eBee. It is adapted to be controlled by the drone's pilot. It has a resolution of 12 MP, image size of 4048 x 3038 pixels and a flight altitude of 100 m above ground level corresponds to ground resolution of 3.5 cm/pixel. This camera acquires image data in bands NIRRG – NIR (near-infrared), R (red), G (green) as shown in Figure 6. For this reason, it is suitable for capturing the state of vegetation since the plants have a high reflectivity in the near-infrared band. This camera is designed to be used in precision agriculture and for monitoring and analysis of the vegetation cover.

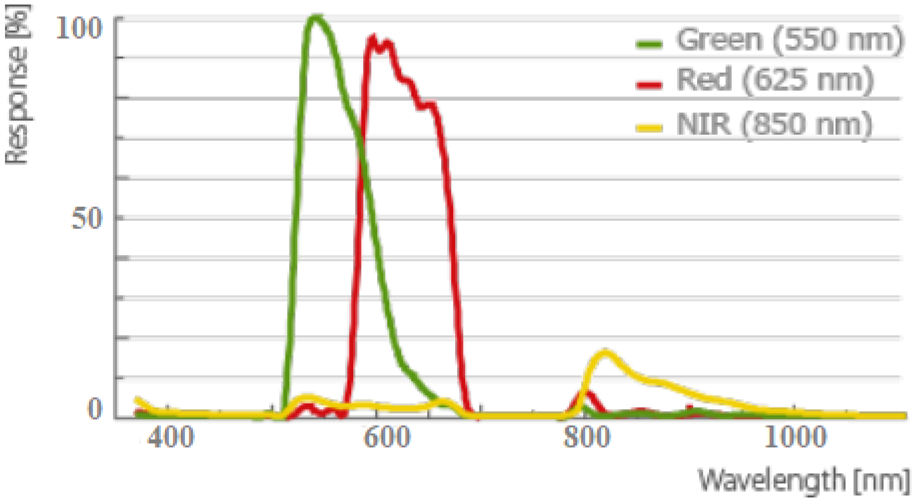


Figure 6- Canon PowerShot S110 bands
source: Šedina, 2016

The predefined mapping flight plan (Figure 8.) was made in the software eMotion, integrated software package that allows to interact with the eBee drone. It was also used during the flight to track its position and monitor the progress of the mapping flight. An internet connection is required to create the mapping flight plan and for the actual flight, as the computer communicates wirelessly via modem with the eBee. With this software, it is also possible to adjust the activity of the eBee or make a forced landing if unwanted activities happen during the flight.

5.2.2 Quadcopter DJI Mavic Pro Platinum

Mavic Pro (Figure 7.) 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. Mavic Pro can fly by predefined plan (autonomously) or manually controlled by a pilot. It is mostly used for documenting smaller areas. Its small, compact body and remote controller that can be folded down and stored in a small bag, make this drone one of the best portable RPAS yet. The Platinum series is improved in comparations with the older models with some internals, as well as increase of the flight time and reduce of the noise.

For this project Mavic Pro was controlled manually, capturing images from two 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 7 - Quadcopter DJI Mavic Pro Platinum
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.

Hardware	
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/PhotoScan (Metashape)
Operation via controller	
Max. flight time	~ 30 minutes
Max. speed	~ 60 km/h (~ 15 m/s)
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 MP 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 on this type of RPAS as it is with the fixed-wing type, where thermal or multispectral camera can be applied.

5.3 Data

As mentioned before, the data acquisition for this project was made in two different flights with two different types of RPAS. The monitored area was captured both manually and automatically with infrared and RGB camera. With the senseFly eBee winged RPAS, using Canon S110 infrared camera, 67 images were made in an autonomous flight with an overlap of 70%. The flight altitude was about 120 meters. In the following Figure 8. a map is shown from the flight plan with marked points at which the images were taken.

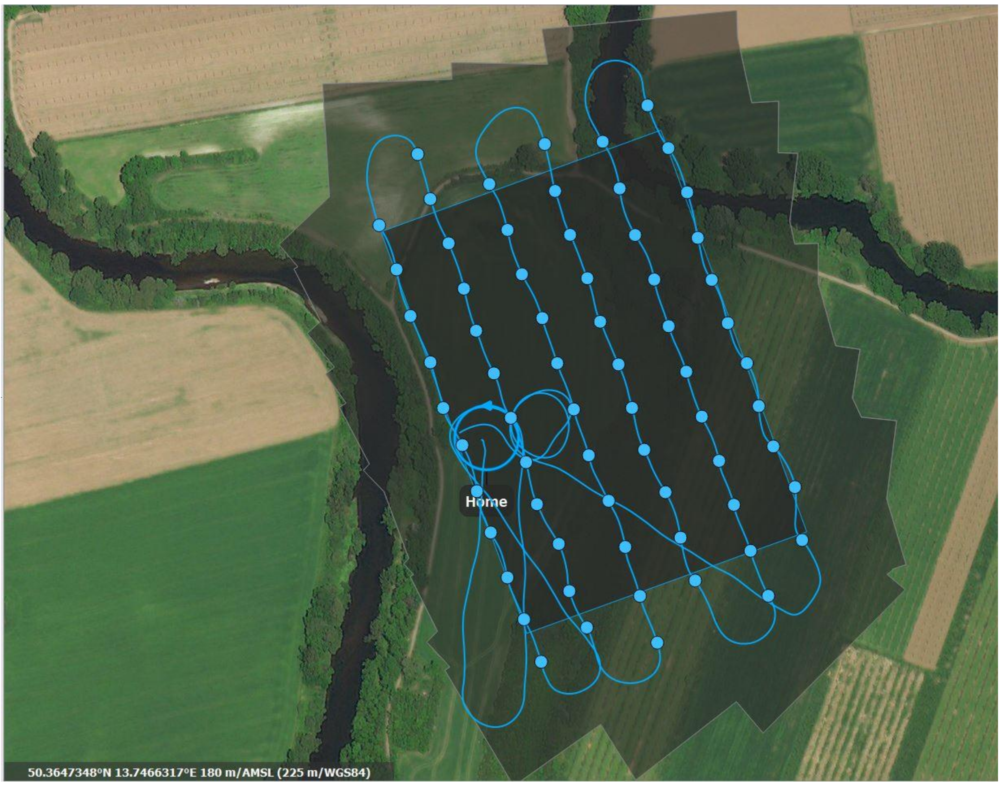


Figure 8 - Flight plan with marked camera positions made in eMotion

The DJI Mavic RPAS was controlled manually and using RGB camera, 121 brighter and 74 darker (higher quality) images were made. Because of the manual control, more images in three height levels were taken (30 to 80 meters flight altitudes), so to be sure there is an overlap.

The advantage from capturing images with RPAS is that the exported images from the camera are already georeferenced, i.e. have geoinformation from the GPS. After both flights, the acquired data was exported from the RPAS in formats that can be processed in the available software. An image transformation was made from the formats RAW and TIF to the image format JPG, in order to reduce the size of the data. Also, information about the image positioning from the INS was exported to a text file. After these changes, the images could be further processed.

5.4 Data processing

In order to generate the main outputs of this project, orthophoto and DSM, two different data processing software were used. In both software, these outputs are created parallelly, i.e. to proceeed to an orthophoto, a creation of DSM is required.

5.4.1 Pix4Dmapper

Processing the images, acquired from the flight with the winged eBee RPAS was made in the photogrammetry software for professional mapping, Pix4Dmapper. It is a software that is able to generate georeferenced, accurate 2D maps and 3D models.

This software is programmed to automatically process the data. For generation of DSM and orthophoto it is only necessary to create a project with several basic parameters for processing and import the images, together with the file containing the camera orientation parameters from the INS. Basically, Pix4Dmapper is processing the imported images in three steps:

- *Initial processing*: Identifying specific features as key-points in the images, finding which images have the same key-points and matching them, locating the model if geolocation information is provided; (An example of output is shown on Figure 9.)

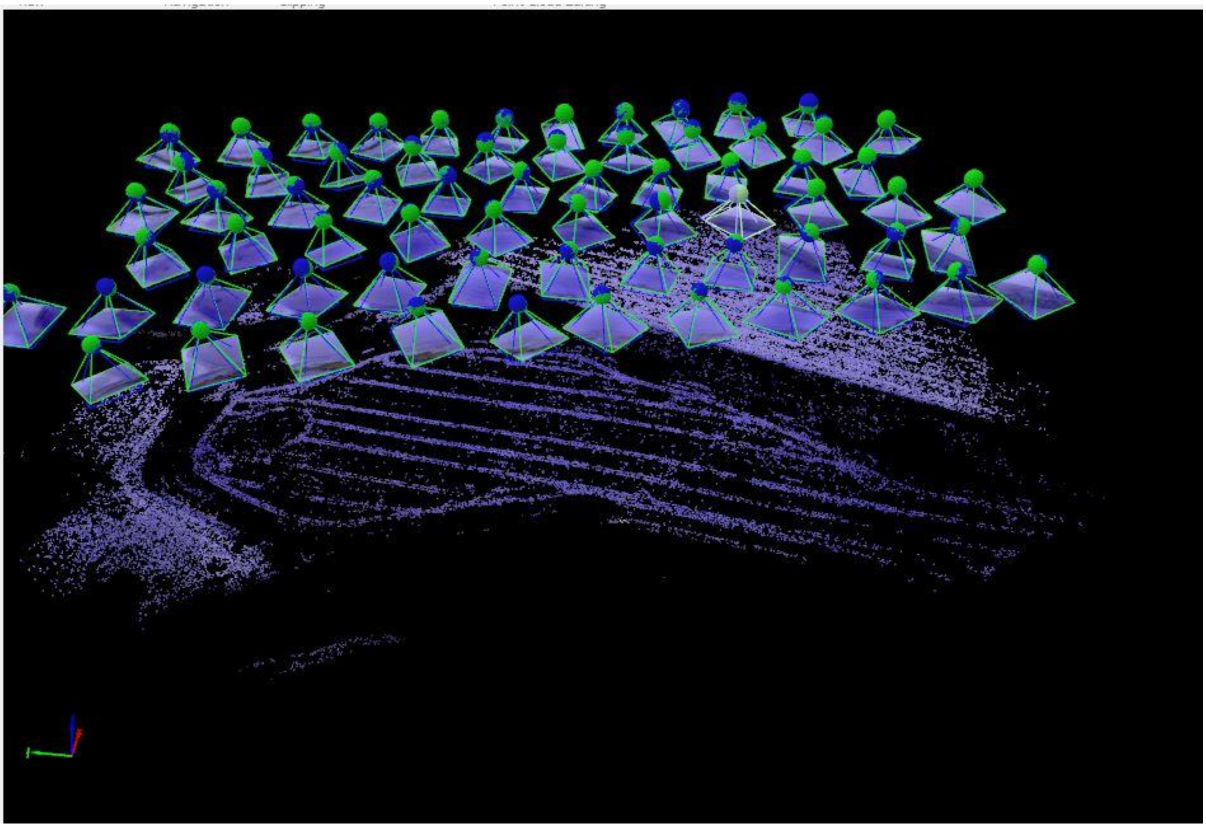


Figure 9 – Raycloud - 3D representation of the project area and cameras with the original images

- *Point cloud and mesh*: Creating of automatic tie points that results with a densified point cloud (Figure 10.), creating 3D Textured Mesh;

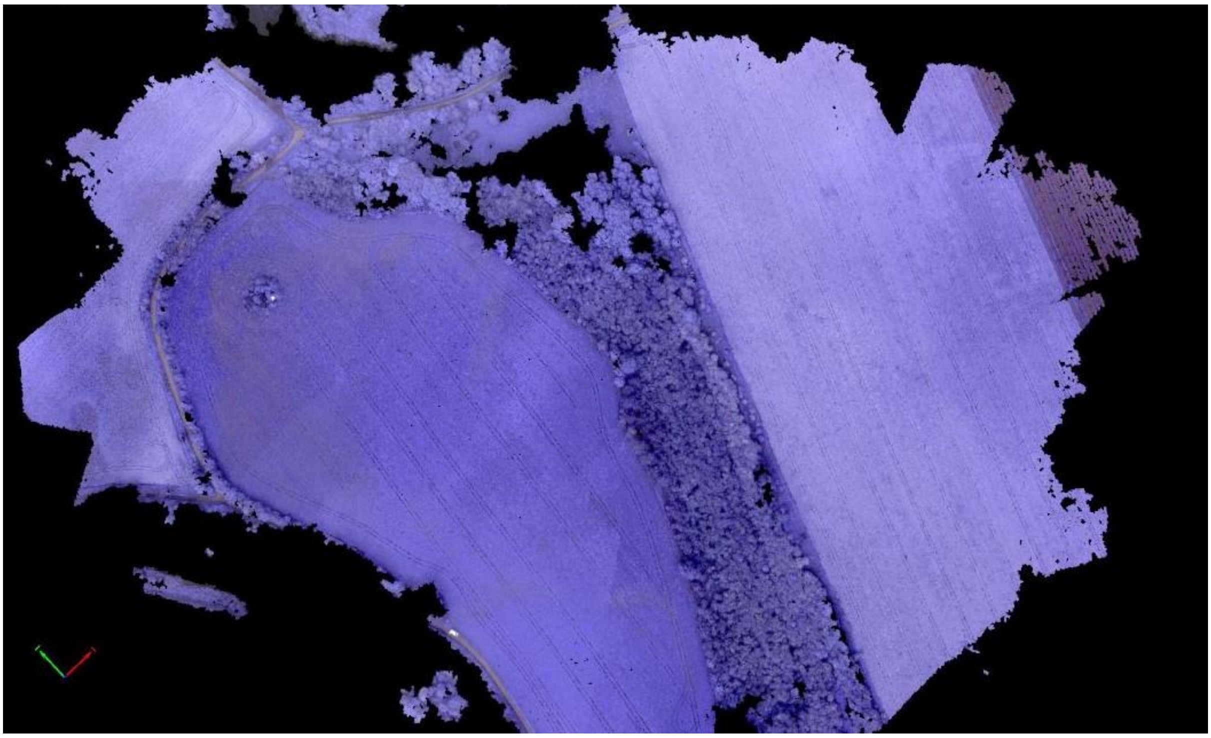


Figure 10 - Point cloud (infrared camera)

- *DSM, orthophoto and index:* Creating a DSM (Figure 11.) that can be used for volumes computation (unnecessary for this project), creating orthophoto (Figure 12.) based on orthorectification, generating an index map (Figure 13.) where the color of each pixel is computed using different formulas.

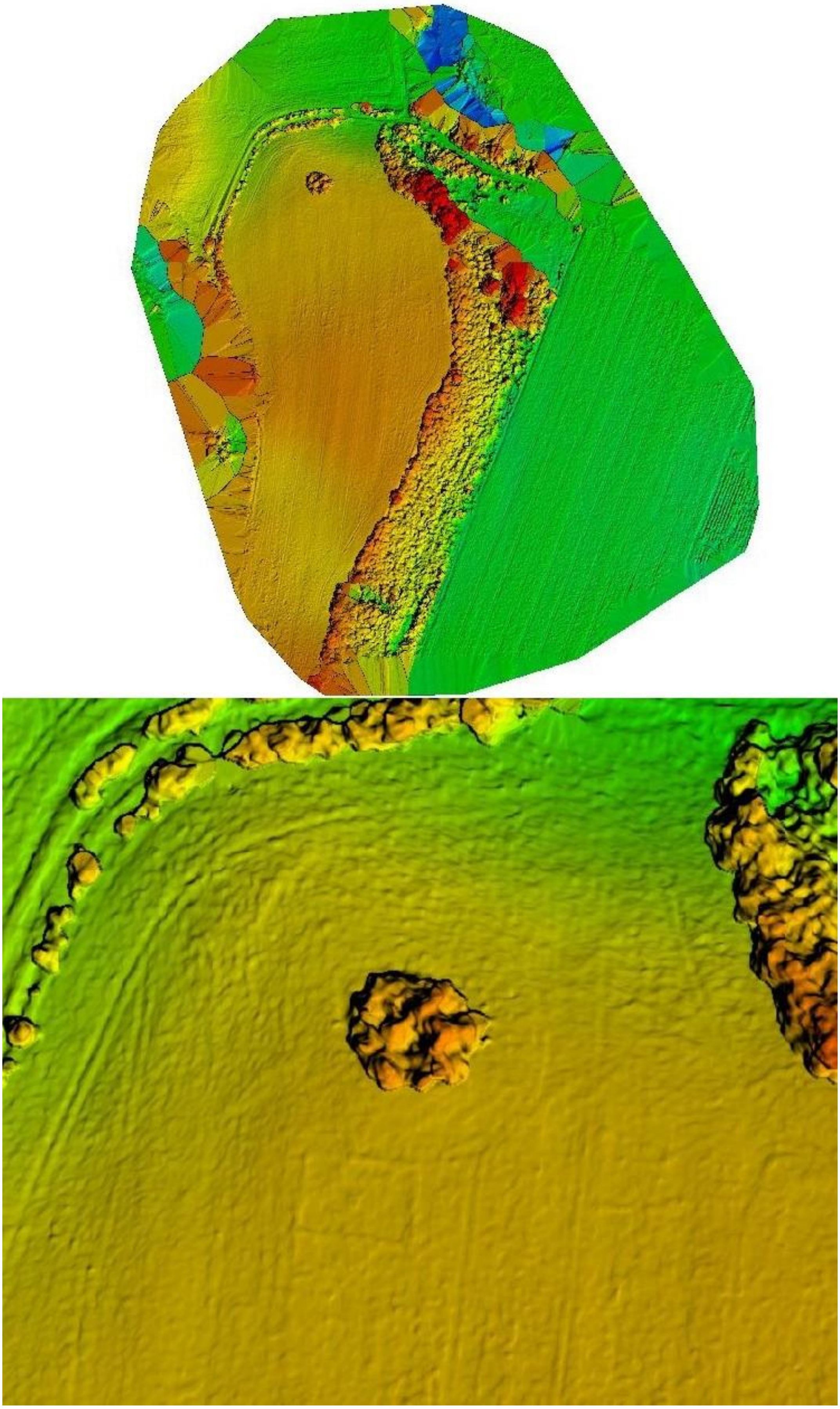


Figure 11 – Generated DSM of the captured area (above), detail of the object (below)

An illustration from the generated orthophoto (lower quality) is shown in the following Figure 12. Because of the size that the original exported orthophoto has (TIF file with around 220 MB), it will be added as an attachment to this thesis. This illustration is shown in order to be understood, what the output from the 3rd step of the data processing in Pix4Dmapper is.

Figure 12 - Orthophoto (illustration)

NDVI (Normalized Difference Vegetation Index) is calculated for analyzing the state of vegetation. It is a graphical indicator that is standardly used in remote sensing. The software calculates this index with the values of the pixels from the red (R) and near-infrared (NIR) bands. The NDVI output from this project is shown in the following Figure 13.

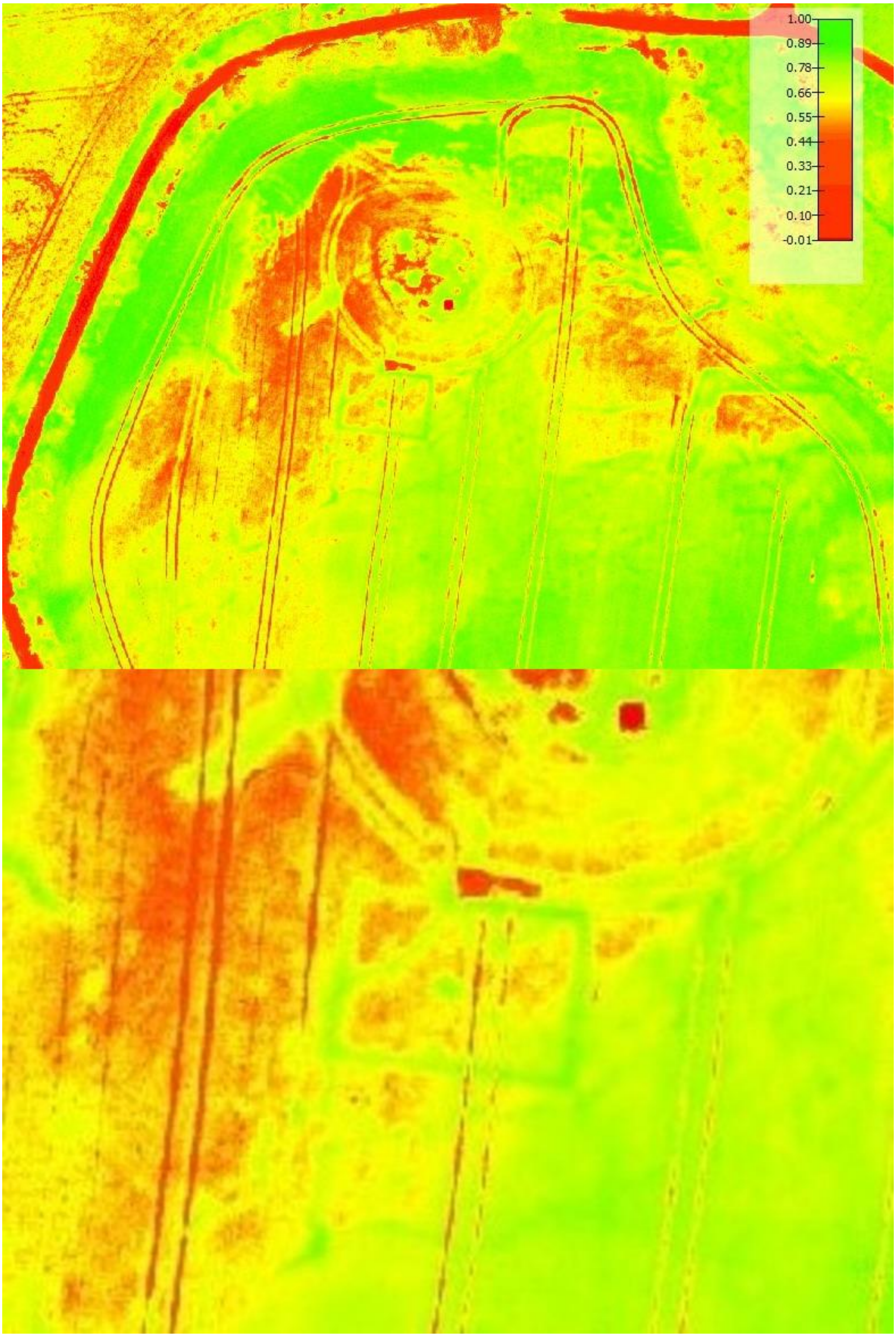


Figure 13 – Illustration of the NDVI index map (above), monitored object in detail (below)

5.4.2 Agisoft PhotoScan Metashape

The acquired data from the quadcopter DJI Mavic was processed in the software Agisoft PhotoScan Metashape. It is a software for photogrammetric processing of digital images and generation of 3D spatial data, producing quality and accurate results. It allows to generate georeferenced dense point clouds, textured polygonal models, DEMs and orthophotos from a set of overlapping images with the corresponding referencing information.

The data processing after the images were imported in Agisoft PhotoScan Metashape was made in several steps that follow consecutively to complete the whole workflow. Every function is started manually with defining some parameters:

- *Load camera positions and check camera calibration;*
- *Align photos,* at this stage PhotoScan finds matching points between overlapping images, estimates camera position for each photo and builds sparse point cloud model;
- *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;

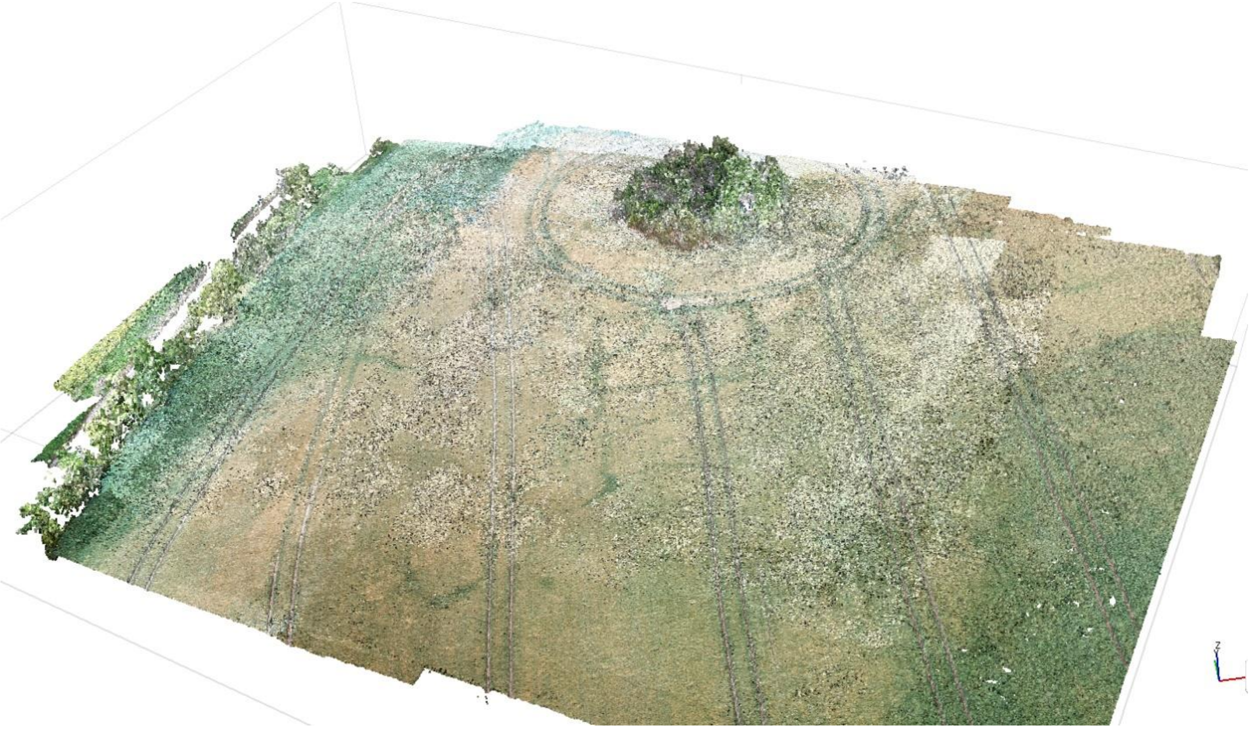


Figure 14 - Dense point cloud in 3D (33 mil. points)

- *Build mesh*, polygonal (triangular irregular network) mesh model based on the dense cloud data;
- *Build texture*, defining color to the polygons created in the previous step;

Figure 15 - Textured 3D model

- *Build Digital elevation model*, generation based on the dense point cloud or the mesh model;
- *Build orthomosaic*, based on the digital elevation model or the the mesh model.

Figure 16 - 2D Orthophoto

5.5 Outputs

This project resulted in a set of thematic maps that are documenting the monitored archaeological site, located in the meander of the river Ohře, near Březno. The software ArcGIS Pro was used to create the thematic maps from the exported orthophotos and DSM in TIF format. All the thematic maps were exported to the coordinate system UTM zone 33N.

Processing the data from the winged eBee drone in the software Pix4Dmapper resulted with two outputs:

- Orthophoto (NIR) from Canon PowerShot S110 images (see Attachments)
- Digital surface model from Canon PowerShot S110 images (Figure 11)

The only output that was generated in Agisoft PhotoScan from processing the data from the quadcopter DJI Mavic, using RGB camera, is an orthophoto (see Attachments).

6 Conclusion and discussion

RPAS technology is one of the non-destructive tools used for monitoring historical objects that shows the archaeology does not refer to field excavations only, but there are other more economical and practical ways to approach. Recently, RPAS usage in the field of archaeology has been on the rise and is soon expected to be the dominant non-destructive approach for exploring new archaeological locations.

The goal of this thesis was to get familiar with the RPAS technology and to carry out a practical survey of an archaeological site. The monitored object has a rectangular shape with a little circle in the middle, which according to the archaeological predictions can be a burial mound from the period between the Neolithic Period to the early Middle Ages.

The observation of the site was conducted with two different types of RPAS, winged and quadcopter. Hereby, the data processing was made in two different software. Both of the used software, Pix4D and Agisoft PhotoScan, for data processing are alike and process similar results. Pix4D in comparation with Agisoft PhotoScan has an advantage which is consisting of it being able to create an index thematic map. Using the winged drone eBee, the observed site was captured autonomously according to the predefined flight plan. The images, using the quadcopter DJI Mavic were captured manually which is a disadvantage in comparison to the eBee system. Both types of RPAS are adequate for this type of survey. However, for larger flat areas, the eBee has an advantage, since it has the ability for a long-range flight and high endurance in the air that is suitable for mapping. DJI Mavic is more stable in the air and it can be used in narrow locations because of the ability to vertical takeoff and landing.

The NDVI thematic map shown in Figure 13 is based on the different reflectivity from vegetation in red and near-infrared spectral bands. On the image, the red color shows the surface with little to no vegetation and on the contrary, the green color presents the healthy vegetation. The vegetation index helps to identify objects underground, meaning it is not necessary to excavate into the ground but based on the state of vegetation it is possible to identify if something is beneath.

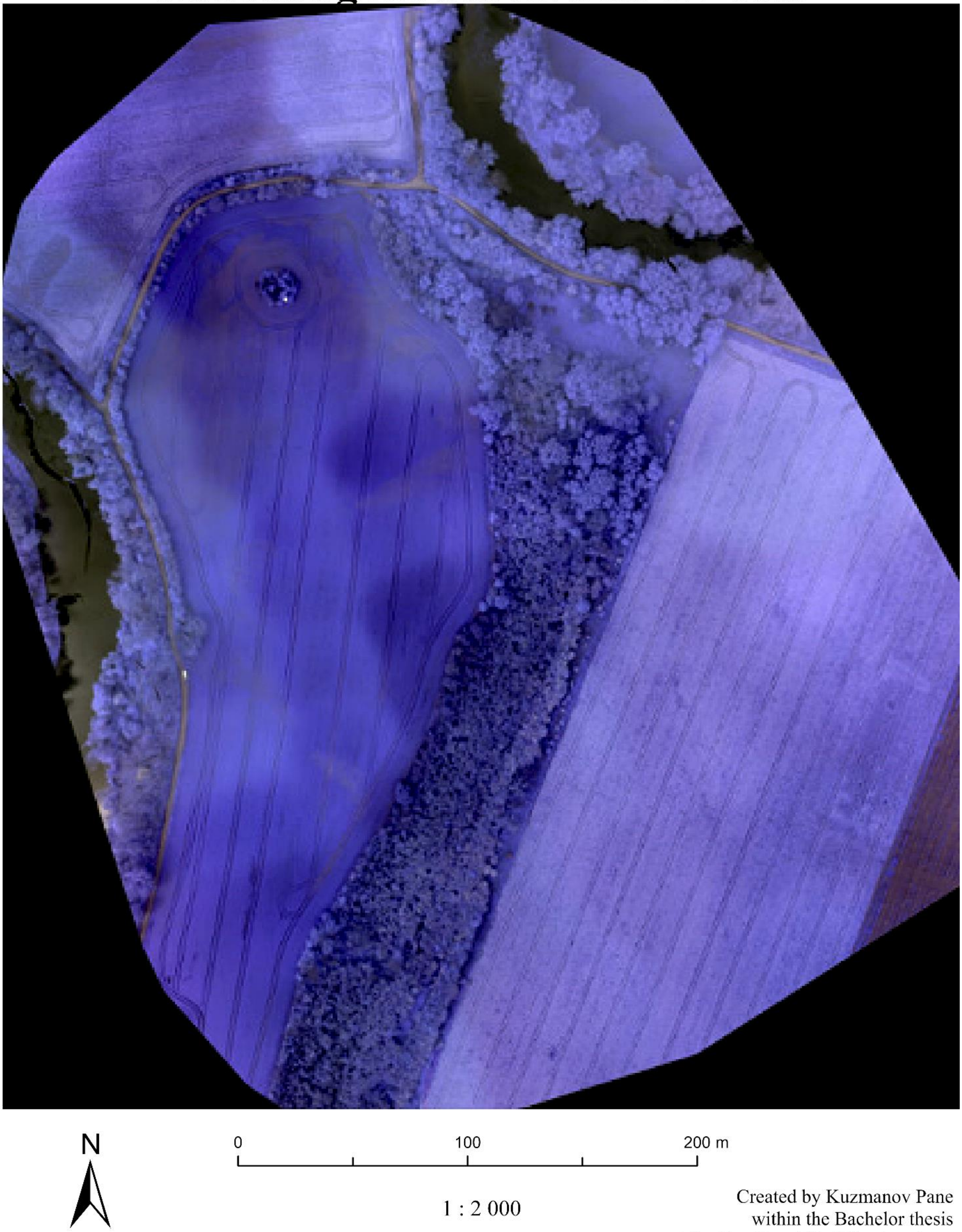
An analysis of the generated outputs was made. On the output shown on Figure 13 (DSM) and on both of the generated orthophotos (Figure 17 and 19) a sub-surface rectangular-shaped object is clearly visible.

During the executed survey a wider area was captured with the eBee RPAS. Judging by the visible vegetation symptoms in the area outside of the initially observed area, there is a high possibility of an existence of another sub-surfaced object nearby. Because that area was not included in the thesis research, further surveys can be done over the site as to confirm the existence of the object that has not been yet archaeologically confirmed.

A geophysical survey was originally planned to verify the historical object, but this was not possible due to COVID-19; at present, there is already high vegetation in this area. Geophysical non-invasive survey can be applied only after harvest.

Attachments

Archeological site Březno u Loun



Created by Kuzmanov Pane
within the Bachelor thesis
at the Faculty of Civil Engineering -
Czech Technical University in Prague
May 2020

Archeological site Březno u Loun

1 : 3 000

Created by Kuzmanov Pane
within the Bachelor thesis
at the Faculty of Civil Engineering -
Czech Technical University in Prague
May 2020

References

1. Aber, J., Marzolff, I., and Ries, J. 2010. Small-Format Aerial Photography – Principles, Techniques and Geoscience application. Amsterdam-London: Elsevier Science. ISBN 978-0-444-53260-2
2. Al-Tahir, R. 2015. Integrating UAV into Geomatics Curriculum. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-1/W4, 387–390, https://doi.org/10.5194/isprsarchives-XL-1-W4-387-2015
3. Brach, M., Cheung-Wai Chan, J., Szymanski, P. 2019. Accuracy assessment of different photogrammetric software for processing data from low-cost UAV platforms in forest conditions In: iForest - Biogeosciences and Forestry, Volume 12, Issue 5, Pages 435-441 (2019) doi: https://doi.org/10.3832/ifor2986-012
4. Brázdil, K. 2010. Projekt tvorby nového výškopisu území České republiky. GIS Ostrava. Available from: http://gisak.vsb.cz/GIS_Ostrava/GIS_Ova_2010/sbornik/Lists/Papers/CZ_5_2.pdf
5. Casana, J., Kantner J., Wiewel, A., and Cothren, J. 2014. Archaeological aerial thermography: a case study at the Chacoera Blue J community, New Mexico. In: Journal of Archaeological Science 45 (2014), pp. 207–219. doi: 10.1016/j.jas.2014.02.015.
6. Civil Aviation Authority, 2014. Letecký předpis. Pravidla létání. L2. Available form: https://aim.rlp.cz/predpisy/predpisy/dokumenty/L/L-2/data/print/L-2_cely.pdf
7. Clapuyt F, Vanacker V, Van Oost K (2016). Reproducibility of UAV-based earth topography reconstructions based on Structure-from-Motion algorithms. Geomorphology 260: 4-15, doi: https://doi.org/10.1016/j.geomorph.2015.05.011
8. Colomina, I., and Molina, P. 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS Journal of Photogrammetry and Remote Sensing vol 92, pages 79-97. [online]. Available from: http://www.sciencedirect.com/science/article/pii/S0924271614000501
9. Colwell, R.N. 1997. History and place of photographic interpretation. 2nd edition. American Society for Photogrammetry and Remote Sensing. Bethesda, Maryland, United States. p. 3-47
10. DJI - The World Leader in Camera Drones/Quadcopters for Aerial Photography. DJI Official. Available from: https://www.dji.com/cz

11. Dolanský, T. 2004. Lidary a letecké laserové skenování. Acta Universitatis Purkynianae n. 99. Ústí nad Labem:UJEP FŽP. Available from: https://moodle.fzp.ujep.cz/pluginfile.php/4978/mod_resource/content/1/160lidaryweb.pdf
12. Dušánek, P. 2014. Nové výškopisné mapování České republiky. GIS Ostrava. Available from: http://gisak.vsb.cz/GIS_Ostrava/GIS_Ova_2014/sbornik/papers/gis2014526faa8a434ef.pdf
13. Eisenbeiss, H. 2009. UAV photogrammetry. Zürich: ETH, Inst. für Geodäsie und Photogrammetrie. Mitteilungen / Institut für Geodäsie und Photogrammetrie an der Eidgenössischen Technischen Hochschule Zürich. ISBN 978-3-906467-86-3.
14. European Commission, 2019. Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft. Available from: https://www.easa.europa.eu/document-library/regulations#uas---unmanned-aircraft-systems
15. Giordan, D., Manconi, A., Tannant, D.D., Allasia, P., 2015. UAV: Low-cost remote sensing for high-resolution investigation of landslides. In: Geoscience and Remote Sensing Symp. (IGARSS). IEEE, pp. 5344–5347. Available from: https://ieeexplore.ieee.org/document/7327042
16. Gojda, M. 2007. Lety do minulosti – Flights into the Past. Exhibition guidebook. Praha: Národní muzeum.
17. Gojda, M., John, J., and Starková, L. 2011. Archeologický průzkum krajiny pomocí leteckého laserového skenování. Dosavadní průběh a výsledky prvního českého projektu, Archeologické rozhledy 63, 680-698. Available from: http://www.arup.cas.cz/wp-content/uploads/2010/05/LIDAR-AR-2011_lr.pdf
18. Gruszczynski W, Matwij W, Cwiakala P. 2017. Comparison of low-altitude UAV photogrammetry with terrestrial laser scanning as data-source methods for terrain covered in low vegetation. ISPRS Journal of Photogrammetry and Remote Sensing 126: 168-179, doi: https://doi.org/10.1016/j.isprsjprs.2017.02.015
19. Hubacek, M., Kovarik, V., Kratochvil, V., 2016. Analysis of influence of terrain relief roughness on dem accuracy generated from LiDAR in the Czech Republic. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B4, 25–30. https://doi.org/10.5194/isprsarchives-XLI-B4-25-2016

20. Ivošević, B. et al. 2015. The use of conservation drones in ecology and wildlife research. J. Ecol. Environ. 38(1): 113-118. Available from: http://koreascience.or.kr/article/JAKO201507964682684.page
21. John, J., and Goida, M. 2013. Archeologie a letecké laserové skenování krajiny – Archaeology and Airborne Laser Scanning of the Landscape. Katedra archeologie-Západočeská univerzita v Plzni. Plzeň. ISBN 978-80-261-0194-9
22. Kuna, M., Beneš, J., Dreslerová, D., Gojda, M., Hrubý, P., Křivánek, R., Majer, A., Prach, K., Tomášek, M. 2004. Nedestruktivní archeologie. Teorie, metody a cíle – Non-destructive archaeology. Theory, methods and goals. Praha: Academia. ISBN 80-200-1216-8.
23. KUNA, Martin, a kol. Archeologický atlas Čech. 2. vyd. Praha: Archeologický ústav AV ČR, 2015. 520 s. ISBN 978-80-87365-82-3. Kapitola Březno u Loun, s. 69–72.
24. Lambers, K., Eisenbeiss, H., and Sauerbier, M. 2007. Combining photogrammetry and laser scanning for the recording and modelling of the Late Intermediate Period site of Pinchango Alto, Palpa, Peru. In: Journal of archaeological science 34.10, pp.1702–1712. doi: 10.1016/j.jas. 2006.12.008.
25. Matese,A., Filippo Di Gennaro,S., and Berton,A. 2017 Assessment of a canopy height model (CHM) in a vineyard using UAV-based multispectral imaging, International Journal of Remote Sensing, 38:8-10, 2150-2160, doi: 10.1080/01431161.2016.1226002
26. Pavelka, K., Šedina, J., Matoušková, E., Hlaváčová, I., and Korth, W. 2019. Examples of different techniques for glaciers motion monitoring using InSAR and RPAS. European Journal of Remote Sensing, 52:sup1, 219-232, https://doi.org/10.1080/22797254.2018.1559001
27. Pavelka, K., Šedina, J., Pacina, J., Plánka, L., Karas, J., and Šafář, V. 2016. RPAS – Remotely piloted aircraft system. Prague: Czech Technical University. ISBN: 978-80-01-05648-6
28. Pavelka, K., Šedina,J., Matoušková, E.,Hlaváčová,I., and Korth, W. 2018. Examples of different techniques for glaciers motion monitoring using InSAR and RPAS. European Journal of Remote Sensing, 52:sup1, 219-232, doi: 10.1080/22797254.2018.1559001

29. Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., and Sarazzi. D. 2011. UAV Photogrammetry for mapping and 3D modeling – Current status and future perspectives. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-1/C22, 2011. Available from: https://www.researchgate.net/publication/263449506_UAV_photogrammetry_for_mapping_and_3D_modeling-Current_status_and_future_perspectives
30. Rijsdijk, M. et al. 2013. Unmanned Aerial Systems in the process of Juridical Verification of Cadastral Borders. In: Presentation at UAV-g Conference, Rostock University, Rostock, Germany. doi: 10.5194/isprsarchives-XL-1-W2-325-2013.
31. Rokhmana, C., A. Gumeidhidta, I., & E. Tjahjadi, M. 2019. Potential Use of UAV-Based Mapping System to Accelerate the Production of Parcel Boundary Map in Indonesia. KnE Engineering, 4(3), 238–246. https://doi.org/10.18502/keg.v4i3.5858
32. RPAS Yearbook. UAS: The Global Perspective. 11th Edition. June 2013. Blyenburgh & Co. Available from: www.uvs-info.com
33. Sauerbier, M., and Eisenbeiss, H. 2010. UAVs for the documentation of archaeological excavations. In: International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 38. Part 5 (2010), pp. 526–531. Available from: https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/26303/2/214.pdf
34. SenseFly: Drones For Professionals, Mapping & Photogrammetry, Flight Planning & Control Software: senseFly SA [online]. Available from: https://www.sensefly.com/home.html
35. Šedina, J., Housarová, E., and Matoušková, E. 2016. Documentation of Urn Graves of Knovíz Culture by RPAS. Geoinformatics FCE CTU. doi: 10.14311/gi.15.2.6
36. Šedina, J., Hůlková, M., Pavelka, K., and Pavelka, K.jr. 2019. RPAS for documentation of Nazca aqueducts. European Journal of Remote Sensing, 52:sup1, 174-181. https://doi.org/10.1080/22797254.2018.1537684

List of figures

List of tables