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PHOTOGRAMMETRY AS A SURVEYING TECHNIQUE

APPLIED TO HERITAGE CONSTRUCTIONS RECORDING - ADVANTAGES AND LIMITATIONS

VOLUME I

João Ricardo Neff Valadares Gomes Covas

Dissertação de Natureza Científica para obtenção do Grau de Mestre em

ARQUITECTURA

Orientação

Professor Auxiliar Luis Miguel Cotrim Mateus

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DOCUMENTO DEFINITIVO

Lisboa, FAUL, Dezembro de 2018

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RESUMO

A presente dissertação tem por objectivo investigar e evidenciar as vantagens da aplicação da fotogrametria, e possíveis integrações com outros métodos de levantamento, como seja o varrimento laser terrestre, posicionamento por GPS, entre outros, para realizar levantamentos de construções patrimoniais ou eruditas e a respectiva produção de documentação base para viabilizar intervenções de conservação, restauro ou reabilitação.

A motivação para a investigação advém da aplicação flexível, versátil, simples, acessível, e baixo-custo da fotogrametria em projectos de levantamento pequenos ou extensos. Tenciona-se igualmente colmatar as desvantagens tradicionais da fotogrametria, nomeadamente a transição entre espaços interiores e exteriores, e registo de espaços estreitos, de difícil acesso, e de geometrias complexas, num único projecto de documentação. Pretende-se ultrapassar estas dificuldades através da utilização máxima das potencialidades da fotogrametria com o uso de imagens olho de peixe e apenas como último recurso utilizar instrumentos complementares.

No caso de estudo principal, o Castelo do Convento de Cristo, demonstra-se a aplicação dos métodos investigados. Nos casos de estudo secundários abordam-se problemas parcelares, desde elementos decorativos até à totalidade do edificado: Convento dos Capuchos, em Sintra; Alcáçova e trecho de muralha do Castelo de Sesimbra; Igreja de Stº André, em Mafra; entre outros. Os casos auxiliaram na determinação de procedimentos a generalizar posteriormente. Por fim, propõem-se algoritmos que auxiliam na produção de documentação.

PALAVRAS CHAVE

| Técnicas de Levantamento Arquitectónico | Fotogrametria Arquitectónica |

| Património Cultural | Conservação, Restauro e Reabilitação |

| Imagens Olho-de-Peixe |

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Abstract

The present dissertation aims to research and demonstrate the advantages of the application of photogrammetry, and its possible integrations with other methods, such as terrestrial laser scanning, GPS positioning, and among others, to perform surveys of heritage or erudite buildings and respective production of base documentation to enable interventions of conservation, restoration, or rehabilitation.

The motivation for researching is due to the flexible, versatile, simple, affordable, and low-cost application of photogrammetry in small and extensive survey projects. It is also intended to overcome the traditional disadvantages of photogrammetry, such as the transition between interior and exterior spaces, and difficulty of recording narrow, hard-to-access, and complex geometric spaces, in a single project. It is intended to overcome such challenges by maximizing the potential uses of photogrammetry with the use of fisheye images and by using other survey instruments as a last resort.

In the main case study, the Castle of the Convent of Christ, the application of the investigated methods is demonstrated. In the secondary case studies, partial problems are addressed, ranging from decorative elements to the entire building: Convento dos Capuchos, in Sintra; Citadel and section of a wall of the Castle of Sesimbra; Igreja de St André, in Mafra; among others; The case studies aided in determining general procedures. Finally, algorithms that accelerate the production of documentation are proposed.

Key Words

| Architectural Survey Techniques | Architectural Photogrammetry |

| Cultural Heritage | Conservation, Restoration, and Rehabilitation |

| Fisheye Images |

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Index of Abbreviations and Glossary

.bat Batch file format. Batch is a script that runs on windows using the syntax of this OS.

.dwf AutoDesk file format. See DWF for details.

.dwg "Drawing", a file format. See DWG for details.

.p4d Pix4D file format.

.psd "Photoshop Document", an Adobe Photoshop file format.

.py Python file format. See Python.

.xml "Extensible Markup Language", a file format. See XML for details.

123D Catch An online photogrammetry web-service, developed by AutoDesk (http://www.123dapp.com/catch)

3D "Three-Dimensions"

A

AE "Auto-Exposure" is a method to automatically calculate the camera settings so that the resultant image contains as much interpretable data as possible.

Add-on or addon Enhances or extends functions or adds new items to the interface of the program. Not to be confused with "Plugin", although both are referred interchangeably.

Agisoft Lens A lens-calibration software by Agisoft. Freeware. Originally was available as a standalone download from Agisoft. Currently is bundled with the main software "Agisoft PhotoScan".

Agisoft PhotoScan Multipurpose and multiplatform advanced digital photogrammetry software. Offers: Crippleware without save and export functions; Trialware for 30 days; Two types of commercial software. (http://www.agisoft.com/)

ALS "Aerial Laser Scanning"

AMD Radeon "Advanced Micro Devices"; Is a company that manufactures computer products, including graphics processing units (GPU) for which are named "Radeon". See Nvidia. (http://shop.amd.com/en-gb/components/graphic-cards)

Apero-Micmac A multiplatform photogrammetry software (free and open-source software) mainly utilized for geographical purposes. It Includes SFM (Apero) and MVS (Micmac) which is based on depth map fusion. (http://logiciels.ign.fr/?Micmac)

ARC 3D An online photogrammetry web-service (http://www.arc3d.be/)

ASCII "American Standard Code for Information Interchange", in computation is a universal standard for representing lower-case and upper-case letters, numbers, and punctuation.

AutoCAD Autodesk product to draft.

B

BA "Bundle Adjustment", a Computer Vision algorithm for refining 3D coordinates of a scene, and distortion parameters of a lens.

BIM "Building Information Modelling"

Binary Package Provides the user with a program (package) compiled for a specific OS and which is given in the form of an executable ".exe" (ready-to-run). Not to be confused with "Source Package".

Binary Is a code whose representation is limited to "0" and "1".

bit "Binary Digit"; is the smallest unit of information that can be stored and/or manipulated on a computer. One bit can either be a "0" or "1", that is, "on" or "off" respectively. The *bits* are clustered, so the computer uses several *bits* at the same time to perform operations.

Bundler Is a structure-from-motion (SFM) software (free and open source) for unordered image collections. To make dense (MVS) reconstruction acquire PMVS2 and CMVS. (http://www.cs.cornell.edu/~snavely/bundler/)

byte 8 bits form up a byte. A *byte* also happens to be how many *bits* are needed to represent letters of the alphabet and other characters. For example, the letter "A" would be 01000001.

C

CAD “Computer Aided Design”

CCD “Charge-Coupled Device”; in photography is a type of imaging sensor. See CMOS for disambiguation.

CDR “Camera Dynamic Range” defines the possible range from the darkest tone to the brightest tone that the camera can capture.

CLI “Command Line Interface” (CLI), commonly known as “Command-Line”, is an interface from which an operator issues commands in the form of successive lines of text in order to interact with a computer program.

CloudCompare A multi-platform 3D point cloud and mesh processing software (free and open-source software), originally started by Daniel Girardeau-Montaut. Free for any purpose, including commercial or for education.

CMOS “Complementary Metal-Oxide-Semiconductor”; In photography CMOS is a type of imaging sensor. See CCD for disambiguation.

CMPMVS Is a photogrammetry freeware developed by Michal Jancosek & Tomas Pajdla for making dense point clouds, meshes, and automatic video generation from an input set of pre-oriented and undistorted photographs; May be executed with VisualSFM workflow. The authors also provide online service reconstructions. (http://ptak.felk.cvut.cz/sfmservice/websfm.pl?menu=cmpmvs)

CMVS “Cluster Multi-View Stereo”

CMVS/PMVS2 “Clustering Views for Multi-View Stereo”/ “Patch-Based Multi-View Stereo”; are free and open-source software developed by Yasutaka Furukawa for making dense (MVS) reconstructions; May be executed with VisualSFM workflow. (http://www.di.ens.fr/cmvs/) (http://www.di.ens.fr/pmvs/)

CMYK "Cyan; Magenta; Yellow; Black"; See RGB for disambiguation.

Code "Code" is a term utilized for statements written in the source code (computer programming language) and object code (machine language, resultant from compiled source code).

Commercial Software Also known as "Payware", are programs whose services are operated if purchased.

Compiled Language Is a form of low-level programming language which requires compilation in order to be executed by the computer. A compiled file usually runs faster than a script.

CP "Control Point"; Used in photogrammetric software by user input to help verify the quality of the data under analysis.

CPU "Central Processing Unit", a hardware component and central unit of a computer. Essential for executing instructions. Distinct from GPU.

CRP "Close Range Photogrammetry"

Crippleware In software, "crippleware" refers to programs with unlimited time usage whose few vital features are deactivated or missing, such as outputs or fundamental tools, until the user purchases a fully functional version of said program. A strategy commonly utilized for demonstration purposes and free of charge. Not to be confused with "trialware" or "freeware."

D

DGPC "Direcção-Geral do Património Cultural". Portuguese institution responsible for the management of cultural heritage in mainland Portugal. (http://www.patrimoniocultural.pt/pt/)

dpi "dots per inch"; A measurement system for determining the number of dots per unit of length (inch) of a printed image. A reasonable indicator to check the quality of a printed image; Although depending on other factors such as ppi. See ppi for disambiguation.

Drone Any kind of autonomously or remotely guided vehicle that travels on land, sea, or air. Colloquially used as a synonym for UAV.

DSLR "Digital Single Lens Reflex Camera"

DWF "Design Web Format", a file format (".dwf") developed by AutoDesk to highly compress files (vectorize), such as DWG and with the main purpose of communicating design information for viewing or reviewing.

DWG "Drawing", a file format (".dwg") commonly used by CAD program software for storing 2D and 3D data and metadata - images, maps, geometric data, and designs. (http://www.autodesk.com/products/dwg)

E

F

Free Software Free software are programs that provide the user with the source code and the freedom to study, share, run, copy, distribute, change, and improve said source code for any purposes or desires. In general, "free" stands for "freedom" instead of "free of charge", thus free software is viewed as the opposite of proprietary software (protected by copyright). Not to be confused with "open-source software". (http://www.gnu.org/philosophy/free-sw.html).

Freeware "Freeware" is software that can be operated at no monetary cost, but not re-distributed or reverse engineered since its source code is not made available by the author.

FOV "Field of View"

G

GCP "Ground Control Point". Used interchangeable with "CP". See "CP".

Georeferentiation The process of locating the contents of a project relative to the corresponding coordinates of the earth.

GIF "Graphics Interchange Format"; is a file format

GIS "Geographic Information Systems"

GPS "Global Positioning System"

GPU "Graphics Processing Unit", a hardware component that performs fast mathematical equations, mostly used for rendering images and to offload tasks from CPU. Distinct from CPU.

GSD "Ground Sampling Distance"

GUI "Graphical User Interface". It displays features thus enabling the user to comprehend and interact with the program.

H

HD "High Definition"

HDD "Hard Disk Drive", a type of computer storage device.

HDR "High Dynamic Range"

hr "hour"

HTML "HyperText Markup Language"

Hugin A multiplatform open-source panorama photo stitching software developed by Pablo d'Angelo and others. (http://hugin.sourceforge.net/)

I

Installer An installer contains the binary (source code), the necessary supporting files (dependencies), and a program to verify the suitability of the system in order to set up everything with the correct pathways, simplifying the process to the average user.

J

JAG3D "Java Graticule 3D"; is a free and open-source software for calculating geodetic 1D, 2D, and 3D networks by a least-square-adjustment; useful for matrix transformations - point-cloud registration. (http://javagraticule3d.sourceforge.net/)

JPG or JPEG "Joint Photographic Experts Group"; is a file format (".jpg" or ".jpeg") that stores information of digital images using lossy compression method.

K

L

LASER "Light Amplification by Stimulated Emission of Radiation"

LCD "Liquid Crystal Display". LCD is a type of flat panel display to visualize digital information.

LIDAR "Light Detection And Ranging"

LINUX An operating system; Usually utilized for managing servers.

LS "Laser Scanning"; see TLS, ALS, LIDAR, ALIDAR, TLIDAR.

M

m "meter"

M "million"

Memento A multiplatform web-based photogrammetry freeware also able to manipulate meshes to present on the Web or to 3D print. Software developed by AutoDesk. (https://memento.autodesk.com/about)

MeshLab A multiplatform advanced 3D point cloud and mesh processing software (free and open-source software), originally created in 2005 at the University of Pisa, and currently developed by ISTI-CNR research centre. (http://meshlab.sourceforge.net/)

MeshMixer A multiplatform state of the art freeware for working with triangle meshes and 3D printing, developed by AutoDesk. See NetFab. (http://www.meshmixer.com/)

Metadata Data that provides information about other data. Metadata can be found in document files, images, videos, spreadsheet and web pages. For example, metadata of a digital photograph contains basic information about the type of photographic camera, camera lens, file format, location, and more. Metadata can be written by automated information processing (by a program) and/or appended manually.

MILC "Mirrorless Interchangeable Lens Camera"

min "minute"

MP "Mega Pixel"

MSSCH "Metric Survey Specifications for Cultural Heritage"

N

Nadir An image acquired with its principal axis perpendicular to the ground surface. Usually aerial images.

NetFab A multiplatform state of the art software for working with meshes and 3D printing. Crippleware: NetFab Basic; Payware: NetFab Professional. See MeshMixer. (http://www.netfabb.com/)

Nvidia A company that focuses on visual computing and computer graphics and designs graphics processing units (GPU). See AMD Radeon. (http://www.nvidia.co.uk/page/home.html)

O

Octree Is a tree data structure to facilitate data processing. For each iteration (recursive), each node is subdivided to contain 8 fractal children.

Open-Source Software Refers to programs that provide the user with licensed source codes in which the copyright holder allows the user to execute certain actions, such as to study, share, run, copy, distribute, change, and improve said source code for specific or general purposes. The main focus is the development of said program rather than the freedom of the user. Not to be confused with "free software". (http://opensource.org/osd)

OS "Operating System"; Is a program that, after booted (loaded) at the start of the computer, is responsible for the management of programs (or application programs) that are run within said OS, while considering the processing capacity of the computer.

P

Photoshop A proprietary software to manipulate images.

Photosynth A free online service to generate panoramas and for photogrammetry. (https://photosynth.net/)

Pix4D Multipurpose advanced digital photogrammetry software mainly for drone-based mapping and with point cloud editing capabilities. Commercial software: Pix4DMapper Pro; Trialware: Pix4DMapper Pro Trial; Crippleware with limited outputs: Pix4DMapper Discovery. (https://www.pix4d.com/)

Pixel The smallest element of representation in an image.

Pixel Resolution The total number of pixels in an image irrespective of area.

Plug-in or plugin Adds an extra function or capability to a specific program. Not to be confused with "Addon", although both are referred interchangeably.

PMVS Photogrammetric software package.

PNG "Portable Network Graphics"; An image file format (".png").

Poisson Misha "Screened Poisson Surface Reconstruction", is an algorithm for surface reconstruction, developed by Michael Misha Kazhdan. (http://www.cs.jhu.edu/~misha/Code/PoissonRecon/Version8.0/)

POV "Point of View"

ppi "pixels per inch", a measurement system for determining the number of pixels per unit of length (inch). In other words, a way to determine pixel density (resolution) of a virtual image or display.

Program "Program", "Program Application", or colloquially referred to as "software", is a specific set of ordered operations written in code for a computer to execute. A program is either: “interactive”, which receives inputs from an operator or another program; or “batch”, which runs automatically without human interaction.

Programming Language Programming languages are a form of code which is used to write statements or instructions to the computer. Several levels of programming language exist, ranging from low level to high level. The higher the language the more human-readable it is. These languages can be organized into two major programming languages: scripting language, and compile language.

Q

R

RAM “Random Access Memory”, is a hardware component of a computer that enables to read information much faster than from the hard drive.

RGB “Red; Green; Blue”. See CMYK

rmse “Root Mean Square Error”

S

Script Script is a program (often referred for small programs) written in a scripting language and that is interpreted (processed) by another program (interpreter) first rather than by the computer processor (if not compiled). As a result, processing a script takes longer due to interpreters. However, it is faster to code for it does not require a compilation process.

Scripting Language Is a form of a high-level programming language (easy human-readable computer programming language), which is usually interpreted rather than compiled.

SDR “Scene Dynamic Range” defines the possible range from the darkest tone to the brightest tone that the scene contains.

sec “second”

SIFT “Scale Invariant Feature Transform”, a Computer Vision algorithm to describe image features, while considering scale, light, and other variables.

Source Package Provides the user with the source code of the program (package) which generally can be used in any OS if compiled correctly by the user. Not to be confused with “Binary Package”.

SSD “Solid-State Drive”, a computer storage device. An SSD has higher performance and durability than hard disk drives (HDD), although currently they are more expensive. (http://searchstorage.techtarget.com/definition/solid-state-drive)

std “Standard”

T

TIF “Tagged Image File Format”; A file format (“.tif” or “.tiff”) for storing high-quality graphics using lossless compression method.

TLS “Terrestrial Laser Scanning”;

Trialware A type of program utilized for demonstration purposes, free of charge, and a full version that only operates for a limited time, typically 15 or 30 days. Not to be confused with “crippleware” or “freeware”.

U

UAS “Unmanned Aerial System”. See drone.

UAV “Unmanned Aerial Vehicle”. See drone.

V

VSFM “Visual Structure-From-Motion” or “VisualSFM”. A structure from motion (SFM) freeware, containing an automated and user-friendly GUI that allows the user to detect features, match images, reconstruct sparse models and georeference the data. This software integrates other projects: SIFT GPU, and Multicore Bundle Adjustment (PBA). For making dense reconstructions either acquire PMVS and CMVS, or CMPMVS. Program assembled by Changchang Wu. (http://ccwu.me/vsfm/)

W

Windows "Microsoft Windows Operating System". See W-OS for details.

W-OS "Microsoft Windows Operating System", also known as "Windows Operating System" or simply "Windows", is a graphical operating system by Microsoft. The version of the system is generally referred after the abbreviation or word: "Windows 8" for example.

X

XML "Extensible Markup Language"; a file format (".xml") designed to describe data with a focus on what the data is. Can work as a complement to HTML. See HTML to differentiate from XML.

Y

Z

1. INTRODUCTION

The present dissertation with the title "Photogrammetry as a Surveying Technique Applied to Heritage Constructions Recording – Advantages and Limitations" has been written in the context of a Master's Degree in Architecture, Faculty of Architecture of the University of Lisbon.

1.1. RESEARCH SUBJECT AND BACKGROUND

The central topic of the dissertation focuses on the use of photogrammetric techniques for the execution of surveys of erudite or patrimonial structures and its respective documentation. It includes subjects concerning practical and theoretical domains that embrace a high degree of interdisciplinarity - subjects such as Architecture, Archaeology, History of Architecture, Documentation, Surveying, Recording, Cultural Heritage, Passive and Active System, Direct and Indirect Methods, Photogrammetry, and more.

From the myriad of subjects that are available and that were considered, particular focus is given to researching the limits of the application of the photogrammetric techniques to overcome challenges that are well known or traditionally accepted in the application of photogrammetry and laser scanning. Challenges such as the transition between interior and exterior spaces, and difficulty of recording narrow spaces, hard-to-access spaces, and complex geometry. Per norm, overcoming such challenges is executed via the complementary usage of other survey methods or instruments. Such challenges were studied thoroughly, and it has been discovered that they can be solved by applying the same survey method but with the right instrumentation, that is, via the use of fisheye lenses – and thus the proposal of the term "close-range fisheye-photogrammetry" that is able to reduce the total number of images by at least 15 times in a single project.

The application of fisheye lenses is not new in the photogrammetric context. However, its use is very infrequent in the terrestrial domain for extreme close range situations. Per contra, fisheye lenses in sports cameras, such as the GoPro, are mostly adapted on drones because sports cameras are light-weight and allow for longer flight schedules. Such adaptation may seem counter-intuitive considering the optical effects of the fisheye images. That is, objects represented on the images appear very small, and photographing from aerial platforms the resultant objects are represented even smaller.

The research, as evident, is within the scope of Architecture but its contributions cover more than that, extending to other fields of study, such as Remote Sensing, Archaeology, Engineering, and others. Such extension is due to the reusability and interpretation of such information by the previously mentioned fields of study.

In addition, there are other survey instruments and methods possible to use, such as Global Positioning System (GPS), terrestrial laser scanning (TLS), and the so-called classical survey techniques that include the use of measuring tapes, plumb lines, total stations, laser distance sensors, laser levels, and others. Considering all of the possibilities, the dissertation focuses on one of the "contemporary" survey techniques such as photogrammetry and laser scanning.

Of the contents that were analysed and that centre around two umbrella terms, "Survey" and "Documentation", it may be noted there are dissimilarities and similarities between the two terms when analysed from the "concrete" vs "abstract" point of view.

Namely, while taking the human body as reference and without the intention to be reductive relative to the importance and impact of the subjects under examination: Survey activity can be seen as an extension of what the human body can offer in terms of precision and accuracy when proceeding with the measurement of the surroundings; and Documentation is the consubstantiation and projection of ideas onto a physical format to extend their longevity, that is, an extension of the human memory.

Specifically, and continuing with the line of thought, Documentation, while not disregarding its "concrete" domain, that translates on the production of support elements for professionals and that are interpreted visually, has a more prominent "abstract" component when compared to Survey activity. By contrast, the action of surveying, while not disregarding its "abstract" components that relate to the use of instruments and its influence in documental representation, is more of a "concrete" activity where the surveyor requires to analyse the observed reality.

Naturally, by identifying the differences both from the reductive point of view and from the studied bibliography, the present dissertation tendentially focuses on the research and application of survey techniques, without forgetting its association to documentation practices. The specific interest for the application of survey techniques resulted from crossing information between the study of diversified theoretical subjects (bibliography) with the application of survey instruments in the main case study, The Castle of The Convent of Christ, in Tomar. That is, it was recognized the lack of bibliographic references containing applications of photogrammetric solutions in regard to its known traditional limitations. Traditional limitations, as referred previously, such as recording of transitions between interior and exterior spaces, and spaces containing complex and intricate geometry.

The limitations that are commonly thought of as the real limitations of photogrammetry, are, in fact, an area possible to be fully explored and whose solutions may contribute, in an extremely positive way, to the production of trustworthy documentation.

In light of what has been mentioned so far, the dissertation starts by articulating notions and concepts related to survey, documentation, and the skills required by the surveyor for a successful recording of a structure. Next, the contents are focused on technical aspects related to the practice of photography and photogrammetry (see Annex 1 as well), including how to operate a photographic camera, the quality of images, the workflows of photogrammetry and its outputs. It is from here, that the researched solutions are presented in the third chapter, along with case studies that not only allow to overcome issues related to recording difficulties but also allow to overcome the limitations of other survey instruments, such as terrestrial laser scanning that has a minimum distance for the scanning operation. As evident, the types of limitations can range from severe to facile. It is situational, depending on the physical configuration of the object. In chapter 4 proposal of algorithms are presented to overcome challenges during the office work, such as the production of plans, section cuts, contour lines, and removing spurious points. Chapter 5 is the main case study, the Castle of The Convent of Christ in Tomar. Chapter 6 conclusions and illations are presented and in chapter 7 future work and prospects are discussed.

1.2. Research Question (s)

In such context, the following research question emerges: How to exclusively apply photogrammetry as an architectural surveying instrument in heritage or erudite buildings? What advantages and limitations arise from this application and how can they be overcome?

1.3. Hypothesis

The exclusive use of photogrammetry, although punctually complemented with other methods and techniques, allows producing a more complete and reliable documentation as the basis for the analysis and planning processes in conservation, restoration, and rehabilitation.

1.4. The Contributions in The Context of Society

The possibility of having partially absent information in the documents or lower quality documentation, as implicitly considered in some case studies from reading the bibliography, reveals the pressing need to explore new methods for acquiring information, not merely for self-personal interest but mainly for the protection of the cultural values inherently associated to the constructions. It also reveals an unexplored area for the application of photogrammetric techniques in "close-range fisheye" applications, and for which should be thoroughly discovered to open new recording possibilities.

Therefore, from our point of view, the presented research is of great importance for scientific, public, cultural, national, and international purposes.

It has scientific interest because the researched methods are related to survey instruments that are increasingly employed more often to acquire information about the physical world. In addition, it has a scientific impact as the potential that fisheye images have to offer for the preservation of cultural heritage is revealed, and it is brought to light the lack of focus given to specific applications - close range fisheye photogrammetry.

It has public interest because it allows the recording of detailed information of hard to record surfaces, thus allowing the possibility of performing conservation, restoration, and rehabilitation interventions efficiently. The increase of efficiency is directly related to the possibility of allowing intervening entities to perform detailed analysis of the constructions and, therefore, determine more adequate intervention processes whose results contribute to highlight the values inherently associated to said constructions.

It has cultural and national interest because the contributions reveal the pressing need of acquiring documentation of Portuguese heritage constructions to preserve Portuguese cultural values and its long History of existence as a country. In fact, Portugal has over 300 castles, many of which have intricate geometries, narrow spaces, and hard to reach spaces. In addition, it has international interest as the presented contributions are applicable – hopefully - to constructions in other countries, allowing the preservation of cultural values.

1.5. Motivation

The motivation to proceed with the research is best explained if divided into two parts, that is, due to personal preference and due to the real need of recording and documenting a world heritage construction.

Relative to personal preference, the reason for bringing forth efforts to research the use of photogrammetry as a surveying technique to record heritage constructions is related to the very personality and potential contribution of the author. Explicitly, I have always had a fascination concerning subjects such as photography, colour, geometry, maths, computer technologies, and the aesthetics of spaces and its impact on the user. Apart from these, there is also an interest in intricate and small details that require scrutinous observation. In sum, an interest in the observable reality and the impact on the human psyche.

As for the second motivation, the development of the current work initiated due to the need of producing documentation of The Castle of The Convent of Christ, in Tomar. For that purpose, it resulted in the collaboration between the research group ArcHC_3D (Architectural Heritage Conservation), me, the Administration of The Convent of Christ, and the DGPC (Direcção Geral do Património Cultural - the Portuguese governmental institution responsible for the management of cultural heritage in mainland Portugal).

Seeing the chance to combine personal interests with the need to contribute to society, the production of the current work was seen as an opportunity for personal fulfilment. For that reason, and also for scientific purposes, the dissertation is written in the English language because: i) the main case study is considered a World Heritage by UNESCO, and ii) the researched recording methods are, to some extent, an innovative solution to overcome challenges that the average user does not consider that often, particularly in medieval architectures. This way, the present document can be viewed and studied by professionals other than of Portuguese nationality or that comprehend the Portuguese language.

1.6. Objectives

From what has been mentioned so far, the main objective of the dissertation can be summarized as the proposal of a methodology that bases mostly on the exclusive use of photogrammetry, even if punctually integrated with other complementary survey instruments and methods in order to execute efficient surveys of architectural buildings and respective 2D and 3D documentation. For the accomplishment of the task these steps were considered:

- Test the exclusive use of images, including ultra-wide-angle images (fisheye images), for 3D reconstruction of digital models.
- To research and determine the geometrical consistency of the resulting photogrammetric survey.

- To inventory and study the processes of registration and documentation of architectural heritage.

1.7. Methodology and Expected Contents

For the executability of the dissertation, a plan was devised to allow the acquisition of information and experiences, that when combined result in what is designated as knowledge. For that purpose, the work was structured in two phases.

In the first phase, a general survey photogrammetry and documentation concepts was performed, and research of exemplary cases was carried out in order to identify disadvantages and advantages of the application of survey instruments. Simultaneously, the procedures and purposes of the documentation and its impact in the context of architecture, conservation, restoration, and rehabilitation were studied.

In the second phase, the proposed methods and survey techniques are verified and corroborated by studying a group of secondary case studies. In the context of the main case study, The Castle of the Convent of Christ, the produced information was determined in collaboration with the direction of the Convent of Christ and DGPC. From that moment, the survey was performed using: i) the researched methods, ii) and the survey instruments available by the Faculty of Architecture of the University of Lisbon through its 3D scanning Laboratory; iii) and in collaboration with the research group from CIAUD named ArcHC-3D.

In the final step, conclusions about the researched methods are presented with the intention of confirming if the exclusive application of photogrammetry and/or the complementarity between photogrammetry and other surveying instruments contributes to the production of trustworthy documentation.

In sum, the majority of subjects of study are as follows:

- Collection and analysis of information regarding the registration and documentation framework in the context of conservation, restoration, and rehabilitation intervention, using the following items:
    - Principles (ICOMOS charts)
    - Orientations (exemplary cases; guides)
    - Specifications (metric specifications)
- Methods and survey techniques:
    - Direct methods vs Indirect Methods
    - Active techniques vs Passive techniques

- Basic principles of photography, and the application of image-based techniques.
    - Architectural photogrammetry versus Computer Vision
- The photogrammetric workflows:
    - Fundamental photogrammetric operations (internal orientation, relative orientation, external orientation, triangulation, 3D restitution).
    - Structure-From-Motion (SFM) and Multi-View-Stereo (MVS)
    - Planning and acquisition of data;
    - Processing of data;
    - Outputs

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2. DOCUMENTATION AND PHOTOGRAMMETRY CONCEPTS

2.1. ON SURVEYING AND DOCUMENTATION

Since the beginning of Humanity, recording and documentation have been essential for planning and erecting buildings, whether they are constructed from the very foundations or designated for conservation, restoration, or rehabilitation work. Both activities concede humankind to study and perceive extensively the inherent and fundamental qualities of a given object, such as the shape, geometry, colour, volumetric relations, and among others. Measuring and recording are components of architectural surveying, a field of study of great importance for it allows one to study and observe intently each and every construction in its entirety, with the ultimate objective of contributing to humankind with valuable, noteworthy, and meaningful documentation containing information of every single perceivable and measurable aspect, such as the physical elements, psychological reflexes, and memories that the architectural object may convey. Each and every building belongs to a specific time (Docci & Maestri, 2005).

It is through a rigorous and methodical process that the essence of the architectural object is acknowledged and appreciated. Furthermore, all of the important information generated from architectural surveying promotes progression, development, and accomplishments in other fields of study, which are strictly related to or included in architectural surveying, and these include: direct observation of the construction; analysis and measurements of the parts, of the whole, and of the context in which the construction is inserted in; topographic survey; archaeological survey; historical-architectural survey; execution of restoration works; among others.

Thus architectural surveying is an activity with its own impact on the development of the human society, and may be interpreted as one of the fundamental tools ever devised in which descriptive geometry is employed to note the values of an architectural object in various systems of representation, which may include, and without limitation, video and audio recordings, photographs, images, illustrations, animations, texts, comments, graphics, obsolete drawings, and amongst other forms of recording. However, from all the systems of representation, the 2D orthogonal projection is frequently preferred. The represented values must express conveniently, clearly, and explicitly the essence of the architectural object, which reflects a society of a particular time and place, with their own customs, tools, and way of thinking and feeling.

Specifically, buildings are associated with a culture with their own worldview and way of designing architecture.

Consequently, it is through a scrutinized observation and thorough research of several objects, buildings, or sites, that one can uncover or understand the culture of a given time and place, and its influence in the society of today. Moreover, surveying allows one to comprehend interventions executed by posterior societies that, with their preferences and styles, embellished or modified the buildings in a specific way. Indeed, certain interventions are perceptible sometimes due to the style associated with a specific architect, or from the employed measurement standard, etc., making it possible to associate said interventions to a specific historical period. Furthermore, when crossing information with other fields of research, it is conceivable to grasp the reasons concerning the execution of such interventions, whether it is through the analysis of the spatial, dimensional, technological, and constructive values.

The execution of an architectural survey must be regarded seriously as it requires the implementation of an operational methodology, though a non-universal one for there is a multitude of survey instruments that offer diverse kinds of information and, therefore, workflows. In addition, the selection and employment of said instruments are equally influenced by the type of architectural object to document.

2.1.1. On the Skills of the Surveyor

Overall, every architectural survey comprises of elementary skills that every surveyor must master to perform efficient work and, above all, to produce trustworthy and valuable documentation. These skills involve the ability to identify, select, analyse, summarize, register, and draw at different scales, all of which are performed through interpretation. The aforementioned skills can be summarized as "discretization", the ability to break down a complex object into its individual parts, a vital procedure for a meticulous evaluation. In essence, an architectural survey not only relies on the application of instruments but also depends on the interpretative skill of the surveyor (Docci & Maestri, 2005).

Thus, it is imperative to proceed with considerable caution to avoid omitting valuable details unintendedly and thus produce poor and untrustworthy documentation. In other words, interpretation skill on pair with discretization is of utmost relevance, since in combination with the most objective part of surveying, the employment of the survey instruments to quantify features, results in the acquisition of information related to the object.

Indeed, discretization allows one to decompose a complex architectural object into significant elements crucial for the characterization and distinction of the said architectural object relative to others, even of the same architectural style. Moreover, one can study intently individual elements and establish comparisons to search for any considerable geometrical defects. The accomplishment of such task results from “seeing” instead of “looking”, particularly one may be “looking” and not “seeing” (as in “aware of”) that two geometrically “equal” objects may contain small and noticeable differences when inspecting thoroughly with or without the support of survey instruments. For this reason, different types of documentation are relevant to recognize minor differences, and that when interlinked with other types of documentation compose the building as it is interpreted in its entirety.

As evident none of this would be achievable if not for the cultural background of the surveyor, that being a powerful element for any architectural survey work allows one to “see” features that otherwise would remain unnoticed by an untrained eye. Therefore, for one to “see” one must first know, yet, for one to know one must first “see”. However paradoxical this may be, it is a prevalent occurrence. In other words, there are a number of features one does not see, and one does not know what there is to see because it hasn’t been seen yet. As asserted, this influences the quality and quantity of the acquired information. In the photogrammetric and architectural context, the skills for recording and documenting involve the knowledge of both photography and architecture. Being proficient in merely one of the aspects is insufficient, and more frequently than not the photographic data is of low quality. Thus good planning is vehemently necessary (D’Ayala & Smars, 2003).

2.1.2. The Documentation of The Observed Reality

Consequently, having support from researchers from other fields of study is desirable to ameliorate the knowledge background of the surveyor to produce trustworthy documentation. There is undoubtedly a symbiotic interaction between the architectural object and the surveyor, whose interpretation sensitivity, the power of observation and knowledge accumulate gradually as new features are perceived with or without the help of survey instruments or experts. Therefore, a good architectural survey should reveal clearly the uniqueness of a given construction and avoid capturing unmindfully superficial data. Ergo the application of survey instruments, on pair with a solid cultural background, should assist in the discovery of the inherent values of any given architectural object, contributing to the correct evaluation of its cultural impact and importance not only relative to the current society but also relative to the society that composed it.

In addition to identifying, selecting, and analysing, the ability to summarize is equally important particularly when representing a given feature at a specific scale, as it requires the surveyor to represent the architectural quality of the object with the minimally indispensable graphics while bearing in mind the intelligibility of said graphics. For example, as the drawing scale decreases fewer details of the features are represented and more effort is required to maintain the interpretability of said features in the drawings. Such procedure demands cultural background and expertise in drawing since the illustrations may be utilized by other researchers who may not be accustomed to interpreting them.

This leads to an important issue related to not fully comprehending the documented architectural values due to the inherent nature of the survey, which cannot fully represent all said architectural values through discretization. Although visiting the site allows the researcher or surveyor to perceive values which are unexpressed in the drawings, different types of documentation still deliver essential information for a strong understanding of the architectural object, as details which could not be perceived without the application of survey instruments are represented.

2.1.3. The Nature of a Survey

Docci and Maestri (Docci & Maestri, 2005) state that surveying is an operation which relies simultaneously on an objective and subjective approach and to refute such is counter-intuitive as surveying is an analytical process based on interpretation and objective data. Therefore, considering surveying activity as a predominantly interpretive operation one risks producing inadequate documentation, in which the reality of the architectural object is misrepresented. By contrast, if considering a survey operation as purely objective that disregards the process of interpretation, it will similarly result in poor documentation. In short, a survey should not be comprehended as the sole application of a technique while ignoring the process of interpretation, if valuable documentation is to be acquired.

This conflicting discussion relates to the intrinsic meaning of the term survey, which has been understood differently by each historical period, including the current one, and that is influenced by the technological evolution, cultural values, knowledge, surveyor experience, methodology, and so on; thus, resulting in the graphical representations of each historical period. No matter how much the act of surveying is inherently affected by the trend of times, apprehending the essence of the architectural object and producing documentation continues to be the main objective to accomplish through the application of survey instruments and discretization.

In light of what has been aforementioned, surveying can be regarded as an operation in which two sequential actions are executed: i) measuring and capturing the qualities of an object, building, 3D model, or terrain, in order to ii) represent the collected data graphically onto a physical support or into a digital support, both capable of bearing such information. In architectural context this operation is referred as architectural surveying, distinct from architectural designing, which consists in creating graphical representations and then in the materialization of the ideas, though only achievable if inserted in a specific context (historical, a site, etc.); and that in conservation, rehabilitation, or restoration is already given in a built form.

2.1.4. Types of Survey

To execute an architectural design, different kinds of recording must be considered, including architectural survey, historical survey, topographic survey, and any other required actions or operations. The same logical approach applies to other fields of study, such as engineering; urban analysis; conservation, rehabilitation or restoration; archaeology; amongst others (Mateus, 2012).

For instance, to execute an historical-architectural analysis, surveying provides crucial information to the historian of architecture, who, in his endeavour, is able to comprehend,

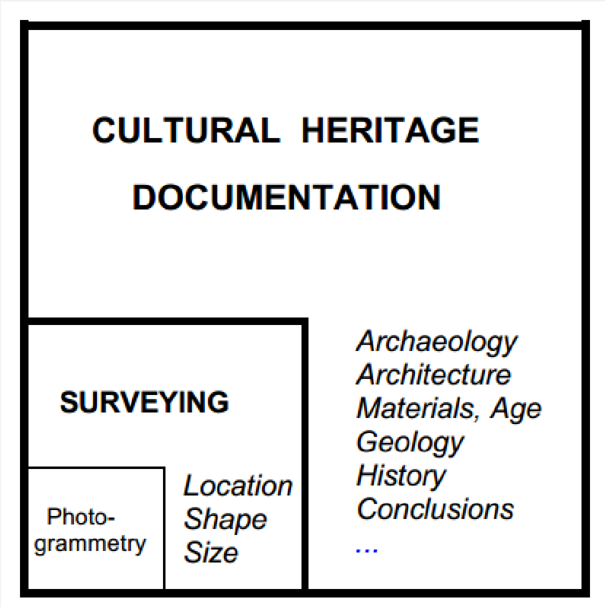

Figure 1: Photogrammetry is but only a method of surveying. Surveying is but only a part of cultural heritage documentation. (Böhler & Heinz, 1999).

determine, and identify diverse construction phases, transformations, or adjustments implemented in the building throughout the centuries. Docci and Maestri (Docci & Maestri, 2005) state that for a true comprehension of a given monument one needs documentation, and when said documentation deviates from reality a detailed description can transmit the architectural, spatial, technological, and structural values. In addition, documentation must have a considerable level of detail, from a general drawing scale down to small drawing scale, so to provide the means for making a step by step regression in time in an attempt to understand the original shape of the building, its architectural values, and confirm proposed hypothesis by other professionals, such as historians of architecture.

Another area of interest for executing a survey operation is in architectural conservation, which requires much detailed information about the architectural object in order to perform the necessary actions of conservation, restoration, reconstruction, or rehabilitation. Particularly, surveying allows the architectural conservator to achieve a sensitive assessment of the history, geometry, morphology, structure, construction techniques, construction phases, measuring systems, colours, materials, pathologies, and etc. of the building. In other words, the architectural conservator through a thorough study of the building is able to determine the causes of certain elements, which may be related to external or internal factors such as stress from the structure of adjacent constructions, aeolian erosion processes, and so on. For this, photogrammetry and laser scanning, which provide a remarkably high level of detailed information, concede one to analyse meticulously the anomalies, such as wall deformations, and hypothesize possible causes. Although the level of detail is determined by the type of work to be executed and the complexity of the building, a survey performed with care is of paramount significance if a successful architectural conservation is to be accomplished. For example, Mateus et al. (Mateus, Ferreira, Aguiar, & Barbosa, 2012) executed an analysis of wall deformations via the use of TLS on the Palácio de Valflores. In addition, Mateus et al. was able to detect interventions from dissimilar periods of time and distinguish organic from inorganic material on construction elements of the Convent of Christ with the use of TLS with different wavelengths. Docci and Maestri (Docci & Maestri, 2005) refer a few types of drawings frequently utilized by architectural conservators, which include: chronological drawings; drawings representing the current state of the construction; construction phases; comparison of old drawings with recent ones; and amongst others. Overall, the analysis performed on the buildings can be summarized to: i) iconic; ii) distributive; iii) constructive; iv) state of conservation; v), and vi) stratigraphic (Mateus, 2012).

Last but not least, surveying is also of great significance to perform archaeological works as it offers essential data for studying past human cultures or prehistoric societies up to recent decades via the identification, analysis, and interpretation of buildings, artefacts, and landscapes. The concurrent development of the site excavation and of the survey allows the archaeologist to monitor the progress of the work, compare diverse stratigraphic documents, analyse every material, compare findings of different historical periods, identify construction techniques, and reveal the existential purpose of the findings. In fact, most prehistoric archaeological works depend on survey operations since writing records are predominantly scarce. For example, Mateus et al. (L. Mateus et al., 2008) performed the recording of the Chapel of S. Frutuoso of Montélios with the objective of creating 2D and 3D data, and to verify the plausible use of photogrammetry and laser scanning techniques in terms of geometric accuracy, time use, advantages and limitations, costs within the framework of archaeology. Bryan et al. (P. G. Bryan, Abbott, & Dodson, 2013) with the use of photogrammetry and TLS demonstrate that The Stonehenge is, for example, extensively covered by numerous species of lichen and said surveying techniques are fit for recording world heritage constructions.

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2.2. Procedures for Documenting

Surveying and documenting are essential activities for accomplishing particular tasks required by architects, engineers, archaeologists, architectural conservators, historians of architecture, as both permit to comprehend and grasp the inherent values of the buildings, their surroundings, and the culture related to it. The information presented in the documents can take the form of photographs, drawings by hand or even text that identifies and clarifies every aspect of the building or terrain, which must follow certain principles (consensus), guides (how to proceed), and specifications (what criteria to accomplish) with the purpose of generating high quality, trustworthy, and valuable information to develop future works. Moreover, surveying is a notable tool for improving the perception of reality and cultural values, as well as for ameliorating or assisting in the architectural design, since it prepares one to perceive the world in a particular way.

Thus far we have referred and specified the key idea linked to the concept of surveying, yet a significant question remains and is related to the concept of "measuring" itself: measuring consists in a comparison between a value and a standard with the ultimate intent of quantifying the measurand. For instance, proportions of the human body are frequently utilized for construction works in particular countries to define the size of computer screens and other objects. For practical purposes, despite being a survey instrument dating back to former ages, it neither inhibits one from employing it nor makes it obsolete. In fact, being part of the human body, one carries it at all times, and if required, one can use it to estimate approximate lengths. A similar approach should be regarded for other survey instruments.

With the technological advancements over the past centuries, particularly in the last decades, new instruments have been conceived in such ways that offer higher values of accuracy and precision than ever before. This led to an increased complexity of such instruments, requiring more knowledge of the inherent operating principles so that an effective application may be achievable. Successively, there are other requirements that must be considered, such as the terms used in metrology, which are indispensable for a clear and accurate communication. Overall, instruments are an extension of what the human body is capable of offering in terms of accuracy and precision when measuring objects.

2.2.1. Principles, Guides, and Specifications

The challenges of documenting are not only relative to technical issues but also related to organisational and societal matters. Indeed, the continuous emergence of new technologies and obsolescence of "older" methods and recording techniques brings to light the need for the existence of governmental institutions and non-governmental institutions whose sole occupation is to set criteria for the preservation of cultural heritage. Cultural heritage is a legacy from the past. Said criteria is ever evolving and has the main purpose of setting homogeneous standards so that professionals, such as architects, surveyors, historians, archaeologists and others, labour with the same overall mindset and purposes and whose work can be intelligible by other professionals. The standards not only are positively reliable to professionals – as it guides them to know how to approach a problem or how to face it-, but also are vital to smaller institutes within or not the national scope, such as libraries, museums, publishers, community groups, archives, research institutes, and amongst others.

In general, the examined homogeneous criteria, even though encompassing a very large territory of topics that can range from very general ideas to specific ideas, relate to copyright laws, complexity of problems related to co-operation, guidance, leadership, sharing of information, strategies on how to proceed with recording and documentation, management of information, archival of information, technical and practical aspects, and so on. It can be thought of as the definition of strategies in the theoretical domain, and the employment of tactics that assume a more concrete aspect and that relate to the realization of the proposed strategies.

For instance, in the context of photogrammetry, in 1994, Waldhäusl and Ogleby (Waldhäusl & Ogleby, 1994) proposed the "3x3 Rules" that encompass the geometric, photographic, and organizational aspects of a photogrammetric project from its fieldwork phase to early office phase. Sometimes contradictory contributions may surface, as mentioned by D'Ayala and Mars (D'Ayala & Smars, 2003). Specifically, the authors refer that, after the publication of the 3x3 rules, a contribution made in 2001 mentions that the sole use of digital cameras with a 1 or 2 MP count represent the minimum requirements to deliver sufficiently good metric data. However, no accuracy figures were provided to substantiate such statements, and such statements were proven to be not so accurate when studies were brought forth that compare the use of film camera vs digital cameras – in the early 2000s when digital cameras were yet in its infancy in photogrammetric context. Therefore, more than reading guidelines, principles, and suggestions, the reader has the obligation to verify if said statements are yet verifiable given the current state of the art – so not to induce in error.

For this purpose, great efforts are brought forth to provide with the necessary materials as accurately as conceivable to support as many professionals as possible and to deliver the best documentation. The documents can be subdivided into three main categories: i) principles (consensus), ii) guidance (how to proceed); and iii) specifications (what criteria to accomplish) (Mateus, 2012).

Concerning point i), the principles are essential for the preservation and restoration of constructions in which it is affirmed the cultural aspect of the built environment and recognizes the cultural impact on the human being. As such, it is a crucial aspect to bring to light the importance of safekeeping the cultural values. Several documents have been published by ICOMOS (International Council on Monuments and Sites) and have been compiled to what is designated as "The International Charters for Conservation and Restoration" (ICOMOS, n.d.). In the compilation, there is an international appeal and awareness raising for the construction of a framework of principles for the conservation of monuments, including recommendations such as the production of inventories and descriptions of cultural heritage. In addition, ICOMOS has also published a "Guide to Recording Historic Buildings" (ICOMOS, 1990) that focuses on crucial aspects of recording, answering questions such as "why", "when", "what", "how", and "where", and above all the document proves the imperative existence of surveying and recording activities as both allow to keep track of changes and allow the current and coming generations to enjoy the existing monuments and associated memories. It promotes the values, interest, and foments the involvement of people for such activities.

Regarding point ii), guidance refers to how professionals should proceed methodically with their activities, and looks forward to answer a myriad of fundamental questions, including, but not limited to: budget and timeframe; how are records organized and presented; what level of detail should be acquired; what methods to apply; what skills are needed; what tools and technologies to use; what is the overall planning; necessity for preliminary recording; how should information be archived and managed and accessed; how should the various professionals interact to provide with valuable documentation; what are the physical conditions on site; with what purpose should the recording be executed; what are the requirements for an effective recording, and other issues. See Figure 2 for a schematic emphasizing the problem of information sharing between diverse fields of study. RecorDIM released two documents concerning these topics: "Recording, Documentation, and Information Management for the Conservation of Heritage Places" (Letellier, Schmid, & LeBlanc, 2007). The first one is focused on theory and the second one provides with practical examples. Other documents are also of great value, such as

“3D Laser Scanning for Heritage” by The English Heritage (English Heritage, 2011) in which narrowed concepts pertaining the use of laser scanning are presented and examples are given, in addition to “Measured and Drawn” by The English Heritage as well (Andrews et al., 2009). Lastly, the “Minimum Requirements for Metric Use of Non-Metric Photographic Documentation” (D’Ayala & Smars, 2003) focus on the application of photogrammetric techniques by complementing with information that was not yet considered at the time of its publication (2003), such as documentation strategies, the use of photographic cameras, lighting conditions, setting of the scene, and others. Such a document is vital in the context of this thesis.

As for point iii), related to specifications, The English Heritage is one of the institutions to have released documentation regarding the use of newer techniques, such as laser scanning and photogrammetry, in the context of architecture, archaeology and other fields of study. Such documentation is the MSSCH – “Metric Survey Specification for Cultural Heritage” (P. Bryan, Blake, Bedford, & Mills, 2009). In this document, detailed information is provided to the reader regarding the control of metric survey, standard specifications for image-based survey, measure building survey, topographic survey, and terrestrial laser scanning. Specific criteria are presented, such as accuracy and precision values to produce documentation at particular drawing scales.

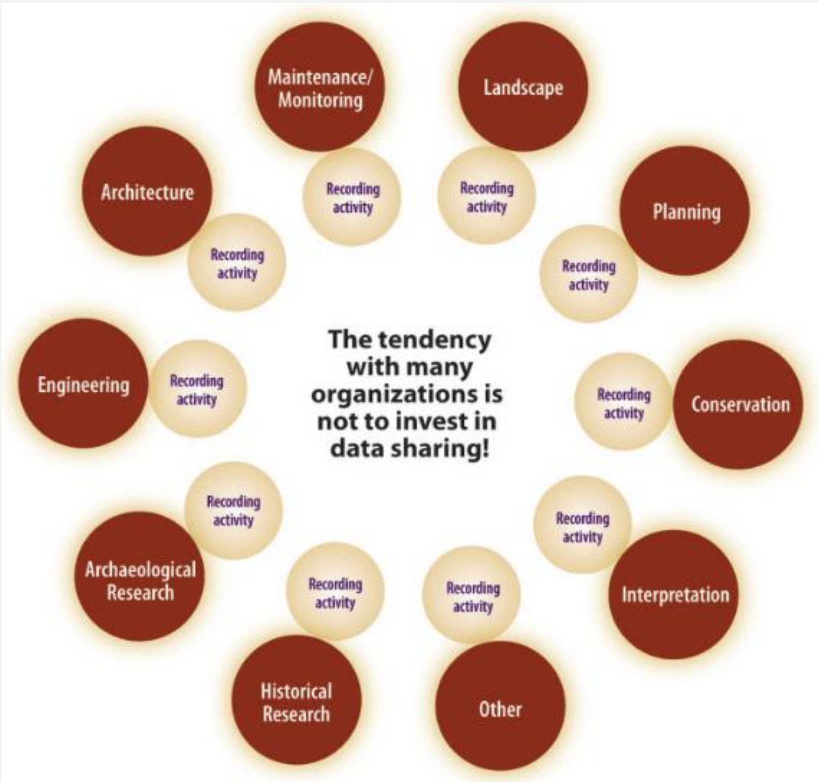

Figure 2: The main problems and concerns involved in documentation and information management. In this case, data sharing. (Letellier, Schmid, & LeBlanc, 2007).

Overall, documents included in points i) and ii) (principles and guidance) are frequently related to general topics than those concerned with metric documentation (specifications), such as the MSSCH that provide with details, and metric accuracy values that operators and surveyors must follow.

If it is not evident, conducting a survey of such extensive bibliography on specifications, guides, and consensus proves to be an exhaustive task but with an extremely positive return on the formation of a professional with interest in recording and documentation. From the documents that have been read by us, we can state that there is the need of producing very specific forms that allow organizing information from the most diverse points of view, such as architectural, archaeological, historical, and so on, and the possibility to share with diverse professionals as the acquisition of information is performed in different periods of time and for distinct purposes. Such forms would ease the production of valuable monographs containing extensive information, but not redundant, of cultural heritage. However, the focus of the current thesis is on the use of photogrammetric techniques, more specifically the application of fisheye images for ad-hoc solutions.

2.2.2. Some Institutions Contributing Towards Cultural Heritage

Some institutions of relevant impact are UNESCO (United Nations Educational, Scientific and Cultural Organization - *https://en.unesco.org/*), ISPRS (International Society of Photogrammetry and Remote Sensing - *http://www.isprs.org/*), and CIPA (International Committee of Architectural Photogrammetry - *http://cipa.icomos.org/*) that is a dynamic international organisation formed by conjoined efforts from ISPRS and ICOMOS (International Council on Monuments and Sites - *https://www.icomos.org/*).

These are merely the main institutions with international recognition. As evident, there are national governmental institutions. As for mainland Portugal, the institution responsible for the management of cultural heritage is the DGPC (Direcção Geral do Património Cultural).

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2.3. The Survey Instruments and Methods

As implicitly referred previously, depending on the complexity of the site to survey, the documentation to produce, the time-window to execute the task, the experience of the surveyor, the available equipment, the weather, and other impactful conditions, the selection of the appropriate survey methods and instruments is significant for the accomplishment of the operation, even if said survey method is considered old-fashioned or up-to-date. Above all, pragmatism should be desired, that is, it should be valued how one approaches the problem practically while considering the conditions that exist, without disregarding previously studied theoretical approaches in its entirety. This procedure and frame of mind allow the surveyor to explore, and fuel new ideas and methods to share among diverse fields of study, and simultaneously achieve the requested results even if failed attempts are encountered.

The research of new approaches is viable due to the technological advances throughout recent centuries, particularly in recent decades, where an amalgam of measurement instruments was developed and that allow obtaining metric values of the object to survey in diverse ways. The many available survey instruments can be structured and categorized as follows:

2.3.1. Direct Methods vs Indirect Methods

The first category: (i) "Direct Methods" and (ii) "Indirect Methods". The main difference resides particularly on how the measurements are physically executed. In the "Direct" (i) approach the survey instruments physically contact the measurand, and in the "Indirect" (ii) approach the survey instruments are deployed at a given distance to collect information while avoiding physical contact with the measurand. Nonetheless, at times direct contact is desirable and advantageous and may lead to a deeper understanding of the object. A survey, as aforementioned, not only focuses on recording numerical values but also focuses on acquiring other effects that the site, building, or terrain echo on the human being. Such information allows determining specific properties at different scales, from a small material to the existential purpose of the building. However, sometimes due to safety reasons or procedural cautions or for the safekeeping of the heritage construction, the direct physical contact is not possible (Docci & Maestri, 2005; Mateus, Nelson, Ferreira, Barbosa, & Aguiar, 2012).

2.3.2. Active Systems vs Passive Systems

The second category relies on the structural organization according to Remote Sensing: (i) "Passive Systems" and (ii) "Active Systems" (Konecny, 2003). The distinction between these two systems resides in how electromagnetic radiation is acquired. While passive systems solely collect electromagnetic radiation reflected by the environment, the active systems collect electromagnetic radiation emitted by the instruments themselves after being reflected by the environment. Mateus (Mateus, 2012) exemplifies succinctly that a photographic camera with flash is an active system, and a photographic camera without flash is a passive system. The importance of using active and passive systems resides in the fact that obtainable information exists within the non-visible spectrum, and allows to identify, locate, diagnose, and pinpoint possible existing construction pathologies. For instance, active and passive systems are able to capture heat distribution in a construction (Brito, Mateus, & Silva, 2012), the growth of organic elements, information in low light conditions, uniformly distributed colourimetric information, etc. Not all of the survey instruments can be categorized within these criteria as they do not fit in the Remote Sensing field of study, which focuses on acquiring information actively or passively from a distance, as suggested by the designation itself. In other words, photogrammetry and laser scanning are examples included in Remote Sensing.

2.3.3. Nature of The Geometric Information

The third category to organize the survey instruments and methods relates to the nature of the acquired information (Docci & Maestri, 2005): (i) measurement of distances; (ii) measurement of angles; (iii) measurement of height, elevations, or slopes; (iv) to create and/or verify: alignments and/or directions; (v) acquisition of information within the visible spectrum; and (vi) acquisition of radiometric information. Bearing in mind the site or building to survey, and the types of information that are required to be acquired, the material to survey, the level of required precision, the volume of the construction, the time-frame, if experts are required, etc., the surveyor is able to select the desired instruments and methods in order to conclude the field-operation with increased efficiency. In other words, decrease the total of man-hours and simultaneously increase the quality and quantity of the acquired information, thus leading to a less laborious operation.

Furthermore, the selection of the survey instruments is not only related to the circumstances and conditions expressed in the previous paragraph but also related to the knowledge and experience of the surveyor about said survey instruments and methods.

Survey Instruments & Survey Methods	Direct	Indirect	Active	Passive	Direction	Alignment	Elevation	Distance	Angle	Radiometry	Visible Light
Plumb Line	■				■	■	■	■			
Bubble Level	■						■				
Water Level	■						■				
Laser Level	■		■		■	■	■				
Compass	■				■						
Angle Ruler	■								■		
Rulers	■							■			
Tape-Measure	■							■			
Laser Distance Sensor	■		■		■	■		■			
Theodolite		■						■	■		
Total Station		■	■					■	■		■
Photogrammetry		■	■	■				■		■	■
Laser Scanning		■	■					■	■	■	■
GPS	■						■				

Table 1: Categorization of the survey instruments and survey methods.

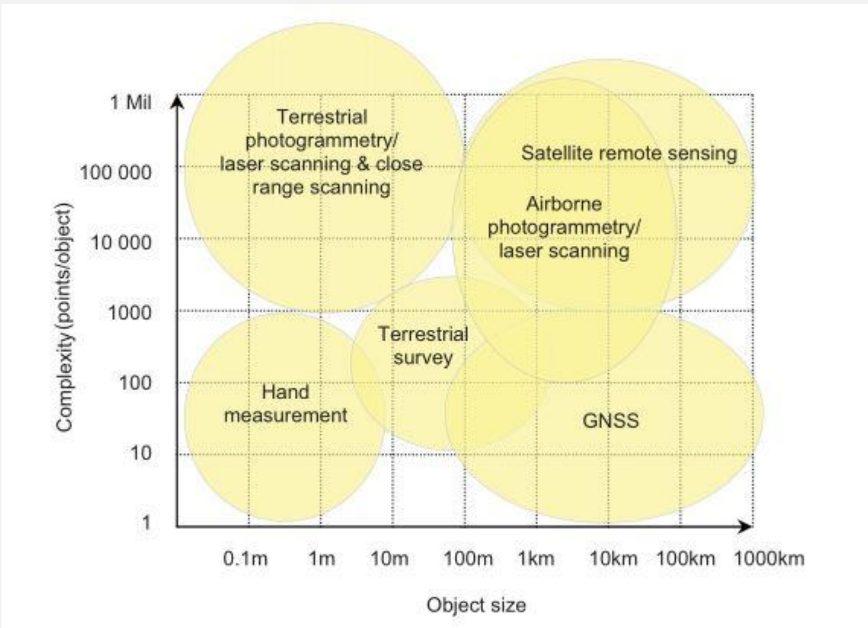

Figure 3: Three-dimensional survey techniques characterized by scale and object size - derived from Böhler presentation CIPA symposium 2001, Potsdam. (English Heritage, 2011)

Specifically, knowing the limits, advantages, and disadvantages that each and every survey instrument and method can offer, the surveyor is able to select the ones most suitable to execute the task at hand. Such selection should consider the three aforementioned categories in which the surveying instruments are structured. In other words, the decision-making process should consider the information presented in *Table 1*. and *Figure 1*. along with the skills of the surveyor.

2.3.4. Method of Application

Nevertheless, a fourth method to structure must be recognized for it indicates approximately the quantity of acquired information per area of coverage that the survey instruments or methods record. Even though *Figure 3* does not demonstrate every survey instrument or method represented in *Table 1*, it further structures the photogrammetric and laser scanning instruments to (i) close-range laser scanning, terrestrial laser scanning, and terrestrial photogrammetry; (ii) airborne photogrammetry, aerial photogrammetry (balloon, kites, drones, airplanes), and airborne laser scanning; (iii) satellite laser scanning, and satellite photogrammetry. Note that hybrid systems are common, where photogrammetry and laser scanning are integrated at varying levels to provide additional information (Rönnholm, Honkavaara, Litkey, Hyyppä, & Hyyppä, 2007).

2.3.5. On The Selection of the Methods

It is imperative for the surveyor to bear in mind the potential applications of the survey instruments and methods and their impact on the workflows for it offers a greater opportunity to accomplish the requested tasks. Therefore, studying the structured categories in which the instruments and methods fall in and considering possible combinations of said survey instruments and methods, it decreases the probability of encountering eventual challenges or difficulties during the project. Even though the surveyor may have a profound knowledge of specific survey instruments, adversities are most likely to succeed, either due to the conditions present at the site or due to new approaches in the workflows. Fundamentally, surveying is a continuous cycle where the surveyor is constantly adapting, improvising, and overcoming obstacles.

For the purpose of the present dissertation, the main focus is on the application of photogrammetric techniques for the recording of cultural heritage constructions. Other survey instruments are referred, such as terrestrial laser scanning because its synergy and complementarity with photogrammetry offer a workflow that verifies the quality of the outputs.

2.4. PHOTOGRAPHY, PHOTOGRAMMETRY, REMOTE SENSING, AND GIS

Photogrammetry is a field of study with specific methods and techniques to obtain 2D and 3D information of the physical world through a rigorous process of recording, measuring, and interpreting images of radiant electromagnetic energy, thus allowing the user to interpret geometric, physical, semantic, and temporal information of the objects under examination. Specifically, photogrammetry is a survey method that analyses an image or sets of images to establish a geometric relationship with the object and to obtain objective data, a purpose distinct from that of photography, which is to create artistic images. While both professions benefit from their own applications, photogrammetry is, to some extent, an extra step for it reuses the photographic outputs as inputs to yield other types of information.

The concept of Photogrammetry must be distinguished from that of Remote Sensing and GIS (Geographical Information Systems). While each field of study benefits from its own independent application and own designation, the dynamic between the fields of study in terms of utility and application fluctuates. See Figure 4.

Briefly, Remote Sensing focuses on the remote acquisition of data ("sensing data") without the need of making direct contact with objects. For that purpose, Remote Sensing not only can make use of Photogrammetry, but can also make use of additional data acquisition methods and techniques such as RADAR, LIDAR, and others to obtain, for instance, heat signals, spectral information, metric information, volumetric information, etc. Generally, the term Remote Sensing is used to refer to satellite and aerial applications, even though it may be used for terrestrial applications as in the case of terrestrial laser scanning (Konecny, 2003).

Regarding GIS, it is the science that analyses and interprets "sensed" data, such as the one obtained via Remote Sensing, in order to derive several types of information for mapping and analysing events on Earth, including, but not limited to: land use, traffic flow on roads, building heights, statistical analysis of populations, analysis of vegetation types, amongst others.

In short, each field of study can be viewed as having its own independent application, but as soon as it is considered from the point of view of "operational dynamic" in which interpretation and usability of information are primarily considered, there is a hierarchized structure. For instance, while taking GIS as reference to obtain data, it makes use of Remote Sensing methods and techniques to derive its own data, while Remote Sensing makes uses of, for instance, Photogrammetry to obtain data remotely (indirect method).

Yet, on a further consideration, the difference between photography and photogrammetry is evident once the root meaning of each compound word is analysed.

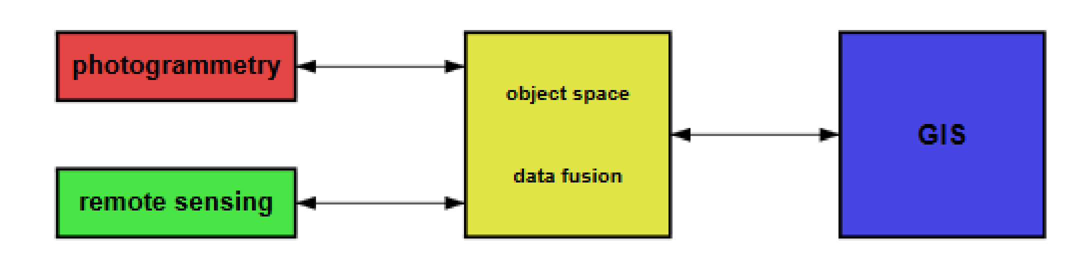

Figure 4: Relationship between photogrammetry, remote sensing, and GIS (Schenk, 2005).

Photogrammetry is formed by the aggregation of: *"**photos**"*, meaning "***light***"; *"**graphos**"*, meaning "***representation***"; and "***métron***"*, meaning *"**measure**"*. Thus, photogrammetry is the field of study with the underlying meaning of "measurements from the representation of light" or, in simpler terms, "measurements from photographs". As for photography, the field of study bears the meaning of "representation of light". Therefore, it can be viewed that photogrammetry is the science dependent on the analysis of photographs to obtain objective data.

It is crucial to emphasize the different purposes and intents of each field of study. Whilst a professional of photography searches for an insatiable demand for visual content and meaning in the act of photographing or in the photographs themselves, a professional surveyor employing photogrammetric and remote sensing techniques aims for the objective and accurate acquisition of metric, radiometric, and spectral information. On a further comparison, a professional photographer manipulates reality by suppressing or accentuating particular features to convey a specific value on the message to be communicated. The photographer may even desire to share a different worldview from the one or a different from the one perceived by the everyday human life. Furthermore, there are professional photographers who, to produce the intended message, highlight or even over-emphasize the object; and other photographers who understand photography as a means to convey a personal message, where the object is not as important but merely a vehicle for communicating an intent. Altogether, photography seeks to communicate a certain perspective and unique worldview either through realistic or abstract images (Langford, 2002).

The outputs of photography are, therefore, subjective oriented. However, photogrammetry, as it is applied for surveying, is objective-oriented because its purpose is to analyse reality as correctly as possible in accordance with pre-established objectives. Even though each professional seeks distinct purposes in their endeavours, photogrammetry does not disregard interpretation for it is a key element for analysing the captured data and the world, and thus photogrammetry must not be comprehended as a fully technical approach in which no interpretation occurs. In other words, surveying involves an objective analysis of the subjective values inherently present in the construction (Docci & Maestri, 2005).

Considering the distinct objectives of both professions, the output of photography may not be ideal as input for photogrammetric processes as the photographs must be acquired methodically for optimal results. Although the input data for photogrammetry requires some criteria to be met, it does not make obsolete and invaluable the images originated by photography. The overall workflow is summarized to light as input for photography to generate images, and images as input for photogrammetry to generate 2D and 3D information.

Regarding the application of photogrammetry, the possibility of sensing objects remotely provides the opportunity to analyse non-tangible heritage constructions, obviating the need for the close physical presence of the surveyor and the employment of classic survey techniques. Therefore, photogrammetry provides with a decrease in logistic costs and survey time when compared to classical survey techniques. On more exceptional situations, such as cultural heritage buildings under safety and preservation regulations or hard-to-reach and/or buildings difficult to survey due to their physical structure, photogrammetry plays an essential and leading role for overcoming such problematic challenges due to their high adaptability, flexibility, and versatility. Do note that photogrammetry is not solely the acquisition and processing of images, but mainly the opportunity to allow the user to derive and interpret various types of information for diverse applications as explicitly expressed in the two following sections.

2.4.1. Types of Data Acquired via Photogrammetry

As previously established, photogrammetry is a surveying method that relies on techniques that make use of instruments, such as photographic equipment or optical sensors, to originate images from which objective observations must be performed. For that reason, the acquired information can be grouped into 4 categories as mentioned by Schenk (Schenk, 2005):

i) Geometric information: focused on the acquisition of positional information and the shape of the objects. This constitutes the major objective of photogrammetry.

ii) Physical information: this type of information relates to the properties of electromagnetic radiation. In other words, to the radiometric information, visible light, radiant energy, and wavelength.

iii) Semantic information: as mentioned previously, photogrammetry relies on the interpretation of the images.

iv) Temporal information: as images are acquired at a specific instant in time, photogrammetry allows to perform a comparison between several images recorded at different times.

2.4.2. The Uses of Photogrammetry

Photogrammetry is employed in diverse situations including underwater, terrestrial, aerial, airborne, and spatial. For instance, photogrammetric applications include, but not limited to, environmental studies, site developments over a given period of time, land use and planning, environmental monitoring, natural disasters, construction works, survey of cultural heritage, agriculture, mining, inspection, real state, forensics, emergency response, military, astronomy, etc (Mikhail, Bethel, & Chris, 2001). The vast application of photogrammetry is of positive importance for architects, engineers, archaeologists, or architecture historians as it allows the creation of more complete and accurate documentation of the reality under examination. Furthermore, with the ever-increasing popularity of UAV in recent years, roughly after the year of 2010 due to the reduction of market prices, aerial photogrammetry is increasingly more prevalent, even for ordinary citizens since such techniques require less operational skills due to its automation. For instance, UAVs are utilized for recreational activities such as drone racing *(http://dronenationals.com/)*.

Most importantly, photogrammetry is a valuable tool for architectural documentation, preservation and restoration of historic buildings due to its ability to acquire information rapidly and with high detail and accuracy. Even if photographs do not meet the photogrammetric standards for processing, they contain information pertaining to the object of interest. For example, UNESCO (United Nations Educational, Scientific, and Cultural Organization) focuses intently on the recording and preservation of cultural monuments. For that reason, there are overlapping efforts and interests with other entities such as ISPRS (International Society for Photogrammetry and Remote Sensing) and CIPA (International Committee for Architectural Photogrammetry).

These developments lead to a fundamental question regarding the skills of the surveyors if the employment of such photogrammetric and remote sensing techniques require less and less training. Such question carries little veracity until thoroughly analysed and compared to the skills required for photographing and the mindset for executing surveys.

As aforementioned, photography and photogrammetry focus on the collection of light and each field of study enjoy their own independent application due to their divergent purposes.

Yet, to take the maximum benefit that each field of study has to offer, one has to master the photographic camera if optimal results are to be achieved.

In a straightforward way, photographing is more than pressing the shutter release button to gather information. It is both an art and technique that requires both experience and knowledge from the photographer. The photogrammetrist not only requires skill to operate the photographic equipment but must equally know how to proceed with the photogrammetric workflow during the field and office phases and in a specific context – architectural, for example. In addition, the know-how of the equipment allows the surveyor to overcome problems that may occur. For that purpose, there are established guides, procedures, and agreements from Institutions that must be followed to produce valuable documentation within established criteria. For example, the 3x3 photogrammetric rules (Waldhäusl & Ogleby, 1994). Apart from the fundamental need of the surveyor to interpret what he observes, and to observe what he has not yet learned or seen.

Thus far it has been referred the dependability of photography, photogrammetry, remote sensing, and GIS on spectral information and intended results, and distinguished the purposes of each field of study. In the following sections and in Annex 1, several topics mainly related to photogrammetry are addressed, such as the evolution of photography and photogrammetry, photogrammetric restitution methods, the geometric principles underlying the construction of a photograph, how to photograph, the types of lenses, and how the information must be acquired to perform photogrammetric works in the context of architecture. All of the presented information should be considered relative to the application of fisheye images.

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2.5. Lenses in The Context of Photogrammetry

One of the main issues that come to light, and impacts the performance of photogrammetric projects, relates to how different lenses can be utilized to fully capture the building under examination.

A considerable number of lenses are available on the market, with the most diverse characteristics allowing to explore an innumerable quantity of representations of a given object, because of the multiple different optical distortion effects caused by the lenses themselves. In addition, other technical notions when combined with each other further increase the total number of possible representations of the subject as well.

Such conditions do not mean that the process of data acquisition is an arduous task. On the contrary, the task is simple and straightforward once the technical differences of the lenses are understood. Undoubtedly, digital photographic cameras benefit from a high level of automation which allow to easily capture any scene or object under the most diverse lighting conditions and without the need for user intervention. However, full automation is not always valuable or desirable if positive results are required.

The main purpose for discussing the types of lenses and its distortion effects relates to the pressing need of adjusting the focal length during photogrammetric projects to overcome a few setbacks, such as the impossibility to acquire transition photographs that allow calculating image correlation between sets of images taken at different places. Therefore, adjusting the focal length increases the possibility for the photogrammetric software to correlate and interrelate scattered sets of images with no transition images between said sets of images. In addition, it is crucial to understand the optical and perspective effects on the resulting image due to changes in the focal length.

Considering the aforementioned reasons, it is addressed, for the most part, interchangeable lenses due to their convenient use in photogrammetric projects. The ability to change lenses and focal length during a project, and instead of having to carry several cameras in the backpack, is one of the superior advantages of MILC (Mirrorless Interchangeable Lens Camera) and DSLR (Digital Singles Lens Reflex Camera) cameras. If the photographic cameras are damaged or broken due to over-usage, lenses are reusable in other cameras with the same mounting system - and sensor size in most cases. For further information of the types of cameras, imaging sensors, and lenses see Annex 1.

Figure 5: Due to inaccessibility or difficult angle to photograph the focal length or lens is changed.

2.5.1. Changing Lenses and GSD

It is user-friendly to use one particular sensor size to facilitate calculations when changing focal lengths. The reason for this preference relates to the fact of being easier to calculate the varying GSD values between images and predict if the photogrammetric algorithms will correlate the different sets of images. See *Figure 5*.

A few experiments (Covas, Ferreira, & Mateus, 2015) reveal that there are limits relative to image correlation algorithms. For example, there is no correlation between images acquired with an 18mm lens and a 55mm lens, if taken from the same POV and location. This is due to large differences in GSD values from the two images. Specifically, the total area covered by each pixel varies in such a way that the information present in both photographs becomes different enough for the software to not detect similarities. However, if the images acquired with the 55mm lens are taken a little farther back and in the continuation of the POV, image correlation is estimated by the photogrammetric software. In practice, this means that during the photographic acquisition and while utilizing several focal lengths, the surveyor knows beforehand if he needs to move closer or farther away from the object in order to ensure a global digital reconstruction.

It is suggested not to photograph from the same position if the focal length difference is superior by a factor of 2.5.

The underlying motive for changing focal lengths during a surveying project has to be furtherly substantiated. In a photogrammetric project, it is advised to utilize fixed focal lengths and avoid using “random” focal lengths in order to preserve the geometric consistency of the point cloud (Wohlfeil, Strackenbrock, & Kossyk, 2013). In other words, processing a project with a lens whose distortion parameters are thoroughly well-known, provides with a point cloud whose geometric accuracy is superior to a point cloud generated with images taken with multiple focal lengths. Despite such information, there are situations that due to the complexity of the construction, the surveyor must adjust the focal length.

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2.6. Workflow of Photogrammetry

As previously stated, photogrammetric methods are those that allow obtaining reliable geometric, physical, semantic, and temporal data of objects. Such an objective is achieved due to the reconstruction of the stereoscopic phenomenon. In digital photogrammetry, in which the calculations are run in microseconds, there are several essential tools and algorithms from Computer Vision field of study that allow estimating 3D coordinates.

Do note that other types of photogrammetry do exist, but the current thesis focuses on multi-image photogrammetry. In fact, photogrammetry can be organized in several ways, as mentioned by Mateus, Remondino, and Mikhail et al. (Mateus, 2012; Mikhail et al., 2001; Remondino, 2006):

i) Depending on the distance to the object. Photogrammetry can be subdivided into satellite, airborne, aerial, terrestrial, close-range, microscopic, and aquatic.

ii) By the number of utilized images. Photogrammetry from a single image, stereophotogrammetry, and multi-image photogrammetry.

iii) By the operating principle. Already mentioned in the section "*The History of Photography and Photogrammetry*", there are 4 phases of photogrammetry. Graphical, analogue, analytical, and digital photogrammetry.

iv) By the time the results are available, that is, video, real-time, off-line, and online.

v) By the field of study. Photogrammetry in the context of architecture, engineering, archaeology, history of architecture, forestry, space, etc.

vi) By the level of automation. Mateus (Mateus, 2012) refers manual processing that involves calibration and selection of homologous points in several images to execute graphical restitution. The same author also refers semi-automatic procedure that can vary from simple detection of targets or geometric patterns and with varying degree of user intervention. Finally, fully automated photogrammetry where the processing is completely automatic, including camera calibration, dense reconstruction, and processing of 3D models.

2.6.1. The Operating Principles

The simplest way to explain how photogrammetry works is to compare to the human vision. When observing an object, humans are capable of determining with relative accuracy the depth at which the object is located. If an object is to be touched it can be done intuitively. However, if one eye is closed, the perception of depth vanishes. Although, it still is possible to determine more or less the dimensions of the object by observing the perspective – as in the case of single image photogrammetry.

Depth perception is achieved due to stereopsis-parallax phenomenon once the two overlapping images captured from dissimilar POV and of the same object in the scene are matched (Mikhail et al., 2001). That is, parallax is the measurement of the angle between two images acquired from different POV relative to the relative positioning of objects in a scene. The apparent difference of the position of the objects from each image, the measurement of angles, and underlying geometry composing the images allow determining 3D measurements. The difference of the position of the objects is more evident the closer they are to the POV. Thus, depth perception is achieved while standing motionless in one position.

In digital photogrammetry, it is uncommon to process merely two images to derive 3D information. In fact, hundreds or even thousands of images are processed in a global project – the so-called multi-image photogrammetry. That is, digital photogrammetry can be viewed as the positioning of several eyes in several positions that are collectively processed by one super-brain dedicated for that sole purpose in order to perceive the scene.

In essence, Photogrammetry consists in capturing 3D information from the real world into 2D virtual information and then reconverting into 3D information in a virtual space. Afterwards, the information can be computed to derive secondary and tertiary types of information. See *Figure 6*.

Bearing in mind such an analogy, it is fundamental to study thoroughly and answer the following questions if 3D models are to be created:

1) how does the software calculate point clouds through the processing of images;

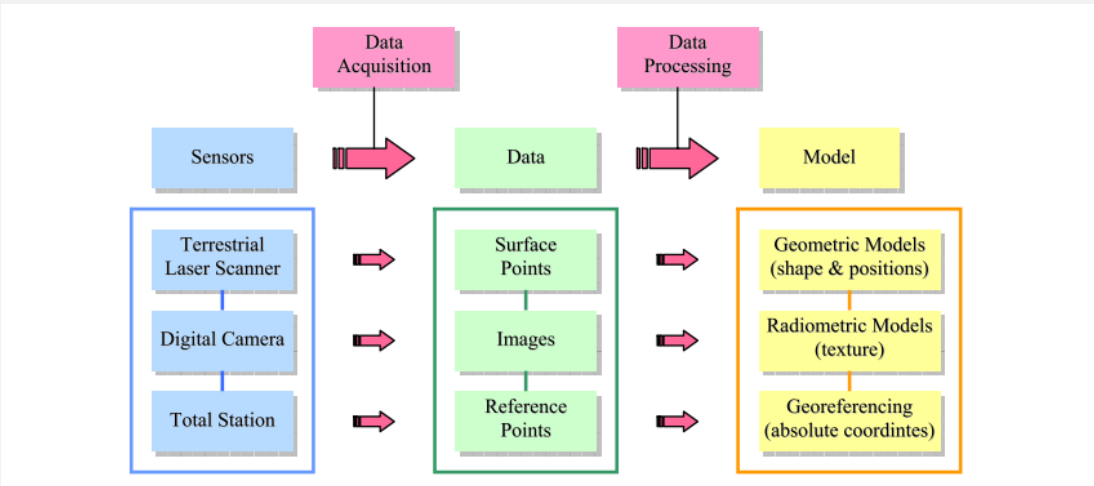


Figure 6: General workflow for terrestrial sensory data. (Lee & Choi, 2004).

2) If the software relies on the input of images, how should images be acquired for the software to successfully run a digital reconstruction

3) What are the minimum and acceptable limits for the software to accept the images;

To explain the workflow of digital photogrammetry it is first explained the processing phase because it dictates how images should be recorded.

In the context of the current thesis, it is mostly explored the use of digital multi-image photogrammetry for the representation of architectural constructions, for it is excluded all techniques relying on photogrammetric restitution that make use of stereoscopic perception.

2.6.2. An Example of Digital Photogrammetry Workflow

For the construction of a 3D photogrammetric model, Computer Vision algorithms are executed. Computer Vision is a field of study that focuses on developing strategies for detecting and extracting features and 3D information from images. The algorithms can be utilized for photogrammetric purposes, and, for Image-Based Modelling (IBM) in which images are used to generate a 3D model and subsequent 3D and 2D output information.

The sequence for the processing phase in digital photogrammetry is as follows: interpretation of elements for each and every image; image matching; structural positioning of the images in a 3D space; and full reconstruction by reprojecting the details into the 3D space.

The digital photogrammetric process is similar to that of freehand drawing. First, the structure and general proportions are drawn, and then the details are added. Therefore, it is discussed the main algorithms and methods developed by Computer Vision and that are used in

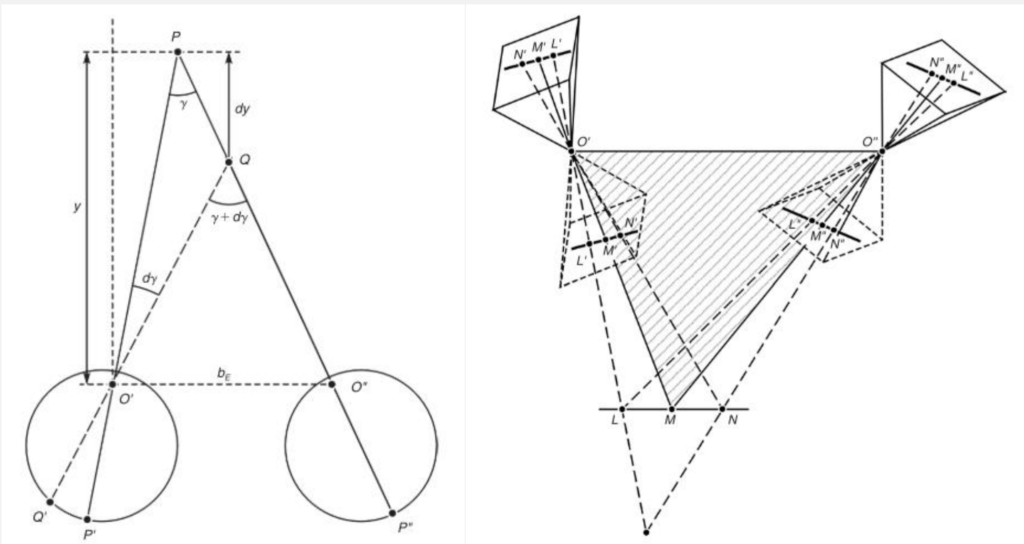


Figure 7: Stereoscopic vision. (Konecny, 2003).

Visual SFM pipeline (Wu, 2013): i) Scale Invariant Feature Transform (SIFT) (Lowe, 2004); ii) Structure from Motion (SfM); iii) Bundle Adjustment (BA) (Triggs, McLauchlan, Hartley, & Fitzgibbon, 2000); iv) and Multi-View Stereo (MVS) (Furukawa & Hernández, 2015).

i) Concerning the SIFT algorithm, such an algorithm is utilized to detect points of interest in an image and describes them posteriorly. The description refers to the characteristics of the selected point and its position relative to other selected points. It is fundamental since the main purpose is to establish a connection or a relative orientation of several points present in several images. On a thorough interpretation of the word SIFT, its application is invariant for translations, rotations, and scale transformation of points present in an image while allowing slight lighting variations of the same points. This degree of variability is important since, for example, the two images representing the same point may have been taken from dissimilar angles and therefore have slightly different colour and light values.

One of the important ideas to retain is the overlapping that must exist with some redundancy between images so that the following steps are executable. Once the various points of interest are detected in the set of images, which contain up to hundreds or thousands of images, it is required to know the position of the points relative to other images in order to detect parallax and reconstruct a consistent structure of the 3D model. Note that other feature detector algorithms besides SIFT do exist, such as SIFT-GPU (Wu, n.d.-a), SURF (Bay, Ess, Tuytelaars, & Van Gool, 2008). It is in this sequence that the SFM, BA and the MVS methods are executed.

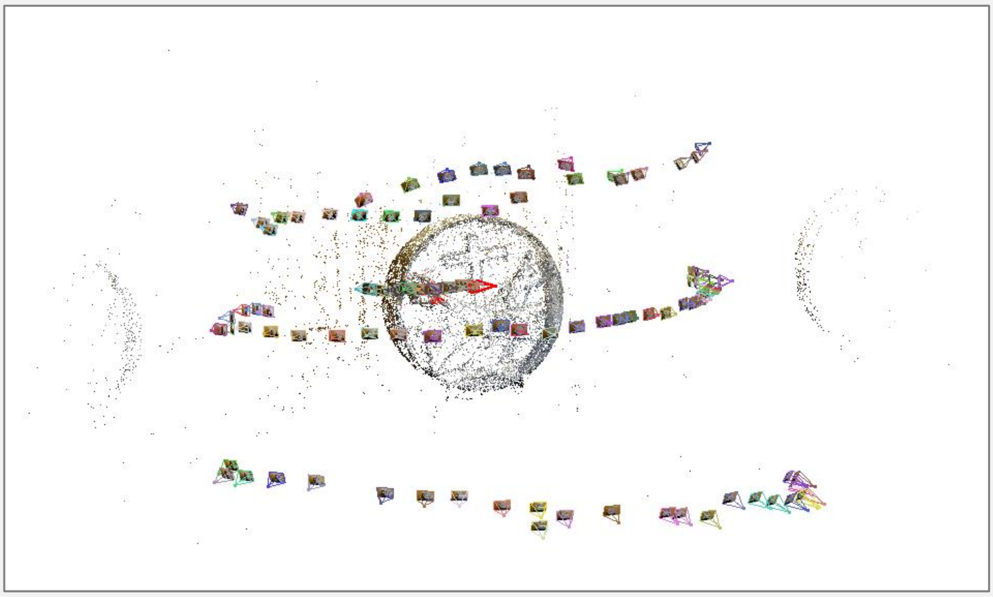


Figure 8: Illustration of a digital photogrammetric processing. The position of the images and key points in the 3D space after running image matching and SFM methods.

ii) SFM method is an essential key element for digital photogrammetry allowing to structure the position of the cameras by projecting them into a 3D space from the detection of homologous points. The SFM algorithms can position the images relative to each other in the 3D space via the triangulation method. The interior, exterior, relative, and absolute camera parameters are computed in this step via the use of key points detected in the previous step. In essence, SFM calculates a 3D sparse reconstruction with keys points. Algorithms used in this step are Bundler (Snavely, n.d.), Multicore Bundle Adjustment (Wu, Agarwal, Curless, & Seitz, 2011), and others.

iii) Regarding BA algorithm, first proposed by Duane Brown, can be defined as a process that simultaneously calculates the geometry of the scene and the relative position of cameras. It should not be confused with the SFM method. The purpose of BA is to perform an optimization of the 3D structure that the SFM executed in the previous step. BA verifies and adjusts, when necessary, the position of the images and the structure if calibration problems are detected. It is, therefore, a tool to minimize the reprojection error or qualitative variations of the reconstruction, which corresponds to an inaccurate distance proportion between points in the world and the virtual scene respectively.

After executing the three previous steps the obtained result is similar to the one represented in *Figure 8*. It is observed that the scene contains several cameras pointed at the object mimicking the moment of the photographic recording. It is also observed key points that correspond to the homologous structural points.

iv) It is from this consistent 3D reconstruction that the remaining information is projected. While the SFM method computes camera poses and the environment, the MVS method assumes that camera calibration has been executed previously (Furukawa, Ponce, Team,

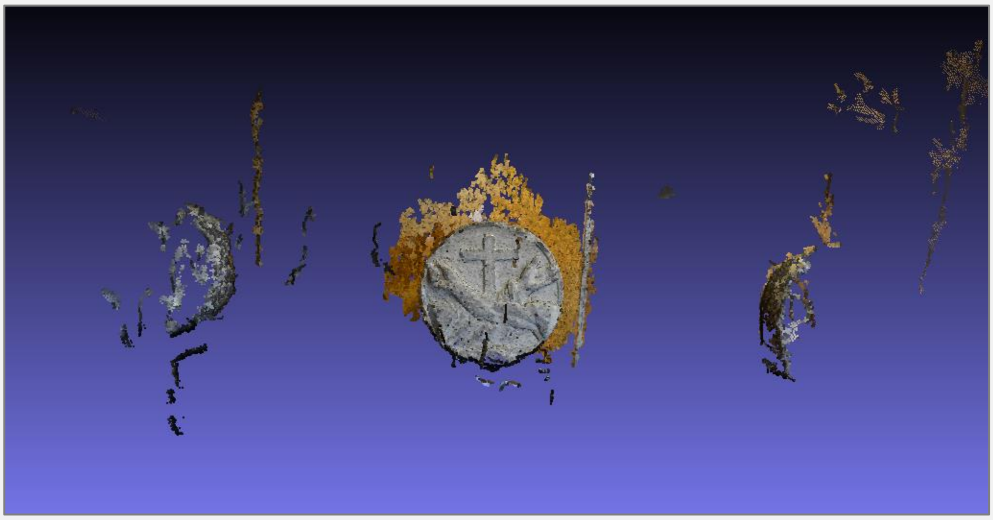


Figure 9: Illustration of a dense reconstruction using MVS method.

& Inria, 2007). Specifically, MVS focuses on executing a dense reconstruction, as opposed to SFM focuses on executing a structural sparse reconstruction. The final outputs are dependent on the quality of the images and the projection of the "dense points" is similarly done as for the calculation of the position of the key points. Example of other software that run MVS methods are CMP/MVS (Clustering Multi-View Stereo / Patch Multi-View Stereo) (Heller, Havlena, Jancosek, Torii, & Pajdla, 2015), Apero-Micmac (Pierrot-Deseilligny, Marc and Paparoditis, 2006), Pix4Dmapper (Pix4D, n.d.), and others.

2.6.3. Interior, Exterior, Relative. and Absolute Orientation

As previously exemplified, the projection of the 2D information into 3D information occurs as the virtual images are positioned in the virtual 3D space to mimic the photographic recording that occurred in the physical world – denominated reconstruction of the orientation (Linder, 2005). This is achieved through the calibration of the interior parameters of the photographic camera in the first step, and then via the calculation of exterior, relative, and absolute parameters respectively.

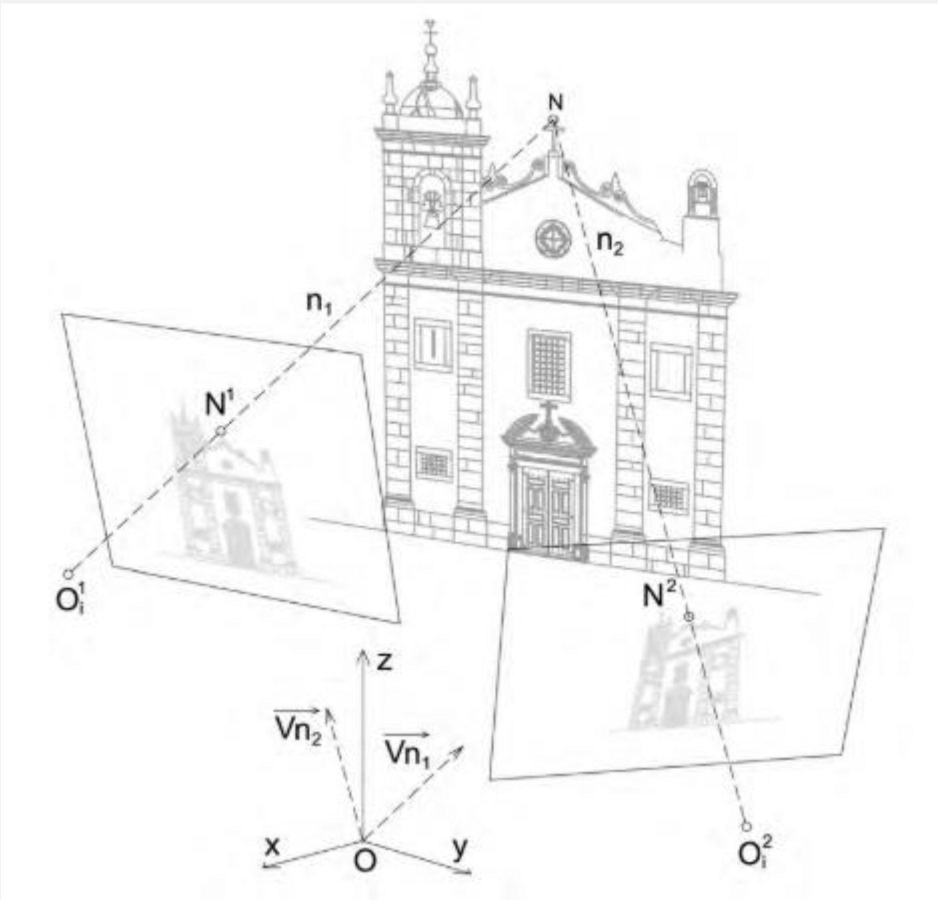


Figure 10: Coplanarity in photogrammetry processing. (Mateus, 2012).

For the calculation of said 4 parameters three main photogrammetric processes are utilized, such as resection, intersection, and triangulation. Succinctly: resection refers to the positioning of a photograph in the virtual space; intersection computes the projection of the pixels identified in at least two images into the virtual space; and the two previous operations are combined in triangulation in which image orientation and projection of pixels into the virtual space are calculated simultaneously (Luis Mateus, 2012; Mikhail et al., 2001).

In addition, for these calculations to be possible two crucial conditions must be met, such as collinearity and coplanarity (epipolar plane). More precisely, collinearity refers to the need of having specific points in a projection line – such as the ones represented in *Figure 10*, that is, **N**, $\mathbf{N}^1$, and $\mathbf{O}_i^1$ of the line $\mathbf{n}_1$, or **N**, $\mathbf{N}^2$, and $\mathbf{O}_i^2$ of the line $\mathbf{n}_2$ (**N** being the point of interest, and **O** the projection centre of an image) – so the internal referential of the image (photo coordinate system) is transformed via translation and/or scaling and/or rotation to coincide with the external referential (object coordinate system), which leads to coplanarity. As for coplanarity, it refers to the condition in which the projection lines of homologous points present in several images result in the one point in the object coordinate system – in Figure 10 the lines $\mathbf{n}_1$ and $\mathbf{n}_2$ are coplanar, and their intersection results in the positioning of point **N** on the object of the object coordinate system. The overall process is executed in a chain. See *Table 2* to observe the required operations for multi-image computation.

More specifically, in the first step, interior orientation consists in calculating the interior geometry of a single image in a photo coordinate system via the employment of approximate distortion values – calibration values are given in the metadata of the image itself or from a previous calibration. The values take into consideration factors such as focal length, radial distortion, the position of the centre of distortions, and others. In other words, an attempt to remove convergence of the light rays so to allow collinearity condition to occur during the exterior orientation process.

Procedure	Correlation between	Mathematical Models and Equations
Interior Orientation	Photographic Cameras Coordinate System of Photo	Removal of Distortions 3D transformation
Exterior Orientation	Coordinate System of Photo Coordinate System of Object	Collinearity
Relative Orientation	Coordinate System of Photo Coordinate System of Photo	Collinearity Coplanarity
Absolute Orientation	Coordinate System of Object Coordinate System of Model	7 Parameter Transf.
Bundle Block Adjustment	Coordinate System of Object Coordinate System of Several Photos	Collinearity
Independent Model Block Adjustment	Independent Model Block Adjustment	7 Parameter Transf.

Table 2: The procedure to calculate the reprojection of points into a virtual 3D space (Schenk, 2005).

In the exterior orientation process, it is established a geometrical relationship between the image coordinate system with the object coordinate system via the use of at least 3 collinear light rays. Specifically, it is determined the position and orientation of a camera relative to the object. In digital photogrammetry, a redundant number of collinear light rays are utilized to increase the robustness of the final model. Each image will have 6 unknown parameters to be calculated, 3 for rotations, and 3 for translations.

Next, relative orientation consists in determining the position and orientation between 2 cameras by relating the coordinate systems of the two cameras via coplanarity condition – for example, with the intersection of the projection lines n_1 and n_2 that result in point N in *Figure 10*. Do note that if the images are acquired from the exact same POV, the spatial position of homologous rays coincides, and a 3D reconstruction of a model is impossible. This step results in a "model" (stereo model) with its own coordinate system defined with an arbitrary scale transformation that is posteriorly determined. Specifically, on a dependant relative orientation, one of the photo coordinate systems is static and other images are transformed relative to the static one. In conjunction with the 6 parameters from external orientation, these form the 7 parameters to be calculated during the absolute orientation step.

Subsequently, absolute orientation is executed, in which there is a 7 parameter transformation –uniform scale, 3 translations, and 3 rotations - to relate the object coordinate system with the model coordinate system. The objective is to transform the model coordinate system relative to an external coordinate system. The external coordinate system can be defined by using other surveying methods to geolocate the resulting photogrammetric model from the relative orientation step.

Bundle block adjustment is executed to refine the final model by minimizing reprojection errors. Specifically, the word bundle refers to the group of image rays that connect a specific point of the object, the perspective centre of an image, and the respective projection of the point on the image. Therefore, a single image corresponds to a "bundle" of image rays that converge to the perspective centre with unknown position and orientation in space and that is better calculated when relating to bundles of other images (Mikhail et al., 2001).

As a final step, it is even possible to account for the correction of the curvature of the Earth. Such is particularly important for projects of great dimension since the photogrammetry software performs all calculations in a 3D Cartesian coordinate system.

2.7. THE DELIVERABLES

The typical final product of a digital photogrammetric processing is a point cloud in which each individual point is designated with a 3D coordinate, RGB values, and possibly a normal vector. See *Figure 9* and *Table 3*. However, correct orientation and scale may be inexistent, merely inserted in an arbitrary coordinate system instead of object coordinate system, thus requiring the application of complementary surveying equipment to provide with additional information. Information vital for transforming the scale, rotation, and translation of the virtual object to match the properties and size of the object in the real world. If no supplementary information is inserted during the processing, such as GPS coordinates or CPs, the generated photogrammetric model is not to scale nor oriented.

Such an occurrence can be problematic if accurate values are needed. Interestingly, photogrammetric models are oriented in the vertical direction, but not very accurately. Such is due to DSLR and Smartphones being equipped with a system to detect if the camera was rotated to take a shot. This is noticed when observing the images in the album of the photographic

```
ply
format ascii 1.0
comment Author: CloudCompare (TELECOM PARISTECH/EDF R&D)
obj_info Generated by CloudCompare!
element vertex 7825
property float x
property float y
property float z
property uchar red
property uchar green
property uchar blue
end_header
21.265 39.2806 -2.89388 187 173 143
20.2832 39.0994 -2.76887 163 164 157
15.8435 39.9315 -4.45586 136 136 142
31.9413 43.4687 -2.00486 107 112 122
31.9 43.3701 -1.99323 145 152 157
```

Table 3: Example of an ASCII Polygon File Format. In this case each point has X, Y, Z, R, G, and B values associated to it. It can include normal vectors (added in the lines).

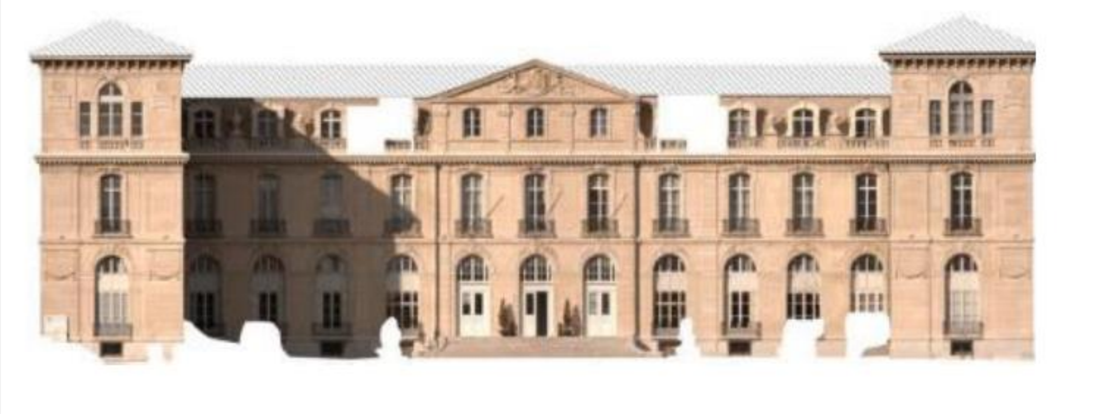


Figure 11: Example of an orthophoto. (Pierrot-Deseilligny, De Luca, & Remondino, 2011).

camera. Images are automatically rotated. Yet, for optimum results, it is suggested the use of additional surveying equipment.

Alternatively, instead of computing a point cloud, image products can be derived.

2.7.1. Image Products

As previously mentioned, photogrammetry has a wide variety of applications, and with its introduction in the digital world several imaging outputs, given in 2D, can be derived to measure the world. These include (Mikhail et al., 2001):

i) Aerial photographs, which can be utilized to interpret valuable information, such as urban planning for instance.

ii) Panchromatic or coloured images, in which the colour, from a particular band of the electromagnetic spectrum, allows the operator to perform urban analysis as well.

iii) Mosaics that are the assembly of several contiguous images to form a composite image.

iv) Rectified images in which the tilt effect is removed, that is, the surface of interest is not parallel to the image plane (is in perspective) so the image plane is transformed.

v) Orthophoto consists of an image in which the perspective effect has been geometrically corrected in such a way that the scale is uniform. In other words, the image corresponds to an orthogonal projection. Therefore, the outputs can be utilized as a planimetric map or even for topographic mapping if contour lines are superimposed. Orthophoto mosaics. This output corresponds to the use of orthophotos assembled together into one continuous image, as explained previously in the “mosaic” image type. The advantage over the mosaic image is the fact that orthophoto mosaic has a uniform scale.

2.7.2. 2D AND 3D OUTPUTS FROM POINT CLOUDS

Point clouds can be the final product or can be utilized to derive other valuable information. For instance, 2D drawings can be created by capturing images of the point cloud or from a voxel model. The possibilities are limitless due to the whole universe of available computer graphics algorithms, which allow manipulating information in accordance with the established purposes of the documentation. Summarily, the following products can be calculated (Grussenmeyer, Hanke, & Streilein, 2003; Mikhail et al., 2001; Fabio Remondino, 2003):

i) Voxel Models: Concisely, a voxel is a value represented in a 3D grid. A voxel has the underlying logic of a pixel, a value represented in a 2D grid, such as an image. In this way, a voxel refers to values occupying a volume. Volumes containing information are filled thus producing a 3D model. Note that when using voxels to produce 2D and 3D information the resulting quality of the images is limited by the size of the voxel grid. For this reason, it is imperative to study and define well the 3D model according to the desired output quality. Specifically, if the dense reconstruction is very dense, the resulting detailed voxel model may have vacant volumes. Per contra, if the size of the voxel grid is big, the resulting outputs may display edges or cubes - aliasing.

ii) Polygon Mesh or simply Mesh: The points in the point cloud are used as reference to create edges, and edges to make faces, and faces to make surfaces. Frequently, faces are made of triangles or quadrilaterals. Other polygon formats are usable. The result is a model with several non-overlapping faces, also known as a polyhedron. Several different algorithms are utilized that deliver different accurate outputs. Sometimes triangulated meshes are designated as TIN (Triangulated Irregular Network). See *Figure 12*.

iii) Non-Uniform-Rational-Basis-Spline (NURBS): If voxel modelling generates a model with cubes, and calculating a mesh generates a smoother model, NURBS produces the smoothest surfaces. Rather than creating an object made from polygons, NURBS are defined by mathematical curves whose curvature is controlled by CPs, in this case, points from the point cloud.

iv) Wireframe model: Application of Computer Vision algorithms to acquire lines resulting from the intersection of planes fitting into the geometry of the point cloud, or from input images.

v) Digital Elevation Model (DEM): DEM is a 3D representation of a terrain surface to retrieve height information and is subdivided into Digital Terrain Model (DTM) and Digital Surface Model (DSM). While the latter represents ground surfaces without objects such as building and vegetation, the former includes said features. DEMs can be calculated as an image (heightmap). Alternatively, DEM format can be made from a TIN model, in which triangles approximate the shape of the surface.

vi) Topographic maps: Planimetric features of the terrain (horizontal positions of ground features) and contour lines (resulting from the intersection of horizontal planes at specific heights to depict the slope of the terrain) are displayed.

vii) Profiles, sections, and plans: The intersection of a plane through the point cloud and respective view perpendicular to the cutting plane or planes. Such a procedure is particularly useful to proceed with conventional CAD drawings.

Figure 12: Hybrid view. Left side: textured mesh. Right side: wireframe of the mesh (Grenier, Antoniotti, Hamon, & Happe, 2013).

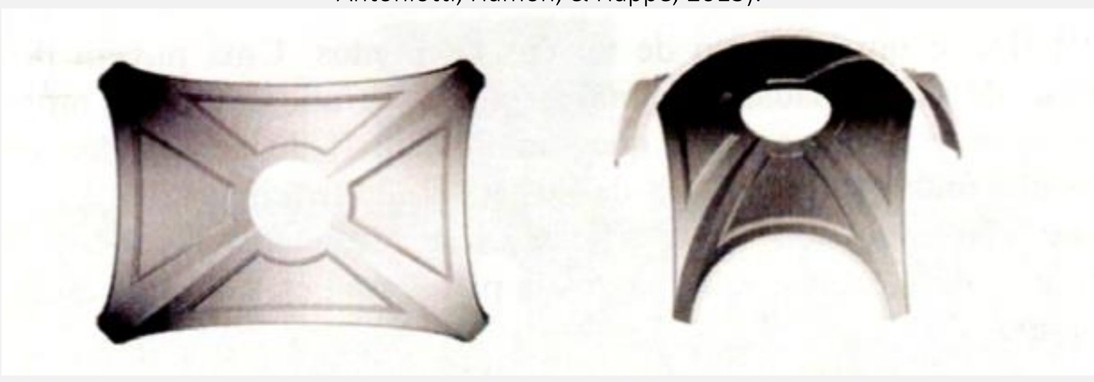


Figure 13: Example of 3D modelling of the dome of the Rua Augusta Arch. (Aguiar, Mateus, & Ferreira, 2006).

viii) Movies and images: From a point cloud or, preferably, a mesh model, videos can be created to better illustrate the spatial and cultural values of the object under observation.

ix) 3D modelling: the information available in the point clouds can be processed to generate 3D shapes in other software, either via the use of Computer Vision algorithms to increase automation or manual modelling. See *Figure 13*.

x) Visual reality: with the ever increasing of computing power and software developments, the resultant 3D models can be viewed in real time for animations, fly-overs, and walk around purposes.

In short, the deliverables can be produced with Image-Based-Modelling (IBM) or Image-Based-Rendering (IBR) in mind. Particularly, IBM refers to the process of creating dimensional models from images, and IBR focuses on providing new viewpoints of a scene from a set of images (Snavely, Seitz, & Szeliski, 2006).

Processing the point clouds to generate surface models opens doors to use the calculated outputs as inputs in other software. For example, in the gaming industry digital photogrammetric methods are utilized and the resulting point clouds are converted into meshes or NURBS to be imported to game engines. Photogrammetry has been used for famous video games such as Metal Gear Solid V: The Phantom Pain; The Vanishing of Ethan Carter; War Thunder; Halo 4; Cyberpunk 2077; etc. Photogrammetry has also been used in films or series: Chappie; Mad Max; and so on (*http://www.agisoft.com/forum/index.php?topic=3730.0*).

2.7.3. Typical Workflow for Calculating Surface Models

Despite the vast application of photogrammetry and possible deliverables, in the context of the current thesis, we focus on the computation of meshes or surface models as these were crucial for the creation of documentation at a drawing scale of 1:50. As previously referred, the output of a digital photogrammetric processing is generally a point cloud whose information was generated via the analysis of several images. In the architectural context, or for representation of artefacts, mesh models are widely utilized to increase image interpretability. For that reason, a typical workflow is mentioned that can be executed in CloudCompare and MeshLab software:

i) Data cleaning: Before proceeding with the application of Computer Vision algorithms, point clouds generated via photogrammetric processes need to be prepared. Since images are utilized to project points into space, and images are recorded at varying distances from the object (affecting the GSD values), the density of photogrammetric point clouds is incongruous. To overcome such issue a homogeneous subsampling algorithm is applied to remove points exceeding the threshold value set by the user. The result is a point cloud whose points are distributed evenly. In addition, there is always and inevitably the projection of spurious points that have to be removed. For example, there is the risk of generating spurious points around edges and corners. These points are frequently pixels representing the sky. The name for this occurrence is referred to as “sky densification”. If the user desires to obtain consistent and clean outputs, the data must first be analysed and then corrected before proceeding to the following steps.

ii) Normals Reconstruction: Yet, each point requires 3 additional coordinates to guarantee a flawless execution of the algorithms: normals. Normals are vectors whose direction is determined by calculating perpendicular intersections to the plane of the projected pixel. Such information is crucial for it allows to control effects such as lighting on surfaces and consequently image interpretability. At this stage, each and every point has 9 values, X, Y, Z, nx, ny, nz, R, B, G.

iii) Surface Reconstruction: Once the point cloud is prepared, surface reconstruction algorithms are possible to execute efficiently. The output is a model made of uncoloured surfaces calculated from the normals and 3D coordinates of the points.

iv) Projection of colours: In the last step, an algorithm is executed to project colours of each and every pixel onto the model.

2.8. Photogrammetric Acquisition

As explained thus far, photogrammetry is an activity that relies on the use of bidimensional images to derive 3D information. Furthermore, it has also been clarified, to some technical degree, the fundamental operations underlying the reprojection of 3D information into the virtual space, along with a practical example on how a typical photogrammetric process develops. Such fundamental operations dictate how image acquisition should be executed.

2.8.1. The 3x3 Rules

Practical photogrammetric rules have been established in one of the publications of Peter Waldhäusl and Cliff Ogleby in 1994 (Waldhäusl & Ogleby, 1994). Although the rules, designated as “3x3 Rules”, were designed for stereo photogrammetry, they can be applied in any type of photogrammetric acquisition project, including multi-image photogrammetry. In fact, a recent adaptation has been released by CIPA (Waldhäusl, P., Ogleby, C. L., Lerma, J. L. & Georgopoulos, 2013) in which information is presented in a single page and in a table with 3 columns and 3 rows along with visual data. See *Figure 14*.

Each column centres on a particular method: the first column concerns the geometric rules, the second column concerns the photographic camera, and the third column concerns the procedural rules. All information considers fieldwork workflow mostly. Specifically, preparation of control information, photographic coverage, photographic overlapping, image geometry of the photographic camera, lighting conditions, type of camera to use, sketches, protocols, and consistent archival of the acquired information to ease the workflow during the office phase. From all the exposed information, it is crucial to bring to light, from our perspective, a few fundamental rules to follow.

First, consistency is vital, which affects the geometric quality of the final outputs. Secondly, the surveyor must always and inevitably consider having at least a 60% overlap between images and fixed focal length by taping the camera. This can’t be stressed enough. Thirdly, and above all, the most crucial aspect is “discretization”, that is, the process of fragmenting the object to its most simple geometric elements, that in turn facilitate the organization and archival of the data in a consistent pattern. For example, naming the images to its respective surface.

THE '3 x 3' RULES

1 - THE 3 GEOMETRIC RULES

1.1- CONTROL

- Measure some long distances between well-defined points.
- Define a minimum of one vertical distance (either using plumb line or vertical features on the building) and one horizontal.
- Do this on all sides of the building for control.
- Ideally, establish a network of 3D co-ordinated targets or points by a loop traverse around the building.

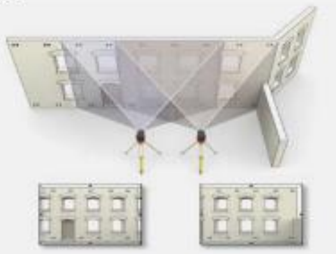
1.2- WIDE AREA STEREO PHOTOCOVER

- Take a 'ring' of pictures around the subject with an overlap of at least 60%.
- Take shots from a height about half way up the subject, if possible.
- Include the context or setting: ground line, skyline etc.
- At each corner of the subject take a photo covering the two adjacent sides.
- Include the roof, if possible.
- No image should lack overlap.
- Add orthogonal, full façade shots for an overview and rectification.

1.3- DETAIL STEREO PHOTOCOVER

Stereo-pairs should be taken:

- Normal case (base-distance-ratio 1:4 to 1: 15), and/or
- Convergent case (base-distance-ratio 1:1 to 1: 15).
- Avoid the divergent case.
- Add close-up 'square on' stereo-pairs for detail and measure control distances for them or place a scale bar in the view. Check photography overlaps.
- If in doubt, add more shots and measured distances for any potentially obscured areas.
- Make sure enough control (at least 4 points) is visible in the stereo image area.



2 - THE 3 CAMERA RULES

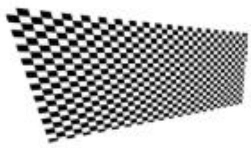
2.1 - CAMERA PROPERTIES

- Fixed optics if possible. No zooming! Fully zoom-out. Do not use shift optics. Disable auto-focus.
- Fixed focus distance. Fix at infinity, or a mean distance using adhesive tape, but only use one distance for the 'ring'-photography and one distance for close-ups.
- The image format frame of the camera must be sharply visible on the images and have good contrast.
- The true documents are the original diapositives, negatives or digital 'RAW' equivalents. Set the camera to use the camera its highest quality format.

2.2 - CAMERA CALIBRATION

Use the best quality, highest resolution and largest format camera available:

- 'Medium' format is better than small format. A large sensor is better than a smaller one.
- A wide-angle lens is better than narrow angle for all round photography. Very wide-angle lenses should be avoided.
- Calibrate the camera with a fixed focus lens and tape it there.



- Standard calibration information is needed for each camera/lens combination and each focus setting used. Shooting the calibration screen before capture with each lens will help.
- A standardised colour chart should be used in each sequence of frames.

2.3 - IMAGE EXPOSURE

Consistent exposure and coverage is required.

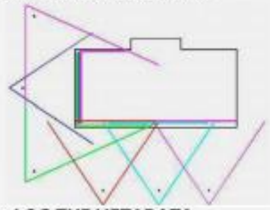
- Work with consistent illumination: beware deep dark shadows!
- Use HDR to capture difficult, unbalanced exposures.
- Plan for the best time of day
- Use a tripod and cable release/remote control to avoid camera movement and get sharp images.
- Use a panoramic tripod head to get parallax-free panoramic imagery
- Use the right media: Black-and-white is sufficient for tracing off lines but colour has some advantages for interpretation and documentation of colours.
- Use RAW or 'high quality' and 'high sensitivity' setting on digital cameras.
- Geotaging the images is recommended.

3 - THE 3 PROCEDURAL RULES

3.1 - RECORD PHOTO LAYOUT

Make witnessing diagrams of:

- The ground plan with the direction of north indicated.
- The elevations of each façade (at an appropriate scale 1:50, 1:100 - 1: 500).
- Photo locations and directions (with frame numbers).
- Single photo coverage and stereo coverage.
- Control point locations, distances and plumb-lines.
- If using 'natural' points a clear diagram showing each point is required.



3.2 - LOG THE METADATA

Include the following:

- Site name, location and geo-reference, owner's name and address.
- Date, weather and personnel. Client, commissioning body, artists, architects, permissions, obligations, etc.
- Cameras and optics, focus and distance settings.
- Calibration report, including the geomaetric and readiomaetric results if available.
- Description of place, site, history, bibliography etc.

Remember to document the process as you go.

3.3 - ARCHIVE

Data must be complete, stable, safe and accessible:

- Check completeness and correctness before leaving the site.
- Save images to a reliable location off the camera. Save RAW formats to convert into standard TIFFs. Remember a CD is not forever!
- Write down everything immediately.
- The original negatives are archive documents. Treat and keep them carefully.
- Don't cut into the format if cutting the original film. If using digital cameras, don't crop any of the images and use the full format.
- Ensure the original and copies of the control data, site diagrams and images are kept together, as a set, at separate sites on different media.

Figure 14: The CIPA adapted version of the original 3x3 Rules by Peter Waldhäusl and Cliff Ogleby. (Waldhäusl, P., Ogleby, C. L., Lerma, J. L. & Georgopoulos, 2013).

2.8.2. METRIC SPECIFICATIONS IN PHOTOGRAMMETRY

In addition to the 3x3 Rules, the English Heritage released a document that includes metric specifications for when it comes to acquiring accurate data for the recording and documentation of reality (Bryan et al., 2009). Said specifications include tables with metric values, such as accuracy of photogrammetric processing, that the operator must consider when performing recording of objects. However, such values refer merely to the documentation at a drawing scale of 1:10, 1:20, and 1:50. For that reason, and not only in the context of architectural documentation in which documentation is produced in other drawing scales, Mateus (Luis Mateus, 2012) summarized and extrapolated values for other drawing scales as seen in *Table 4*.

In detail, and from our understanding, the "output scale" takes into consideration the capacity of human vision to distinguish details. Docci and Maestri (Docci & Maestri, 2005) mention that the human vision is able to distinguish graphical changes for every 0,1mm of distance. For practical purposes, lines must be separated by a minimum spacing, otherwise, it would correspond to a texture instead of a line. For that reason, it is impossible to distinguish two lines within a spacing inferior to 0,2mm or 0,3mm. Thus, acceptable graphical representation errors correspond to that same value.

Therefore, in the context of metric specifications – "output scale", a pixel on the final image that corresponds to 0,1 mm on the drawing in the real world must represent an area equal to 5mm of the object in the real world, if considering a drawing scale of 1:50. In essence, the output scale considers changes for every millimetre on the drawing. Such is particularly useful if plotting the typical 2.5D drawings that show non-interrupted texture. Relative to the "accuracy of processing", it takes into consideration the minimum line width used on the drawings, which

Photogrammetric Processing and Orthophotographs (adapted from MSSCH)						
Scale of images for photogrammetry and orthophotography		Accuracy of Processing	Output Scale	GSD (mm in reality) of the image in function of the print resolution (dpi)		
Scale of Representation	GSD (mm)	In reality (mm) relative to a 0.18mm line in a drawing	Millimetre (mm) per pixel (px)	150 dpi	300 dpi	600 dpi
1:1	0,05	0,2	0,1	0,17	0,08	0,04
1:2	0,1	0,4	0,3	0,34	0,17	0,08
1:5	0,2	0,9	0,5	0,85	0,42	0,21
1:10	0,5	2	1	1,69	0,85	0,42
1:20	1	4	3	3,39	1,69	0,85
1:50	2	9	5	8,47	4,23	2,12
1:100	4	20	10	16,93	8,47	4,23
1:200	8	40	30	33,87	16,93	8,47
1:500	20	90	50	84,67	33,87	21,17

Table 4: Performance of image collection, the accuracy of processing, and output scale to represent drawings accurately. Originally expanded by Mateus from the MSSCH, and now adapted to English.

corresponds to 0.18mm. The value is then calculated by multiplying the line width with the corresponding output scale. For a drawing scale of 1:50, a line with 0.18mm of width corresponds to 9mm on the object in the real world (per rule, the values are rounded up). As such, the maximum threshold for photogrammetric errors must be lower than that value, that is, 9mm. The accuracy of processing is particularly useful for drafting as it reflects the graphical accuracy of lines.

Mateus (Luis Mateus, 2012), apart from contributing with extrapolated information in the previous table, presents other vital information in his work relative to the graphical representation of drawings. Specifically, the author compiled information as to what level of detail should be represented in documentation while taking into consideration the objectives, contents, drawing scale, and tolerances of said documentation.

2.9. Illations

Given the contents that have been presented so far, which include subjects related to survey and documentation, the several international or national, governmental or non-governmental institutions for the safeguarding of Cultural Heritage, the camera mechanisms and its effects on resultant images, the photogrammetric processes and possible outputs, it is now summarized the particular characteristics regarding the use of fisheye lenses:

- Interesting visual effects for artistic purposes;
- Offer high distortions due to its extremely wide FOV, 180º;
- Possibility to photograph very up close because of its FOV;
- Commonly used on aerial platforms such as drones;
- Can focus everything from 30cms up to infinity.

Considering such unique characteristics, it is brought forth the possibility of taking advantage of fisheye images to overcome the limits of the application of photogrammetry. Specifically, photogrammetry relies very much on image overlapping as seen in the 3x3 photogrammetric rules, and as the acquisition of images is dependant on the type of lenses in use, it is hypothesized that the use of fisheye images is able to:

- Increase flexibility and user-friendliness;
- Reduce the total number of images to compute, at least up to 15 times when compared to wide-angle images;
- Reduce the total number of man hours during the fieldwork;
- Possibly acquire information of hard-to-reach spaces, intricate and complex volumes, and narrow spaces.

Such aspects should be impactful in image processing since photogrammetry is very dependent on the flexibility that the instruments offer the surveyor to photograph the building. The higher the flexibility the more applications are possible to achieve, and various types of data can be created. Apart from the fact that images can be reused in several other contexts than photogrammetry.

It is in this context that in the following chapter, designated “Close-Range Fisheye Photogrammetry”, it is discussed and presented several case studies with the use of fisheye images

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3. CLOSE-RANGE-FISHEYE-PHOTOGRAMMETRY

3.1. CONTEXT

In this chapter research on the application of fisheye images to execute photogrammetric recording of morphologically complex buildings is presented.

Executing photogrammetric recordings may convey the idea that it is an easy and straightforward activity due to simple and automated operating principles underlying photogrammetry and user-friendly software. From experience, photogrammetry is a rewarding activity as the surveyor discovers and appreciates the good artistic taste present in the constructions. However, photogrammetric recordings grow into a challenging task to complete as extremely complex constructions are to be recorded, even more so when other complementary recording instruments that offer high flexibility and output quality are inefficient for the same task (Kedzierski, Alczykowski, & Fryskowska, 2009).

The issues presented throughout the chapter originated when experience on the field increasingly grew with the execution of multiple small and large-scale exercises, and as the limitations of the application of photogrammetric instruments were noted when recording inaccessible locations, bridges, wide areas followed by small and limited spaces, battlements, towers, walls occluded by vegetation, and narrow spaces predominantly present in heritage constructions. One of the authors to share the same experience is El-Hakim (El-Hakim, Beraldin, Picard, & Godin, 2004). All prementioned problems prolong the required time to complete the tasks if using any conventional surveying approach or classic surveying instruments. In fact, as concisely stated in the following article, recording of features must follow a few criteria:

«In general, most applications specify eight requirements: high geometric accuracy, capture of all details, photorealism, high automation level, low cost, portability, application flexibility, and model size efficiency. The order of importance of these requirements depends on the application's objective – for example, whether it's for documentation or virtual tourism» (S. F. El-Hakim et al., 2004)

The apparent impossibility of surveying geometrically complex volumes led to the research of specific approaches or ad-hoc solutions for these "extreme" situations. Extreme situations infrequently brought to light in the photogrammetric literature, except for a few cases mentioned in recent years (released after the researched case studies developed by us) that interestingly mention identical problems identified throughout the current chapter and relate to the same type of structures: heritage constructions and castles.

For these reasons and in the context of the current thesis, it is explored the application of fisheye lenses to overcome the identified setbacks. Thus, we propose the name “close range fisheye photogrammetry”. For the same motives, panoramic photogrammetry has also been researched as it follows identical underlying objectives as fisheye photogrammetry.

Having in mind the possibility of connecting interior and exterior photogrammetric data sets, the focus is on pushing the application of fisheye imagery to the limits and execute recording of other challenging features such as morphologically complex volumes, and, above all, extremely narrow spaces (50cm up to 150cm) such as those frequently present in The Convento dos Capuchos in Sintra, Portugal.

Furthermore, it is also intended not only to corroborate the applications researched by other surveyors but also to demonstrate that it is possible to apply the proposed hypothesis in this thesis in other types of constructions. It is not intended to convey the idea that the few recording projects executed and presented in the current chapter with the use of fisheye lenses is statistically relevant to firmly state or generalize that they are applicable in any context. On the contrary, it is intended to illustrate, even with the few case studies, that it is possible to do much more than initially thought or expected, and that these methods do work to overcome the identified setbacks. In other words, it is intended to declare that what was considered only as “theoretically possible” is, in fact, “practically possible” in the context of close-range fisheye photogrammetry.

3.2. Contents and Structure

In this outline, the first step consists in the execution of a bibliometric analysis to determine the utility, impact, popularity, and application of fisheye photogrammetry in the past few decades, followed by a section dedicated to related work in which it is also emphasized the impact, importance, and type of applications of fisheye photogrammetry and possible applications yet to be explored.

Next, case studies are presented in a hierarchized order, from the initial process of finding a method to remove the distortions of fisheye images to the application of ultra-wide-angle images in a large project. The reason for this approach is to best clarify the advantages and disadvantages of using extremely short focal length lenses to the researchers and surveyors who seek or wish to apply photogrammetric techniques in structures that are seemingly impossible to acquire data. In other words, what is thought of as a linear path is, in fact, a path that at times: needs to be adjusted to obtain the desired results; needs a step backwards so to take two steps forward, or a pause for evaluation and observation of the results obtained so far. These momentary interruptions and deviations are outside the main predicted path, but without them, the development of the work would not be possible for they are contributions granting fast improvements of the acquired data linked to the main path. The great advantage of these contributions is their reusability and long-term application in other projects.

Relative to the presentation of the information of the case studies, it follows a structure identical to scientific writings: Title; Research Purpose; Research Question; Keywords; General Methods and Conditions; Exercises; Data; Results; Discussion and Conclusions; and Summary.

In addition, as the physical or digital information used to execute the exercises and research are of considerable size, the information is succinctly described in *annex 2*. The information should be consulted as the reading of the contents is proceeded to promote an easier understanding. Specifically, in annex 2 photographic records are illustrated in a hierarchized order and that occupy dozens of pages, tables with detailed information about the obtained outputs, and other types of information. It should be noted that the information is greater than 1 TB of space and the complete storage of said data on CD, DVD, or Blu-ray is non-practical. All information, if need be viewed, should be consulted with the research group ArcHC-3D at the Faculty of Architecture – University of Lisbon.

The structure of the case studies is as follows:

De-Fisheye

In this case study it is addressed the difficulty of using highly distorted images to generate 3D digital reconstructions, and the efforts to find a method to undistort the images. It is presented in a step by step process in which several point cloud software and photogrammetric software have been tested. Images of The Faculdade de Arquitectura – Universidade de Lisboa are used to carry out the fisheye tests.

Software Comparison

Photogrammetric software programs are tested and compared to analyse the differences in the outputs, such as density, the total area of reconstruction, and computation time. Subsequently, it is indicated which software is best to use depending on the object or building to survey. The software programs that were tested are VisualSFM; CMPMVS; Apero/Micmac; Pix4Dmapper. Images of The Faculdade de Arquitectura – Universidade de Lisboa are used.

Recording of Complex Elements

After calculating the distortion coefficients of the fisheye images, it is studied if the application of said images is reliable and efficient to overcome specific problems when recording constructions, such as morphologically complex volumes. For this purpose, the results were compared with the outputs of a conventional lens. The Castle of S. Jorge, Castle of Sesimbra, and Igreja de Stº André were chosen to proceed with the photogrammetric tests.

Recording of Narrow or Hard-to-Reach Spaces

Another topic of interest is to determine if the application of highly distorted images is usable for recording spaces that are inefficiently recorded with the use of conventional or classic surveying instruments. For this end, the Convento dos Capuchos and a spiral staircase of The Convent of Christ were used for testing.

Proposal of Contiguous Transitions and Remote Transitions

In this section it is researched photogrammetric recording methods to ease the recording workflow and facilitate data organization during the office phase. While bearing in mind the imperative condition of overlapping between images, two methods are proposed that allow to reduce the object into its elementary parts while taking the limits of photogrammetry itself as reference.

Coverage and Topographic Recording

In the final case study, it is studied if fisheye images for photogrammetric purposes allow to recover tangible and useable information of ground surfaces when compared to conventional photographic equipment, and if it obviates the use of complementary or additional surveying instruments.

3.3. State of The Art of Fisheye Photogrammetry

3.3.1. Bibliometric Analysis

It may be discussed that the application of fisheye images is not new, however, it is unusual for terrestrial applications and to record complex structures. This is mainly due to the inherent complexity of the extreme distortion in fisheye images, which require the use of specific computer algorithms to reproject visual information correctly into a 3D virtual space and the use of powerful computer equipment to process hundreds or thousands of images in one global project.

To demonstrate that the application of fisheye images is unusual and increasingly more common only in recent years, a bibliometric analysis using Google Scholar search engine *(https://scholar.google.com/)* was performed to study interesting dynamics from 1990 to 2017. See *Figure 15*. The analysis comprises such specific range to include digital photogrammetry as best as possible. It should be noted that the analysis is for estimation purposes as it does not include contributions made in other languages than English, even though it includes conference papers, theses and dissertations, academic books, pre-prints, abstracts, technical reports, etc. from major and minor sources as notified in the help section. Yet related to the coverage of Google Scholar, a few restrictions to include items in the search are imposed. For example, untitled documents and authorless documents are generally not included, just as websites requiring accounts, installation of plugins, and other situations. No matter how convenient such search engine is, to search for very precise topics it is recommended not to rely merely on one search engine and on very precise keyword combinations (*https://scholar.google.com/intl/en/scholar/help.html#coverage).*

For the bibliometric analysis, specific keywords were selected: "Photogrammetry" (198,000 references) displayed in green colour; "Photogrammetry AND Fisheye" (2,057 references) displayed in blue colour; "Photogrammetry AND Panorama" (5,406 references) displayed in red colour. See *Figure 15.* The graphic includes percentual values that add up to 100% for each keyword combination, meaning that the total number of publications for each year of a specific keyword combination was divided by the grand total number of publications from all years of the very same keyword combination. The major reason for this is to easily compare any noticeable dynamics or trends over time.

Starting with the keyword "Photogrammetry", it can be observed that its evolution is majorly affected by Computer Vision developments and computer hardware components. For instance, the number of publications from 1990 to the year of 2000 is approximately the same but with a slight growth and haven not exceeded 15% of the total corpus of photogrammetry literature – while considering the time interval. From 2000 the line inflects resulting in a growth superior to 500% percent when compared to the year 2017. The causes are due to the availability of lower cost computer parts and photographic parts to the public in general, that allow the computation of larger datasets and overcome limitations on the use of classical survey instruments, in addition to the availability of more user-friendly software for the public instead of private and/or public proprietary software (Rizzi, Baratti, Jiménez, Girardi, & Remondino, 2011). For example: PhotoModeler (proprietary) was released in 1994; Agisoft Photoscan (proprietary) was released in 2006; VisualSFM, free for personal, non-profit, or academic use was released in 2011; Apero-Micmac open source software since 2007; Pix4Dmapper (proprietary) released in 2014; and other software that has contributed to the ubiquitous use of photogrammetry by the average user. In other words, the use of affordable quasi-automatic photogrammetric software with well-developed Computer Vision algorithms removes the need of photogrammetrist specialists, permitting users with average state of the art computers to calculate thousands of images (even with non-ideal images) in a short time interval with high-quality outputs. The effect is a sudden increase in photogrammetry references, particularly from the start of the century (Van Damme, 2015). To see the average state of the art of computers of today (August of 2018), see *Figure 16*.

When studying the evolution of fisheye photogrammetry, a few peculiarities are noticed. Up to the late 2000s, most of the published literature focuses on Computer Vision solutions, mathematical answers, multi-integration with other surveying instruments, application to analyse forest canopy, space exploration, cartography, UAV application, and other fields of study. Interestingly, one article in 1999 mentions the use of fisheye images to acquire information of indoor spaces (Toz & Wiedemann, 1999). It is very possible to be one of the earliest uses of fisheye lenses for such a purpose. Further information concerning related work and case studies, such as castles, is revealed after the bibliometric analysis.

To find literature regarding the application of fisheye lenses for close range fisheye situations proves to be immensely difficult. Not many references are found merely a few from the late 2000s to 2012, and a few more from 2012 to 2018. This coincides with the release or update of open source or free trial or low-cost fisheye supporting software such as Apero-Micmac

(2007), Pix4Dmapper (2014), and Agisoft Photoscan (with an update in 2014). By 2012 it can be observed that extra efforts are brought forth to study the application of fisheye images as the total number of references suddenly spikes relative to the volume of references of photogrammetry in general – do note that we are not analysing absolute values, but percentual values to derive these conclusions.

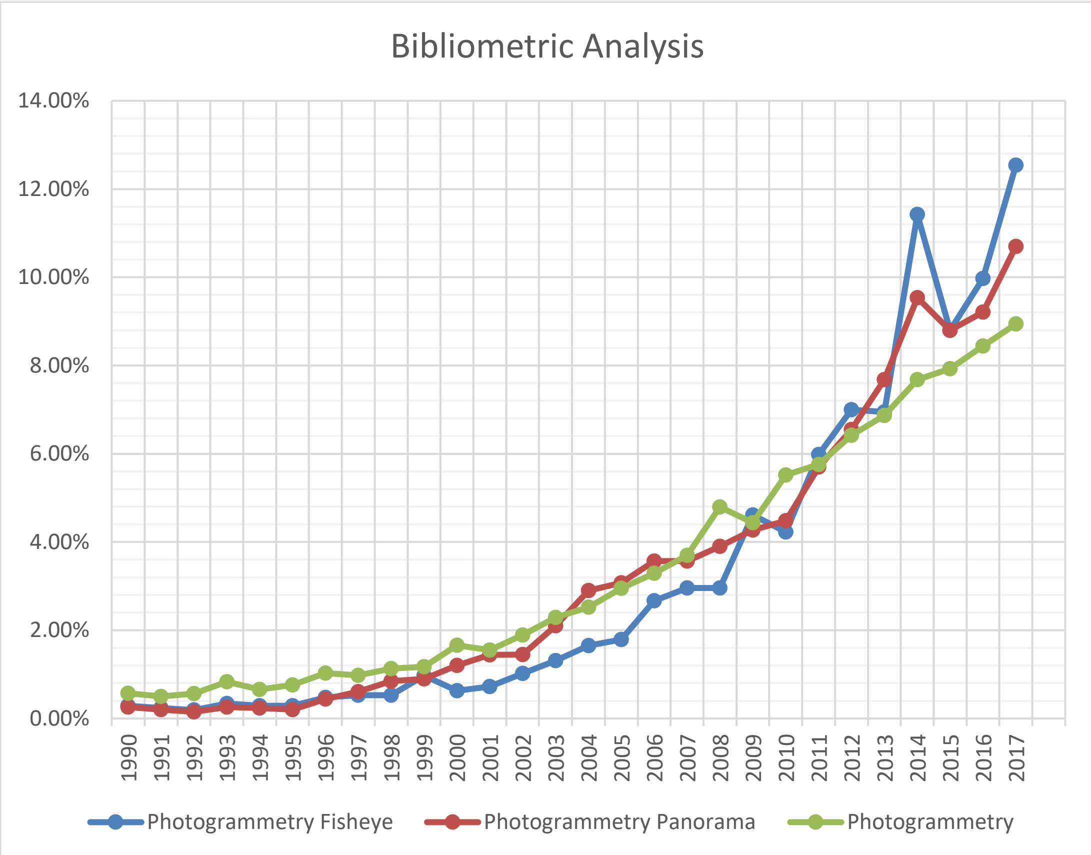

Figure 15: Bibliometric Analysis from 1990 to 2017 of the terms “Photogrammetry Fisheye” vs “Photogrammetry Panorama” vs “Photogrammetry”.

Less than 512 MB	0.00%	0.00%
512 Mb to 999 MB	0.01%	0.00%
1 GB	0.29%	0.00%
2 GB	1.77%	+0.04%
3 GB	4.42%	+0.16%
4 GB	11.07%	-0.10%
5 GB	0.49%	+0.04%
6 GB	2.51%	+0.21%
7 GB	2.25%	+0.22%
8 GB	38.79%	-1.84%
9 GB	0.03%	0.00%
10 GB	0.29%	+0.02%
11 GB	0.23%	+0.05%
12 GB and higher	37.85%	+1.23%

Below 1.4 Ghz	0.44%	+0.06%
1.4 Ghz to 1.49 Ghz	0.27%	+0.01%
1.5 Ghz to 1.69 Ghz	1.47%	+0.10%
1.7 Ghz to 1.99 Ghz	2.68%	+0.32%
2.0 Ghz to 2.29 Ghz	4.13%	+0.43%
2.3 Ghz to 2.69 Ghz	15.48%	+1.41%
2.7 Ghz to 2.99 Ghz	13.07%	+0.58%
3.0 Ghz to 3.29 Ghz	17.29%	-0.69%
3.3 Ghz to 3.69 Ghz	22.46%	-3.14%
3.7 Ghz and above	6.71%	-0.26%

1 cpu	0.94%	-0.03%
2 cpus	30.09%	-4.31%
3 cpus	1.72%	+0.12%
4 cpus	59.22%	+2.54%
5 cpus	0.00%	0.00%
6 cpus	6.70%	+1.47%
7 cpus	0.00%	0.00%
8 cpus	1.20%	+0.21%
9 cpus	0.00%	0.00%
10 cpus	0.05%	0.00%
12 cpus	0.03%	0.00%
14 cpus	0.00%	0.00%
16 cpus	0.03%	0.00%
17 cpus	0.00%	0.00%
18 cpus	0.01%	0.00%
20 cpus	0.00%	0.00%
22 cpus	0.00%	0.00%
24 cpus	0.00%	0.00%
28 cpus	0.00%	0.00%
32 cpus	0.00%	0.00%

Figure 16: Computer hardware statistics from Steam software - August of 2018. Left image: System RAM; Middle image: Intel CPU Speeds; Right image: Physical CPUs. Information from *https://store.steampowered.com/hwsurvey*

Relative to panoramic images in photogrammetry, it is interesting to analyse its evolution as well, which is identical to fisheye photogrammetry. That is, precision, accuracy, and mathematical models are examined and later on more and more examples of application are presented (Haggrén et al., 2004). It can be observed that both fisheye and panoramic photogrammetry applications have increased more and more, predominantly in the past 5 years.

The reason to research panoramic images in photogrammetric context is due to its FOV being able to be equal or greater than fisheye images – 180º up to 360º of FOV. However, a few key differences are identified. While each fisheye image is created from merely one shot, panoramic images require manual, semi-automatic, or automatic stitching of several images, resulting in single viewpoint images with super high resolution, more homogeneous GSD, and lower chromatic aberration ratio.

From the performed bibliometric analysis it can be confirmed that the access to powerful state of the art computer hardware by the average user combined with free and open source or free trial photogrammetric software capable of accepting non-conventional imagery as input, has led to more and more use of said non-conventional imagery – fisheye and panoramic images – in diverse fields of study, including cultural heritage. Furthermore, it reveals that the full potential of using fisheye images, even though not new, is yet to be discovered and applied in the most diverse fields of knowledge.

By way of explanation, the application of fisheye imagery, since the mid-2000s, has been hypothesized to be the solution to overcome the recording of problematic scenes, but due to the lack of better equipment and developments in Computer Vision, acceptable outputs were unattainable. Nowadays the photogrammetric paradigm has evolved to include non-conventional imagery effortlessly. In addition, such developments stimulate dissemination of these techniques, increasing awareness on how 2D and 3D information can be acquired fast and represent more – one of the concerns indicated in one of the publications of Rizzi (Rizzi et al., 2011).

3.3.2. Related Work

From the abovementioned information, it is apparent that panoramic images are somewhat identical to fisheye images when considering the FOV that both can offer. However, the main difference pertains to the gathering of information during the fieldwork. Whilst fisheye lenses may be handled without complementary equipment such as a tripod, panoramic images require the use of tripods that allow rotating the camera, or tripods with multi-camera systems.

Such conditions reflect on the lower flexibility of information acquisition. Specifically, fisheye lenses may be utilized while static or in motion, whilst panoramic images, for the most part, must be acquired while stationed. Several applications of panoramic imagery are possible.

For example., from a panoramic image several images can be exported with extra high resolution and with no distortion and then be computed to generate a point cloud via photogrammetric processes (Annibale, Piermattei, & Fangi, 2011; D'Annibale, Tassetti, & Malinverni, 2013; d'Annibale, Tassetti, & Malinverni, 2014). Alternatively, panoramic images may be utilized as input in a software developed for such purpose to originate metric information (Fangi, Malinverni, & Tassetti, 2013). Such workflow results in fewer images to acquire geometric information. However, from our experience and as presented in the case studies throughout the current chapter, panoramic images are suited to record large areas and volumes from very few viewpoints, rather than to capture complex and long narrow spaces. See *Figure 17* to observe the few stations to execute a panoramic photogrammetric project. In addition, Maas states:

«[…panoramic images are] very suitable for capturing indoor scenes or city squares in applications requiring very high resolution. Precision and resolution have to be discussed separately when comparing panoramic cameras to conventional digital cameras.» (Maas & Schneider, 2004).

In the context of the current thesis, fisheye lenses are better suited to perform the recording of complex, narrow, and hard to reach spaces due to its higher flexibility. Furthermore, photographic cameras of nowadays contain imaging sensors with high MP count that result in images with a high level of detail, even more so when said images are captured at very close distances - down to 50cm.

Nonetheless, other interesting applications of panoramic images are possible to achieve. For example, for visualization purposes of virtual or real-life scenes, web presentations, advertising, and measurement of said scenes (Kwiatek, 2015; Pomaska, 1999; Schneider & Schwalbe, 2005); Another interesting application is the use of 360º panoramic film to perform image-based modelling and virtual tours of a bombed church in the UK - no use of point clouds (Kwiatek, 2012); Use of a complex system of cameras mounted on a barge to record panoramic images of dimly lit underground waterways that extend for hundreds of meters, and that are characteristically very confined spaces to not use conventional surveying equipment (Albert et al., 2013). The reason to use panoramic images in the last example is due to the impossibility of having the barge static and to return to the previous position as it is a one-way travelling-canal.

Concerning the application of fisheye lenses, and within the main framework of the thesis that consists of collecting information of cultural heritage constructions or castles (medieval architecture), a few references can be mentioned that reveal the faced challenges and adopted workflows. Said references can be organized in two distinct periods: publications from 2000 to 2010, and publications from 2011 to the present moment. The cause for such separation is related to the evolution of photogrammetry as discussed in the bibliometric analysis. Specifically, early case studies use a multi-sensor approach in which: very few images are obtained so to manually model the general configuration of the scene (wireframe model for instance) and project high detailed textures; and laser scanning is utilized with the purpose of obtaining highly detailed geometry of a few elements of interest. Such approach was commonly adopted due to hardware limitations for the computation and visualization of data. Other workflows were adopted as well, depending on the size of the scene. In general, acquiring information of large scenes with TLS would be a monotonous task. By contrast, during the second period, as hardware is highly developed along with Computer Vision algorithms, it is observed the main use of a surveying instrument complemented by positional data, such as GPS for instance.

Starting with publications within the period 2000-2010, there are a few articles that focus on the recording of castles, indoor spaces, or extremely challenging scenes to record. El-Hakim mentions that recording geometric data of castles proves to be a challenging task due to inaccessible locations or lack of flexibility to utilize the surveying instruments. For that reason,

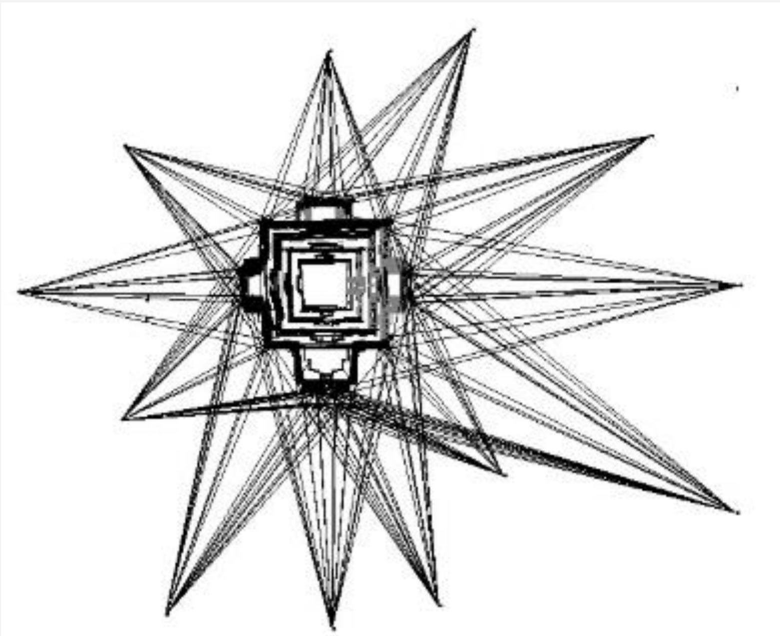

Figure 17: Network of the oriented panorama. (Fangi et al., 2013).

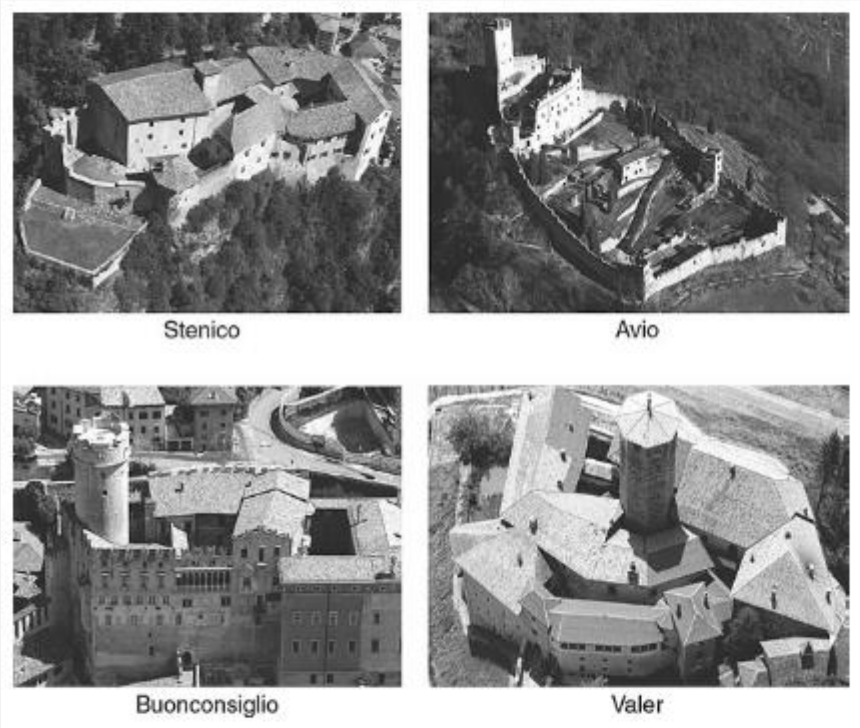

Figure 18: Example of complex structures to survey – castles. (S. El-Hakim et al., 2007)

and realising the apparent situation, the strategy focused on acquiring: a global model via photogrammetric processes; panoramic images to insert the final object in a local context; details of elements via the use of TLS that are posteriorly stitched to the global model. In addition, pre-existing drawings were used as a reference to manually model the floors and complete the 3D project whenever it was impossible to gather information. In short, a combination of multiple techniques - aerial and terrestrial - was required as no surveying technique can fully satisfy all requirements of large-scale complex scenes (El-Hakim et al., 2004; El-Hakim et al., 2007; Remondino et al., 2009). See *Figure 18*.

In another case study that focuses on recording castles, although, with very simple volumetric geometry, the author makes use of conventional photography via helicopter, cranes, and boats to record exterior facades. Precision values were obtained between 1 and 2cm with the application of a 6MP compact camera with a 2/3 sensor size, which was considered modern in the year 2004 – vs 16MP or 20MP of cameras as of 2018. The total number of photographs for each castle varied between 48 and 374, while projects of today make use of up to thousands of images. As expected from early applications of digital photogrammetry, the measurements were selected from the photogrammetric calculations and a model was manually created in another software such as AutoCAD. Do note that, for this project, targets placed on the walls provided with information to compute image matching and to georeference the final model (Kersten, Pardo, & Lindstaedt, 2004).

In another project (Chiabrando, De Bernardi, & Curetti, 2009), the authors use a GPS system to establish a network of points around the construction, use a total station to create contour lines, and finally employ a UAV to execute a simplified photogrammetric survey of the remains of the castle. Identically, the recording of the Castle Landenberg made use of terrestrial and aerial photogrammetry combined with GPS CPs to georeference the project (Püschel, Sauerbier, & Eisenbeiss, 2008). In 2010, Mateus (Mateus, Martín, Rúbio, & Alonso, 2010) executed a survey on a ruined tower of a castle with TLS combined with photography to project colour information to the point clouds.

One of the few case studies to use fisheye images within the period of 2000 and 2010 is the recording of the church of the Salinas National Monument in New Mexico (Arias, Runge-Kuntz, Richards, Watson, & van der Elst, 2004). The authors proved that it is possible to use ultra-wide-angle images to overcome the need for numerous images while reducing computation time. Specifically, one fisheye image can capture 11m high walls in their entirety from standard tripod height.

From the researched case studies within the established period, depending on the scale of the scene, and outputs to produce, different strategies are adopted. Nonetheless, it can be determined that the sole use of photogrammetry to acquire information of constructions, such as castles with intricate and complex volumes, proves to be insufficient and ineffective, thus requiring the employment of TLS, GPS, or total station to complete the resulting models. In more detail, to obtain geometric information of large scenes photography is utilized while for smaller scenes laser scanning is preferred. Such a trend is observed and adopted mostly due to hardware limitations for visualization and management of data.

In fact, in 2004 the following was stated:

«To our knowledge, no large complex site model was completed based purely on fully automated image-based techniques, but sections of castles were modelled automatically» (Gonzo, El-Hakim, Picard, Girardi, & Whiting, 2004)

Undoubtedly, such statement may have been true considering the state of digital photogrammetry at the time. However, in current times, with the development of advanced computer components and software, such statement is out of date as large scenes have been recorded with thousands of images and with the sole use of digital photogrammetry - excluding, as expected, the use of complementary information to scale the final model.

For example, Pix4D team not only developed a multi-purpose photogrammetric software that supports the use of fisheye images, but also went a step further in 2014 by utilizing fisheye lenses in "close range fisheye photogrammetry" applications as in the case of The Chillon Castle (Krull & Betschart, 2014; Stretcha, Krull, Betschart, & Pix4D, 2014a, 2014b). This is one of the most important contributions in the context of "close-range fisheye photogrammetry", offering the possibility of automatically connecting interior and exterior spaces of complex buildings within hours and in a single-global project containing hundreds or thousands of images. The level of automation is higher than ever before, allowing even non-experts to produce 3D models. By contrast, in 2002 the photogrammetric restitution of the Medieval Fortress Kufstein took 4 years, which included analytical and digital methods (Hanke & Oberschneider, 2002).

It is during the second period (2011 to present) that the use of fisheye images is more prominent. For instance, in 2012 Apero-Micmac software was used to successfully reconstruct a stairwell while reducing computation time and costs relative to the application of TLS or conventional photography (Georgantas, Brédif, & Pierrot-Desseilligny, 2012). In 2015, the Delizia Estense del Verginese, a renaissance castle in Italy with simple volumetric geometry, was photogrammetrically recorded with a UAV with the purpose of discovering an efficient workflow to process fisheye images in Agisoft software (Bolognesi, Furini, Russo, Pellegrinelli, & Russo, 2015). In the same year, we published a paper to demonstrate and increase awareness that fisheye images have the potential to record complex volumes, extremely narrow spaces, and hard to reach spaces typically present in medieval castles (Covas et al., 2015). Specifically, a castle, a portion of battlements, and a narrow staircase with approximately 80cm of width were photographed. The use of TLS proved to be impossible or quasi-impossible to record the narrow staircase, and exhaustive use of TLS would be required in more open areas to capture all surfaces of the battlements.

Interestingly, the availability of fisheye supporting software not only has led researchers, (including our research team – ARCH-3D) to study the use of fisheye images to survey narrow streets, narrow spiral staircases, and tunnels, but also to study the precision and accuracy of said methods compared to TLS and conventional images (Barazzetti, Previtali, & Roncoroni, 2017; Fiorillo, Limongiello, Fernández-palacios, & Grassini, 2016; Kossieris, Kourounioti, Agrafiotis, & Georgopoulos, 2017; Perfetti, Polari, & Fassi, 2018; Perfetti, Polari, Fassi, & Troisi, 2017).

Indisputably, the introduction and application of new recording methods are only plausible if within established criteria. Working with highly distorted imagery increases the probability of generating noisier or imprecise point clouds. Other factors affect the quality of the outputs such as the non-linear variability of GSD, particularly of pixels near the limits of the imaging sensor, which affect the external orientation parameters. Barazetti and others (Barazzetti et al., 2017) state that good metric accuracy with fisheye lenses are obtainable, if the operator makes use of pre-calibrated camera parameters, and GCPs and CPs to control the geometric quality of the outputs, because the probability of obtaining distorted models is higher compared to those obtained with "normal" images. Specifically, with no targets, an overall RMS of image coordinates was obtained between 0.2 and 0.4 pixels while a typical calibration with coded targets has an approximate RMS of 0.1 pixels. The same authors executed a few experiments in varying software (Pix4D, Agisoft Photoscan, ContextCapture) to then statistically conclude that similar results are obtained between photogrammetric software– 3.3-3.5mm for mean distance, and 2.1-2.2mm for standard deviation when comparing photogrammetric points clouds to TLS point clouds with an accuracy of 2mm. When analysing a figure related to metric accuracy in said article, Pix4D seems to offer the denser and more accurate outputs.

Pix4D (Strecha et al., 2015) performed tests and concluded that fisheye lenses offer identical errors to perspective lenses (0.1 up to 0.3 pixels of mean reprojection error – see *Figure 19*) if the FOV was not too large, and the images acquired with the use of a tripod had the lowest deviations when aligned to TLS data. In addition, it is determined that rolling shutter cameras, such as those present in GoPro Hero3+ contribute to greater uncertainty values.

Other researchers (Fiorillo et al., 2016) executed an analysis on the reprojection error of GCPs and similarly concluded that Pix4D has the lowest errors (2.2cm for average error and 2.6cm for standard deviation) when compared to Agisoft Photoscan (3.5cm for average error and 4cm for standard deviation) and 3DF Zephyr (7cm for average errors and 10cm for standard deviation). Do note that such comparison was executed between photogrammetric point clouds and not relative to an external reference, such as a point cloud generated with TLS.

Indeed, many reports that evaluate errors, focus on distances measured in the metric system, instead of reprojection errors measured in pixels. The latter is favoured as it allows to better quantify how closely the reprojection of a point is relative to the hypothetical true projection of said point. The values analysed in the former method depend greatly on the distance to object from which the images were acquired. That is not to state the former method is implausible to determine if the accuracy and precision of point clouds are within the established criteria to produce the intended outputs.

In short, it is expected for point clouds generated with fisheye images to have lower geometric accuracy, but such can be overcome with the use of CPs (Thoeni, Giacomini, Murtagh, & Kniest, 2014). Furthermore, the benefit of acquiring photographs closer to the object due to the narrowness of spaces produce outputs well within the established accuracy.

Not always close range fisheye photogrammetry or fisheye imagery is the solution to overcome difficult recording of narrow structures. For instance, information of narrow streets in the village of Calvola, Italy, was obtained via the use of TLS mounted on a trolley for easier manoeuvring (Rizzi et al., 2011). However, it should be noted that the first approach of the authors consisted in using “conventional” terrestrial photogrammetry, but such was abandoned due to consistently poor geometry network. Other authors suggest that a multi-level integration of TLS with terrestrial and aerial photogrammetry is the solution to overcome obstacles, such as hardly accessible terrain (Bartoš, Pukanská, Gajdošík, & Krajňák, 2011). In another case study, the authors make the sole use of TLS on a lifting platform to record Sivillier Castle (Vacca, Deidda, Dessi, & Marras, 2012). Mateus et al. (Mateus et al., 2012) performed the recording of a small house, including interior spaces, in the downtown of Coimbra via the use of photogrammetry and TLS to compare outputs. From the recording, the authors concluded that using a smartphone – iPhone 4S -, even though faster than TLS, yielded poorer geometric results in areas containing no texture. In addition, the authors concluded that executing transition between interior and exterior areas was challenging and that required a comprehensive series of photos of doors and windows for interconnectivity.

From the abovementioned, multiple approaches are possible to adapt depending on the complexity vs simplicity of the site to record. It is case specific. Therefore, the sole use of a single survey instrument or method is deemed ineffective particularly when other survey instruments or methods may be utilized to record the same space or volume with the equivalent or higher quality.

Camera	Sony NEX 7	Sony Alpha	Canon 7D	Canon 6D	Canon 6D	Canon 6D	GoPro Hero3+	Phantom2 Vision
Lens	16mm perspective	16mm fisheye	20mm perspective	8mm fisheye	10mm fisheye	28mm perspective	fisheye	fisheye
Number of images	157 landside 152 seaside	376	1,041 landside 165 seaside	664	135	628	709	92
Average GSD	0.71 cm	0.84	0.42 cm	1.5 cm	1.74 cm	0.52 cm	1.23 cm	1.78 cm
3D points for bundle block adjustment	1,690,661	2,781,688	3,675,673	1,186,377	207,311	1,540,623	864,360	309,390
Mean reprojection error	0.16 pixels	0.28 pixels	0.24 pixels	0.18 pixels	0.13 pixels	0.12 pixels	0.43 pixels	0.46 pixels
RMS error to all used GCPs (cm)	1.1 / 0.8 / 0.8	2.1/ 1.8/ 1.3	1.6 / 1.8 / 0.8	1.7 / 1.0 / 1.6	1.2 / 1.1 / 1.3	1.2 / 1.1 / 1.3	2.6 / 2.5 / 2.2	2.6 / 2.5 / 2.2

Figure 19: Accuracy of fisheye lenses vs perspective lenses. (Strecha et al., 2015).

Various solutions are possible to achieve depending on the flexibility of the employed equipment. For instance, fisheye lenses are frequently utilized in drones for aerial photogrammetric recording of rooftops, land mapping, agriculture, earthworks, real estate, etc. In other words, used for “long-range applications”, or aerial mapping. Fisheye lenses produce results with the least amount of detail when compared to any other type of lenses due to their particularly short focal length values and high FOV. In this respect, proceeding with an aerial photogrammetric recording using fisheye lenses provides with point clouds with lower density or general information of the scene. One of the methods to increase density, albeit not enough when compared to outputs generated via conventional imagery, is to use high-resolution sensors or to greatly decrease the distance between the subject and the photographic camera.

Such disadvantages and uncommon applications previously identified are one of many reasons to fuel efforts at researching the use of fisheye lenses for “close-range fisheye photogrammetry” applications. At such extremely close-range distance, it is possible to acquire details and, most importantly, information that otherwise would be exceptionally difficult to obtain with conventional equipment.

3.4. De-Fisheye

Research Purpose

One of the crucial aspects of using digital photogrammetry to generate point clouds is determining information on the distortion parameters of the lenses. In general, such information is calculated automatically by the photogrammetric software for images captured with conventional lenses. If miscalculations occur, two possible scenarios are possible: the values are relatively close to insignificant, thus affecting insignificantly the final geometric quality of the point cloud, or the values are within what is considered significant and generate an incorrect model. Residual errors occur always and inevitably due to the uncertainty associated with the photogrammetric processes, including the photographic equipment.

When fisheye lenses are utilized the automatic task of calculating distortion parameters may become challenging due to the inherent geometric distortions of fisheye images. If a miscalculation occurs, however small it may be, lower quality outputs are produced. Typically, the resultant point cloud appears curved, identical to a spherical surface. The effect is evidently more prominent the higher the error in the calibration parameters.

An accurate and precise calibration is crucial to benefit from the application of fisheye images. Accurate and precise photogrammetric software should be utilized that offers the possibility of processing a considerable number of unordered images with quickness and generate geometrically consistent outputs. For that purpose, a few software packages were studied.

It is presented the steps that have been taken to find software for calibrating fisheye images and to process point clouds.

Research Question

For the photogrammetric application of fisheye images, what are the strategy, workflow, and photogrammetric software to be utilized?

Keywords

Fisheye Images; Photogrammetric Software; Image Distortion

General Methods and Conditions

Bearing in mind the main objective to determine a workflow consisting on the use of fisheye images to generate photogrammetric point clouds, the following conditions must be considered:

i) First, software for image calibration and photogrammetric processing should be researched for then tested.

ii) To determine the best software, input images for comparison must be the same across all software, and software options for maximized outputs are turned on to analyse the point clouds under the same criteria and conditions.

Employed Equipment

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)
Wide-angle lens	(18mm focal distance)
Tripod	

Software:

Pix4Dmapper

Apero/Micmac

VisualSFM + CMVS/PMVS

VisualSFM + CMPMVS

Several camera calibration toolboxes

3.4.1. De-Fisheye

The first challenging objective to process fisheye imagery is to procure a viable and efficient method to determine the image parameters for the highly distorted images.

In conventional imagery, image parameters correspond to, for the most part: radial distortion, the centre of distortion, tangential distortion, and uneven illumination. In the case of fisheye images, additional parameters or dissimilar formulas are required to account for the high distortion. Developing tools to achieve such a task would require the study of geometric projections concerning fisheye images, in addition to the complex mathematical operations underlying each type of projection. This endeavour requires resources and advanced knowledge in mathematics. For these reasons, several free and open source software was searched for considering the two following workflows:

i) Undistort the images in a semi-automatic approach via the use of an imaging software and process the undistorted images in a photogrammetric software;

ii) Find an all in one photogrammetric software that automatically calculates the distortion parameters and generates a point cloud.

i) Regarding the first workflow hypothesis:

During the first attempts, no free photogrammetric software could be found to proceed with the second defined workflow, therefore efforts were brought forth to proceed with the first condition.

Before initiating the calculation of image distortion parameters, it is fundamental to acknowledge the type of geometric distortion of the images produced with the fisheye lens under usage. The fisheye lens is a "Samyang 8mm F3.5 UMC Fisheye CSII", with Nikon F mount able to be mounted on a Nikon D3100. The fisheye lens produces images with stereographic projection. In detail, objects appear more "normal", or less "squeezed", at the edges of the image, unlike other types of fisheye lenses. In addition, the lens creates images with a maximum FOV of 180º in the diagonal axis – "full frame fisheye", the technical term.

Despite the information, there are many hard-to-understand mathematical formulas. The best approach consisted of finding a semi-automatic image processing software that calculates all required parameters and undistorts the images afterwards. In other words, a pseudo-black box software tool, allowing the user to roughly understand the internal workings of the software, and with the possibility to manipulate specific parameters. However, remapping a fisheye image with 180º of FOV to a rectilinear projection and insert in a photogrammetric software afterwards is impossible, because an undistorted image with infinite area is produced. *See Figure 20, images 3 and 4.* Yet, efforts were made to undistort cropped and uncropped versions of the fisheye images.

The first experiment was executed with VisualSFM photogrammetric software by processing original fisheye images to check for any interesting outcomes. The images represent an indoor space with 3 stone medallions each placed over a pedestal and in front of a planar wooden wall. The photographic camera, a Nikon D3100, was attached to a tripod and for each POV 2 images were shot: 1 with the 8mm lens (fisheye); and another 1 with the 18mm lens (wide-angle lens). As expected, the resultant 3D model produced with fisheye images resembled a sphere. The wall is spherical instead of planar. *See Figure 20, image 8 for example.*

After a thorough research on VisualSFM forum in Google Groups (Wu, n.d.-b), it was suggested to process with undistorted images as input and to deactivate the option of the software to calculate radial distortion. VisualSFM has merely 1 coefficient for radial distortion. To process fisheye images more than 1 parameter is needed.

To execute the suggestion from the forum, a few toolboxes to undistort images were gathered. Many of the toolboxes required the user to know computer programming, such as python (Python Software Foundation, n.d.; Stevens & Boucher, 2015) or c++ (Standard C++ Foundation, n.d.), which was not known by the operator at the time. For example, the operator would be required to write a python code using "OpenCV" library - Open Source Computer Vision Library (OpenCV Team, n.d.). Even with previously compiled codes, it was not possible to compute because it proved to be difficult to understand the code and what parameters to change. The same situation occurred similarly when running "OCamCalib: Omnidirectional Camera Calibration Toolbox" (D. Scaramuzza, Martinelli, & Siegwart, 2006; Davide Scaramuzza, n.d.; Davide Scaramuzza, Martinelli, & Siegwart, 2006), or "MATLAB"(Bouguet, n.d.), a working environment with integrated programming language.

As a result, it was decided to discover software tools that run automatically and are user-friendly, such as:

- Hugin
  (*http://hugin.sourceforge.net/)*
- 3DF Lapyx from 3DFLOW company
  (URL: http://www.3dflow.net/);
- CamChecker
  (URL: http://matt.loper.org/CamChecker/CamChecker_docs/html/index.html);
- Agisoft Lens
  (URL: http://www.agisoft.com/);
- Adobe Photoshop
  (http://www.adobe.com/products/photoshop.html)

Most of the software listed above provided with unproductive results relative to the initially established objectives. For example, Adobe Photoshop offers a "Lens Correction…" tool in the “Filter” menu, but the correction is merely for visual purposes as specific calibration values for each individual lens is not utilized. Instead, Photoshop uses a general lens model and applies to all the lenses of the same model.

Concerning the remaining software tools, the workflow is dissimilar to that of Adobe Photoshop. A checkerboard is needed for the software to calculate calibration values via the use of the images with the checkerboard represented in them. The checkerboard was printed in A1 paper format, glued to a thick wooden board, and it was checked for any misalignments. Subsequently, images are acquired.

In Agisoft Lens very accurate values are obtained when analysing images produced with the 18mm lens. The same did not occur with the fisheye images (8mm lens). The parameters varied greatly when compared to those of the 18mm lens. Both CamChecker and 3DF Lapyx software performed well when processing the set of images produced with an 18mm lens, and both programs crashed with the set of fisheye images. Perhaps due to the checkerboard being represented on a portion of the image instead of occupying the full area. Extra attempts with new images were executed and data was unobtained

Lastly, Hugin software offers two methods *(method A and method B)* to determine distortion coefficients. Either launch the main UI of Hugin software or execute “calibrate_lens_gui.exe” located in the installation folder.

Executing the former method *(A)* requires loading two photographs containing the checkerboard to Hugin, and process under the tab “Control Points”. Here, the two images are displayed side by side, and the user manually picks homologous points to posteriorly generate calibration values. *See Figure 20, image 1*. The assignment can take more than a day to complete - may even cause troubled boredom to the operator for such a monotonous task, as several homologous points must be picked, particularly at the margins of the images. In the following step, the “Optimizer” tab is opened, and the distortion values are presented, including the horizontal FOV of the lens and image centre shift.

With method *(B)*, the same values are obtained in an automatic approach by running “calibrate_lens_gui.exe”. Specifically, the tool includes an algorithm for edge detection. *See Figure 20, image 2.* The operator includes straight features in the images. Next, the standard Hugin UI is opened and the values obtained from the tool are inserted in the software to allow to export rectified images.

Interestingly, the images are in a star-like shape. *See Figure 20, image 4*. Distortion is still visible to the naked eye, meaning that data is not optimal for processing. The star-like shape means that every image is “stretched” and pixels are translated from the image centre, thus

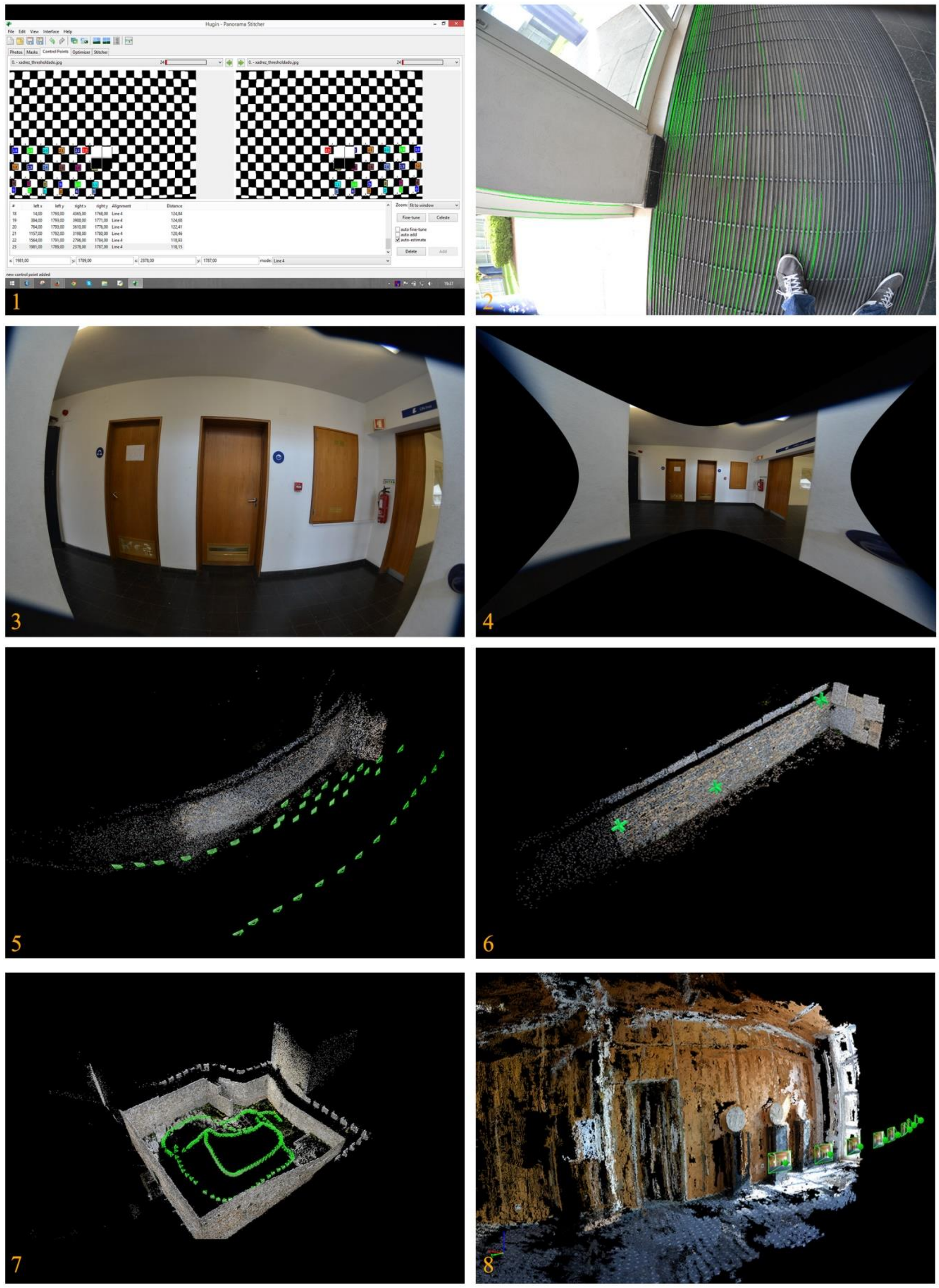

Figure 20: De-fisheye. 1: Manual homologous point picking between two checkerboard images to calculate calibration parameters in Hugin software; 2: Automatic line detection to calculate calibration parameters in Hugin software; 3 and 4: Fisheye image and pseudo-undistorted fisheye image, respectively; 5 and 6: Distorted point cloud and quasi-undistorted point cloud, respectively; 7: Successful calibration in Pix4D software; 8: Failed digital reconstruction in Pix4D with fisheye images.

vacant pixels or blank areas are created and automatically filled with interpolated "false" information. In addition, the number of vacant pixels between "true" pixels grows as the distance from the image centre increases. Therefore, to preserve true information, images are exported with great dimensions, that is, from the original 3,072 x 4,608 pixels to up to 18,720 x 13,312 pixels. Exporting images with the original size would result in the loss of true information and downsizing of features represented in the images.

Despite the identified downsides, the resultant pseudo-undistorted images were computed in VisualSFM software with radial distortion deactivated as suggested in the online post. All work thus far yielded inadequate outputs for the processed point cloud resembled a sphere, but with its curvature on the opposite direction relative to that of the model generated with original fisheye images. Moreover, the model displayed several floating, noisy patches.

ii) Regarding the second workflow hypothesis, relating to fisheye supporting software:

Even though images were undistorted, the previous method originates non-promising outputs. For that reason, photogrammetric software able to integrate fisheye images in its workflow is the best solution. As images were being undistorted previously, an open-source software program had been found: Apero/Micmac (Institut Géographique National (IGN), n.d.). The software, released in 2007, is a collection of open-source tools for photogrammetric purposes. There are numerous tools and thus several possible workflows to implement. The software delivers very good results, though some background in photogrammetry and computing is required as the software runs in three distinct methods: i) via command line, ii) by opening a GUI via command line; iii) or via the use of a batch file.

Note that inexplicable errors may occur during the processing and may be necessary to change the running method in mid-processing. For example, image orientation can fail when running with a batch file or via command line, and the solution is to run the GUI through the command line. Other times no errors happen when reprocessing the project anew - such occurrences are frustrating and time-consuming.

Another setback is related to the acquisition of the software itself. The operator can download a binary package or an installer, both available for multiple OS. Some of the downloaded files didn't work due to missing dependencies or malfunction when executing the tools. Moreover, the major downside is that the software runs with CPU, and the GPU can be activated to increase the processing speed by changing some features of Microsoft software – which may be risky in our view. In addition, the website for downloading the files, as well as most of the posts in the forums, are in the French language. The latter is easily overcome with automatic translation in Google Chrome. Nevertheless, part of the manual is in French.

Despite all obstacles, there are positive aspects to consider, Apero/Micmac can process fisheye images for it includes multiple robust geometric distortions models that produce point clouds with low noise, but at the cost of processing time – no GPU usage unless activated. Apero/Micmac does not include image parameters for stereographic projections, however, it includes other fisheye models, that when combined with self-calibration step produce very good results, at least visually - on a side note, however unusual it may be, each tool is named after a beverage, a dish, or food.

A general workflow for processing with Apero/Micmac software is presented henceforth. Regardless of the 3 distinct methods to operate the software, the tools are the same for each workflow. In the first step, the operator executes "Tapioca" command to detect homologous features for a given set of photographs. Depending on how the photographs were acquired, the user selects a method of matching, such as "Line", "All", and so on. Such procedure is limitative because, if a complex project requires the acquisition of photographs in dissimilar methods, subprojects must be processed and then merged afterwards – it is a time-consuming fragmented procedure. In the following step, "Tapas" command is executed, a geometric distortion model is selected, and a sparse point cloud is generated after image correlation. Next, "AperiCloud" command is run to export the sparse point cloud with the camera positions. This step should always be executed to check for geometric inconsistencies, as the GUI does not display the outputs in real time. The penultimate tool to execute is "Malt", which generates depth maps from the images, and computes a dense point cloud from one user-selected master image. Note that several temporary files are created with incremental levels of detail. Therefore, during the last step, while exporting with "Nuage2Ply" command, a level of detail is chosen to generate the final point cloud via the use of one of the computed levels of detail.

The main challenge of Apero/Micmac is the selection of merely one image to reproject the pixels to form a dense point cloud. To overcome this inconvenience and to ease the workflow, the surveyor must acquire images in a pyramid-like structure, that is, acquire the necessary photographs close to the object of interest, then obtain a last photograph covering the whole site. The last image is operated as a master image. Another method to overcome the problem, even though not as time-efficient, is to export a dense point cloud for every image. This way, all exported dense point clouds are automatically inter-aligned as they are originated from the same processing project. Nonetheless, a computer with powerful CPU is advised.

Meanwhile, other photogrammetric software packages were discovered: Pix4D (Pix4D, n.d.), and Agisoft Photoscan (Agisoft LLC, n.d.). Pix4D license management is identical to that of Agisoft Photoscan. Specifically, both software packages offer one-time purchase license, demo mode, and trial mode with limited time and all features unlocked. In Agisoft Photoscan and in demo mode the operator is unable to export the reconstructions and save the processing. By contrast, in Pix4D reconstructions can be saved but not exported. This enables to explore all tools using the same project, in different sessions and eliminating the need to reprocess everything anew. In addition, if the operator activates the trial version or purchases a license, reconstructions can be exported immediately. Permitting to save projects while in demo mode allows the operator to generate large-scale projects, and thus test the computational limits of the software. For these reasons, Pix4D software was selected to use for processing fisheye images due to its friendly-usage. Moreover, Pix4D software obviated the use of Apero/Micmac for the following reasons: i) the possibility to compute projects within a reasonable time-frame; ii) uses GPU for processing; iii) more user-friendly due to the design of the UI, in which tools are executed with no need to run a batch file, command line, or UI for every tool; iv) lastly, Pix4D automatically calibrates fisheye images, not requiring the user to select specific geometric models, except for selecting between "Perspective Camera Model" and "Fisheye Camera Model".

The workflow of Pix4D software is presented as well. To test Pix4D workflow and its outputs, the same 8 fisheye images – of the 3 stone medallions of the Faculty of Architecture of the University of Lisbon - to test Apero/Micmac were used. The first processing provided with an unsuccessful reconstruction with curved surfaces resembling a sphere. *See Figure 20, image 8.* As abovementioned, Pix4D software supports 2 main camera models: "Perspective Camera Model" or "Fisheye Camera Model". However, for the fisheye lens in use, the user is forced to select Perspective Camera Model, perhaps due to the type of geometric distortion: stereographic projection. Interestingly, Fisheye Camera Model is selectable for the GoPro mounted in Phantom 2 Vision+. Despite such minor inconvenience, good reconstructions are obtained at the cost of FOV. Specifically, Pix4D uses about 160º of FOV instead of the full 180º of FOV provided by the fisheye lens. For the purposes established in the current thesis, 160º is well within the range of what is a fisheye image or an ultra-wide-angle image.

The pix4d photogrammetric software offers other remarkable tools for calibration. For instance, "Ground Control Points" (GCP) are possible to be selected in numerous images to process and/or reprocess the project. Such a method improves the geometry of the point cloud by recalculating accurately the distortion parameters of the lens used in the project. Utilizing such strategy, a quasi-perfect model was generated from the 8 fisheye images of the 3 medallions.

So far, compared to other professional photogrammetric software, Pix4D software provided the best outputs. Nevertheless, an acceptable calibration must be calculated. For that purpose, a masonry wall in a pedestrian pathway by the sea, located in Paço D'Arcos, Lisbon, Portugal, was photographed. The final model still presented with distorted features.

It is concluded that, if correct calibration is desired, a loop (closed-polygon) of photographs is mandatory. Executing such photographic acquisition provides the best control to verify that one end of the model aligns contiguously to the other end. If such conditions are verified, the point cloud is accurate, at least visually, and correct distortion parameters are calculated. Undoubtedly, to truly verify the geometric accuracy of the resulting photogrammetric models via the use of fisheye imagery, it is fundamental to compare the photogrammetric point cloud relative to other data acquired with other accurate surveying instruments, such as TLS, or GPS.

To test the hypothesis, the courtyard of the citadel of The Castle of Sesimbra was photographed with: 8mm fisheye lens and 18mm wide-angle lens. The latter lens, whose camera distortion parameters are easily calculated using Pix4D, is utilized as a backup to accurately calibrate the fisheye lens. In other words, it is expected for Pix4D photogrammetric software to align and correct the distortion parameters of the point clouds generated with fisheye images with the group of wide-angle images. Impressive results are obtained using this method.

However, on close inspection minor anomalies were visually detected. Manual tie points are selected across several fisheye images and wide-angle images, and the project is posteriorly reprocessed. A seamless digital reconstruction is achieved. *See Figure 20, image 7*. The newly calculated distortion parameters are saved to be utilized in future projects. To ensure that results are universal across all photogrammetric projects, the 8 fisheye images of the stone medallions were reprocessed. High-quality results were obtained. The walls, pedestals, and floor are planar, even when inserting a plane object for quality assessment.

Concerning Agisoft Photoscan, the software offers identical tools to those of Pix4D software. For instance, the operator can select distinct camera models, such as perspective, fisheye, and spherical. Both photogrammetric software packages are somewhat equivalent.

RESULTS

Most software utilized to remove the distortion of fisheye images provided with unproductive results for photogrammetric purposes, except for Apero/Micmac, Pix4D, and Agisoft Photoscan software packages that are utilized for professional applications.

DISCUSSION AND CONCLUSIONS

The execution of software to undistort images produced vital information related to the application of fisheye imagery for professional purposes. It is concluded that Pix4D software offers the best outputs due to the implementation of powerful and user-friendly tools, and real-time visualization UI. Note that Agisoft Photoscan was not fully tested nor experienced in depth as much as Pix4D software due to restrictions imposed in demo mode. For that reason, and for practical purposes, the current discussion and conclusions does not consider Agisoft Photoscan software.

For professional purposes, in which accuracy and precision are of utmost relevance, fisheye supporting software purposefully designed for photogrammetric applications is the solution to consider, if detailed information is to be produced for specific objectives, such as architecture, archaeology, engineering, and other fields of study. The same software packages are designed to be user-friendly, without needing the operator to attain knowledge underlying the mathematical models of camera lenses. In turn, automated workflows encourage surveyors to dedicate the remaining time on discovering new recording possibilities, methods, and approaches.

The software to execute the exercises were utilized with the main objective of generating point clouds with the use of highly distorted imagery as input. Even though visually appealing outputs were obtained and compared to planar surface objects, further tests must be carried out to assess the geometric quality of the point clouds by comparing to data acquired with other more accurate surveying instruments.

SUMMARY

i) Several image calibration tools were unsuccessfully utilized to undistort fisheye imagery.

ii) Professional photogrammetric software including tools specifically designed for fisheye imagery, such as Pix4D, Apero/Micmac, and Agisoft Photoscan, is the best approach.

iii) From the executed exercises, Pix4D is the preferred software for it delivers geometrically accurate point clouds, is more user-friendly, and processes fast. Agisoft Photoscan is not considered in this comparison due to demo restrictions.

3.5. SOFTWARE COMPARISON

RESEARCH PURPOSE

In current times, the advent of computers in previous decades has brought forth the ubiquitous application of digital photogrammetry software, supported by Computer Vision and Computer Graphics algorithms. Thus, several photogrammetric software packages are available and ready for use that deliver outputs with varying quality.

For this reason, it is crucial to consider the reconstruction of the point clouds as each photogrammetric software delivers somewhat distinct outputs, even though the same images are utilized as input and maximized setting are selected. Each photogrammetric software generates point clouds with distinct levels of detail, density, accuracy and precision, and coverage. As a result, a study to identify overall differences in the photogrammetric software is executed and results are discussed to determine which software is best for utilizing fisheye images or conventional images as input.

Such issue is of highest interest when executing large projects containing thousands of images. Computing power and processing time of a single, global project are valuable aspects to consider to deliver outputs within an established deadline.

RESEARCH QUESTION

Given the available photogrammetric software packages, which software delivers the best outputs for processing fisheye images or conventional images?

KEYWORDS

Fisheye Lenses; Wide-Angle Lenses; Photogrammetric Software Comparison; Pix4D; VisualSFM; CMPMVS; Apero/Micmac.

GENERAL METHODS AND CONDITIONS

To evaluate the efficiency and efficacy of fisheye lenses and wide-angle lenses a controlled approach is mandatory for a fair comparison:

i) The images must be acquired from various specific POV using a tripod, and for each position two images are obtained, one with the 8mm fisheye lens and another one with the 18mm wide-angle lens. Such approach ensures the images are acquired from the same POV.

ii) During the office work phase, it should be verified if 3D virtual reconstructions are achievable given the type of images – fisheye or wide-angle.

iii) After acquiring successful reconstructions, that is, non-distorted outputs, the photogrammetric models should be, for the most part, visually compared with or without the use of rigorous tools readily available in point cloud editing software.

iv) The criteria under which point clouds are analysed are the following: the total number of points; coverage; point density; vacant areas vs non-non-vacant areas.

v) The study should be interpreted as a general approach to determine the major differences that each software delivers as it is believed that due to the application of dissimilar photogrammetric packages discrepant outputs are expected.

EMPLOYED EQUIPMENT

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)
Wide-angle lens	(18mm focal distance)
Tripod	

Software:

Pix4Dmapper

VisualSFM + CMVS/PMVS

CMPMVS

Apero/Micmac

3.5.1. SOFTWARE COMPARISON

In current times the use of imaging sensors is more and more common, and the application of photogrammetric techniques is increasingly more known by the public, whether due to its application on the gaming and film industries, or due to the application in other fields of study such as architecture, engineering, archaeology, and amongst others. Quite a few photogrammetric software are available for which outputs should be studied to verify discrepant results as dissimilar photogrammetric packages are utilized.

The current research focuses on finding the photogrammetric potential that each software has to offer. Bearing in mind such objective, every test is executed with maximized densification settings and with the same set of images for a fair comparison of the outputs. The scene for executing the comparison contains three stone medallions, each placed over a pedestal and in front of a planar wooden wall. A Nikon D3100, capable of creating images with 14.2MP, was mounted to a tripod and for each POV 2 images were shot, one with the 8mm lens (fisheye) and another with the 18mm lens (wide-angle lens).

Note that the sun was illuminating the room and created areas with intense light. *See Figure 21, 18mm – CMPMVS.* The stone medallions and the floor, unlike the wooden wall and the pedestals, reflect light diffusely. The scene presents variations in light, materials, and textures, potentially increasing the likelihood of processing point clouds with distinctive geometric qualities due to the use of varying photogrammetric software packages.

To exclude externals factors affecting the performance of reconstructions, merely one computer is used: ASUS K56CB with 8gb RAM, Intel Core i7 processor, and Nvidia GeForce GT 740M. The experimented software includes VisualSFM with PMVS and CMVS packages; VisualSFM with CMPMVS package; Apero/Micmac, and Pix4d.

For the group of images acquired with the 18mm lens, all previously mentioned photogrammetric software programs were experimented. The main noticeable differences between all outputs are the total number of points, noise, coverage, and processing time. *See Figure 21.* On close visual inspection, VisualSFM with PMVS and CMVS packages produced the least coverage with noticeable noise, particularly on the background planar surface. Pix4D computes outputs with higher density and wider coverage because more points are calculated, in addition to computing more points per unit of time relative to other software. VisualSFM with CMPMVS package creates a 3D model with the same coverage as Pix4D but with visually higher coplanarity at the expense of computing time and density. *See Figure 22 for a comparison between VisualSFM with CMP/MVS packages versus VisualSFM with CMPMCS package*. From all the software programs, Apero/Micmac produces the most visually satisfying results considering that coverage is outstanding, and points are highly coplanar, although the operator must manually select a master image from which the 3D points are re-projected. However, there may be issues if more than 1 image is to be re-projected, in which case the processing time greatly increases.

For the group of images acquired with the 8mm lens, merely fisheye supporting software programs were tested: Pix4D and Apero/Micmac. *See Figure 20, images named as 8mm.* The major concern when utilizing fisheye imagery relates to the high distortion, for which the

18mm	Points	Time (minutes)
VisualSFM+CMVS/PM	1.8~	18~
VisualSFM+CMPMVS	1.5~	70~
Apero/Micmac	2.9~	90~
Apero/Micmac	-	600~
Pix4D	15.5~	42~
8mm		
Apero/Micmac	1.25~	90~
Pix4D	10~	47~

Table 5: Comparison of photogrammetric software performance, considering aspects as total number of reconstructed points and processing time to generate outputs.

Figure 21: Software comparison. Note that in Apero/Micmac only one image was utilized for re-projecting points. In addition, the 8mm point cloud generated with Pix4D utilized "Perspective Camera Model" instead of "Fisheye Camera Model".

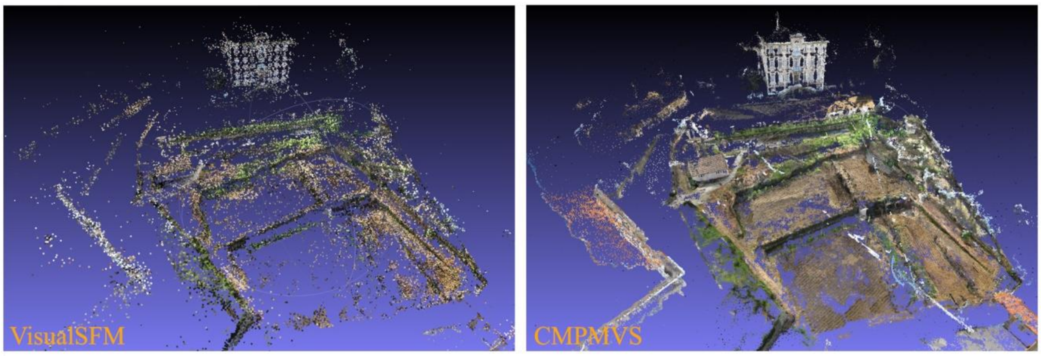

Figure 22: Dense reconstruction comparison between VisualSFM with CMVS/PMVS packages and VisualSFM with CMPMVS package.

operator must compute very accurate image distortion parameters if trustworthy outputs are to be obtained. *For a more detailed description of the calibration process read "De-Fisheye" section*. Major differences between the two software are identified: while Pix4D produces outputs in a shorter time, Apero/Micmac offers outputs consistently with lower noise but at the cost of processing time. Although the latter software, from the experiences that were executed, is suitable for very small scale photogrammetric projects, the processing time of Apero/Micmac increases beyond any useful time-frame if numerous images, reaching up to thousands, are to be computed. Thus, potent hardware is essential. For these reasons, the application of Pix4D software is preferred from medium up to large-scale projects.

The experiments were executed having in mind a general visual assessment with occasional application of tools available in point cloud editing software for a close-up inspection when visual assessment proved to be difficult due to similar reconstructions. Consequently, after deriving conclusions from the use of each photogrammetric software and its ideal usage, a comprehensive study of the outputs should be performed on selected software to verify the geometric consistency.

Results

The execution of several photogrammetric software with the same images as input resulted in the digital reconstruction of point clouds that were analysed under the same conditions: coverage; density; and noise. The results demonstrate that each software has its own strengths and weaknesses.

DISCUSSION AND CONCLUSIONS

The execution of the experiments provided with vital information concerning the performance of the various photogrammetric software.

However interesting the results, it is desirable to study with more depth the differences between these software programs by photographing other scenes containing other materials under distinct lighting conditions. Moreover, an analysis of the precision and accuracy is also needed to quantify the performance of each photogrammetric software. Nevertheless, if differences can be identified visually, the same outputs are expected in future experiments. The execution of precise and accurate analyses should be performed for software whose outputs are visually indistinct.

Therefore, the current comparison presented thus far should be taken as a general guideline because similar outputs are possible to be obtained. For example, Pix4D and VisualSFM visually present equivalent noise level. Overall, it is concluded that if fisheye images are to be used, the best approach should be using photogrammetric software such as Pix4D or Agisoft Photoscan, even though the latter one hasn't been tested due to its limitative demo restrictions – no possibility to export the outputs.

When reconstructing small-scale projects with very few images, it is possible to use Apero/Micmac as it delivers seamless and visually satisfying dense point clouds. If time is of the essence, VisualSFM should be ideal. In addition, if large-scale projects are to be processed, Pix4D software should be preferred, also due to the availability of useful tools.

It should be noted that the comparisons presented thus far do not take into consideration the purchasing value of the software to fully benefit the complete use of tools.

SUMMARY

i) To execute recording projects with fisheye images Pix4D software should be operated instead of Apero/Micmac as the former software offers outputs within a shorter time frame and supports computation of large-scale projects containing up to thousands of images

ii) To execute recording projects with other types of images from wide-angle to telephoto, VisualSFM with CMPMVS package should be preferred for it grants higher coverage when compared to other software. However, Pix4D should be preferred instead if projects are of considerable size, in addition to its faster processing of information.

iii) Further studies must be executed on preferred software to evaluate the geometric integrity of the outputs.

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3.6. RECORDING OF COMPLEX ELEMENTS

RESEARCH PURPOSE

Acquiring data from complex elements in close-range circumstances is a problematic endeavour, particularly due to the design of old heritage constructions such as castles containing volumes with intrinsically irregular shapes that when photographed result in images with exceptionally low coverage. Thus, in the current study, it is executed an evaluation of the performance of fisheye lenses and wide-angle lenses to record complex elements frequently observed in heritage constructions.

Such evaluation offers the opportunity to study the impact of the recording equipment in surveying projects to produce data with high quality in a short time-frame, and plausibly obviate the need to employ other high-cost surveying instruments such as UAV or TLS.

To achieve the proposed objective 3 sites were selected based on their geometric complexity: i) the battlements of the Castle of S. Jorge, in Lisbon; ii) the battlements of the Castle of Sesimbra, in Sesimbra; iii) and the portal of the Igreja de Stº André, in Mafra. The first two sites are grouped into one subsection - EXERCISE A- as the elements under analysis have the same design and offer similar results. Subsequently, the Igreja de Stº André is presented - EXERCISE B. General methods and conditions are presented as well as specific methods and conditions for exercises A and B given that each exercise focuses on distinctively complex volumes.

At the end of each recording project observations and recommendations are presented to better understand the advantages and disadvantages of the proposed methods and problems that were encountered.

The results of the current study offer the opportunity to consider the application of fisheye lenses to record morphologically complex volumes, instead of the common application of conventional lenses. Most importantly, the experiments provide with different approaches and methods possible to implement across a multitude of projects. In fact, the purpose of recording battlements, or complex elements, relates to the difficulty of recording said complex elements in the main case study, The Castle of Tomar of the Convent of Christ.

RESEARCH QUESTION

The application of fisheye lenses provides with similar or quasi-equivalent outputs as the outputs provided with conventional images but with fewer images?

KEY-WORDS

Close-range-fisheye photogrammetry; Close-range-photogrammetry; Fisheye Lenses; Wide-Angle Lenses; Complex Elements.

GENERAL METHODS AND CONDITIONS

To evaluate the efficiency and efficacy between fisheye lenses and wide-angle lenses a rigorous approach is mandatory, in which several factors are addressed and considered during the field work and office work phases.

i) During the fieldwork phase, it is considered: the total number of photographs; the time for recording; and if the surveying equipment under usage is user-friendly. These three factors are interrelated given the fact that by reducing the number of acquired images it reduces the recording time and increases user-friendliness.

ii) During the office work phase, it is confirmed if a 3D virtual reconstruction is achievable given the set of photographs acquired during the fieldwork and if said reconstruction meets the criteria established in detail within each subsection.

iii) Furthermore, considering the number of images play a major impact on the outcome of the experiments, photographs created from each lens type should be shot, whenever possible, from the same POV, location, and principal axis direction, except if a newly defined POV or location provides with beneficial results. Whenever the exception is practicable, a set of photographs should be acquired from the standard and exceptional position for further studies.

iv) During the office work phase, computing data in one photogrammetric software is imperative, as each software utilizes dissimilar algorithms and parameters for reprojecting 3D points into the virtual space. Therefore, the photographic acquisition must follow photogrammetric rules and be computed in a specific software to substantiate the plausibility of the results.

v) Lastly, for plausibility purposes, the conclusions pertaining the photographic acquisition must be flexible enough to be applicable in other sites of similar design and configuration. Stating differently, it is also verified quantity-efficiency to prevent computation problems and hardware limitations during office work phase.

By implementing the previous conditions, it is thought that the performance and advantages from the application of different FOV provided by each lens are determined as accurately as possible, given the established objectives of the exercise and the fact that in photogrammetry the quantity of input images affects both the processing time and reconstruction quality.

The approach of operating with the fewest images as possible is expected to be the best solution for it is more user-friendly and less time-consuming both on-site and in the office phase.

3.6.1. Exercise A - Recording of Battlements

Considering the main objective of evaluating the efficiency of the surveying instruments to record geometric complex elements, battlements were elected due to their simple, yet complex architectural design composed of horizontal, vertical, and oblique surfaces.

Battlements are a parapet wall topped with protruding elements - merlons - containing vertical slits - arrow slits. Furthermore, random rubble masonry is a common construction technique employed in medieval military structures such as castles, thus adding a layer of difficulty on the recording of features as numerous surfaces may become occluded if consistently photographing from the same angle relative to said surfaces. Therefore, computing a complete 3D virtual reconstruction of the battlements requires the positioning of the photographic camera in multiple POV to increase coverage.

Regarding the sites, the Castle of S. Jorge and Castle of Sesimbra were selected based on the proximity to the office for economical and research reasons. Particularly, the site of the main case study, The Castle of Tomar, is approximately 200km away from the office, thus precluding the advancement of the exercise if several recording sessions are required. The castle of S. Jorge is 10km away and the castle of Sesimbra is 30km away from the Faculty of Architecture.

EMPLOYED EQUIPMENT

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)
Wide-angle lens	(18mm focal distance)
Wired remote shutter release	
Straps for the wiring	
Metallic demountable pole	
Aluminium demountable pole	
Aluminium telescopic pole	(adapted painter pole)

Software:

Pix4Dmapper

VisualSFM + CMVS/PMVS

VisualSFM + CMPMVS

METHODS AND CONDITIONS

The methods and conditions for acquiring and analysing the information of the battlements are as follows:

i) The photographic camera mounted on a telescopic pole must be employed with the purpose of acquiring photographs from stipulated positions due to the design configuration of the battlements.

ii) The stipulated positions must follow an arc shape and must be determined as the recording occurs since the FOV of the lenses are unknown to the surveyor and therefore influence the distance of the camera to the battlements.

iii) Furthermore, the stipulated positions must cover all surfaces of the battlements thus leading to a full digital reconstruction.

iv) For a fair comparison of the results, the same software should be used to analyse the differences between every photogrammetric model.

3.6.1.1. Castle of São Jorge

The Castle of São Jorge, located in Lisbon, was designated the first site to execute the study for being the closest location to the office. The recording of the battlements lasted merely one day due to impending internal and external factors that led to the premature termination of the recording. However, some conclusions could be derived.

For the recording session, a conventional lens was used since no fisheye lens was available in the inventory. Until a fisheye lens was to be acquired, the main objective consisted in making a point cloud with a wide-angle lens - 18mm for an APS-C sensor.

The first noticeable issue once at the site was the long queue to buy entry tickets. Even though the castle is in the city of Lisbon with many other sites of touristic interest, a large crowd was not expected. It was noted that most of the visitors were foreigners and brought forth most of the questions regarding the purpose of the equipment under use. Such occurrence revealed to be a huge setback because a task accomplishable in 10 minutes took 30 minutes or more.

In addition, fearing that the surveying equipment could be stolen, the feeling of security was minimal as it was needed to safeguard the equipment simultaneously. Such situation was more evident when recording the battlements if one considers the narrowness of the chemin de ronde. Work had to be consistently interrupted to allow visitors through the pathway. Inevitably, visitors were recorded in the photographs.

Besides the external factors strongly affecting the progress of the recording, some other internal factors related to the surveying equipment were evident: A 2m demountable metal rod was being used with a photographic camera mounted at one end. To acquire the images a wired remote shutter was wrapped around the rod and connected to the photographic camera. The main difficulty was pressing the shutter release button while holding the substantially heavy rod. For that reason, several breaks to reacquire arm strength were needed.

Seeing the work was not progressing as planned, the project was cancelled for the day, and it was decided to further explore the rest of the Castle of S. Jorge for any other possible challenges that may have gone unnoticed during the first recording of The Castle of Tomar, that occurred previously to this study. For instance, another possible study would be the employment of fisheye lenses to record narrow or hard-to-reach spaces as in the main case study.

RESULTS

The exercise executed in the Castle of S. Jorge brought forth no positive results regarding the accomplishment of the main objective of determining if fisheye images are advantageous relative to wide-angle images. Nonetheless, important experiences were acquired apart from a small set of images.

Due to reasons explicitly expressed previously, merely 35 photographs were collected during the recording session. No digital reconstruction of the battlements was computed for there were insufficient and unordered images. Lastly, the surveyor, through repetitive exercises, must acquire higher sensitivity as to what the photographic camera is recording from a remote POV and given its own FOV.

IMAGES	Top Position	External Position	Unsystematic
1m extension	5	17	1
2m extension	5	7	
TOTAL	35 images		

Table 6: The total number of images acquired via the use of a 2m demountable metal rod.

Figure 23: Example images of the collected data from the Castle of S. Jorge (18mm wide-angle lens). Group A: Vertical position, 1m extension; Group B: Vertical position, 2m extension. Group C: Exterior position, 1m extension; Group D: Exterior position, 2m extension.

DISCUSSION AND CONCLUSION

From the performed study several notions can be discussed to meliorate future projects.

The acquired data suggests that the employment of a wide-angle lens - 18mm - mounted on a metal pole precludes the production of quality and time-efficient work, even though necessary precautions were considered. Furthermore, surveyor experience indicates that acquiring information of complex elements, such as battlements in a hard-to-reach and low-coverage type scenario, specific photography skills and notions are necessary, such as the FOV of lenses; and how far the photographic camera must be positioned for optimal coverage, which should be attained from methodical experiences.

The lack of photography skills led to the acquisition of perpendicular images relative to the surfaces of the battlements, thus creating low-quality images for a time-efficient 3D reconstruction - or even no reconstruction at all - due to consistent short coverage. Moreover, the application of a metallic rod as an extension to reach desired positions proved to be tiresome to the surveyor due to its weight, indicating that an aluminium pole should be utilized instead.

Regarding the external factors impeding the execution of the recording, necessary pre-preparation on site should be arranged to facilitate the work being performed. For instance, create inaccessible areas for visitors to avoid unsolicited interruptions and potential loss of equipment. However, as such solution involves coordination between the surveyor and entities responsible for the management of the site, it does not fit the unpredictable nature of the exercise as several recording days may be necessary to complete the exercise. Such a solution should be adopted when executing a professional recording.

In the end, it was realized this site was not the best for proceeding with the exercise due to two main reasons:

First and most obvious, the lack of experience of the surveyor. The ideal positioning of the photographic camera was not known, considering the FOV of the 18mm lens. Due to this, photographs were shot perpendicularly to the surfaces of the battlements leading to low coverage.

Secondly, if the recording had to be executed once more, tickets would need to be purchased again for each day. Beyond that, large groups of curious people would be faced, who interrupt the recording operation to ask the same questions repeatedly. Furthermore, the surveyor would have to use some of his little remaining focus to safeguard the surveying equipment. For all these reasons, choosing another castle to proceed with the exercise and acquire more experience with the photographic equipment was crucial.

SUMMARY

i) Before proceeding any further with the study, acquire skills and experience with the photographic camera and lenses.

ii) Acquire a fisheye lens and an aluminium telescopic pole for user-friendly purposes.

iii) Find another castle that is less frequented to ease recording operations.

3.6.1.2. CASTLE OF SESIMBRA

Considering the previous experience in which information proved to be unproductive, the Castle of Sesimbra was chosen for executing further studies. Stating differently, all previously collected information could not be used for processing, since unspecific camera positions for photographing were yet undetermined, and no photogrammetric processing could be achieved due to lack of overlap between images. Beyond that, a more user-friendly pole was desirable.

For the first few recording sessions at the new site, a 2m metallic demountable rod was utilized with a wired remote shutter. Unlike in the the Castle of S. Jorge, in the Castle of Sesimbra, there were far fewer visitors, thus promoting a safe work environment in which the surveyor could focus entirely on the study.

Being aware of the lack of skills when photographing, the first part of the study consisted in acquiring photography skills: to approximately know what the camera was seeing in terms of coverage and from a remote position. The acquisition of the two skills required effort, especially the latter one.

As the photography skills were being honed, specific positions were determined simultaneously. Such a step was crucial for making a photogrammetric model because not only it is required to have overlap between photos, but also it is required to know the maximum angle between each photographic position. Trial and error were constant.

Note that the requirements for making a 3D reconstruction may vary from software to software. Specifically, different software can generate more coverage and more points while using the same photographs as input. Moreover, different software programs have dissimilar settings for thresholds, such as the angle between photographs and minimum overlap. Some of these thresholds may be changed and others may not. The operator must study deeply all these dissimilarities to benefit from the limitations.

Having in mind the differences, specific camera positions to record the battlements were calculated in such a way to allow all images to be processed in any software, at least with the ones being utilized: VisualSFM with PMVS and CMVS packages, VisualSFM with CMPMVS package, Apero/Micmac, and Pix4D software.

The photographic skills mentioned before were acquired quite successfully after a few attempts. They were even easier to acquire with a 2m demountable aluminium rod, which was lighter and easier to handle. However, the joint of the second rod weakened in a similar fashion as in the first rod. Therefore, a telescopic painter pole was acquired, and some tweaking was done to have a screw for attaching a photographic camera support. The telescopic pole offers more advantage than any of the previous poles, that is, the user can define the exact height by leaving a part of its extension inside the main pole to avoid bending. In fact, the two previous poles bent when held in the horizontal position due to stress in the material.

Once the photographic skills and a good telescopic pole were acquired, it was possible to proceed with the proposed hypothesis relating to the application of fisheye images to record complex elements commonly present in old heritage constructions.

For the accomplishment of such objective 7 specific positions were designated for each battlement: 3 positions in the interior; 3 positions in the exterior, and the last position being a nadir photograph from the top of the battlement. The angle between each position is approximately 30^{o}. Meaning there is an arc of photographs and an angle of 180^{o} between the first and last images. *See Figure 24, images identified with the letter D.*

The reason for specifying positions is to study the effects of the FOV accurately in one of the axes. In this case in the horizontal direction along the chemin de ronde because the photographic positions were defined along an arc parallel to a vertical plane.

Having 3 positions both in the interior and exterior of the battlements offers good overlapping between photographs. More than that, photographs from adjacent battlements are used to complete missing information. The last situation has different effects depending on the lens being utilized. The different approaches are presented.

Exercise - 18mm for Recording Battlements:

For the 18mm lens, 2 divergent photographs were acquired for each designated position of the arc of photographs, in addition to recording 3 images from another top position between the merlons to capture the lower horizontal surface of the crenel. See Figure 24, all images identified with the letter A, image D1, and the two outer camera positions in D2. Each pair of divergent photographs was shot in such a way that there would be approximately an 80° between their principal axes. A total of 17 images per battlement were necessary for a full reconstruction.

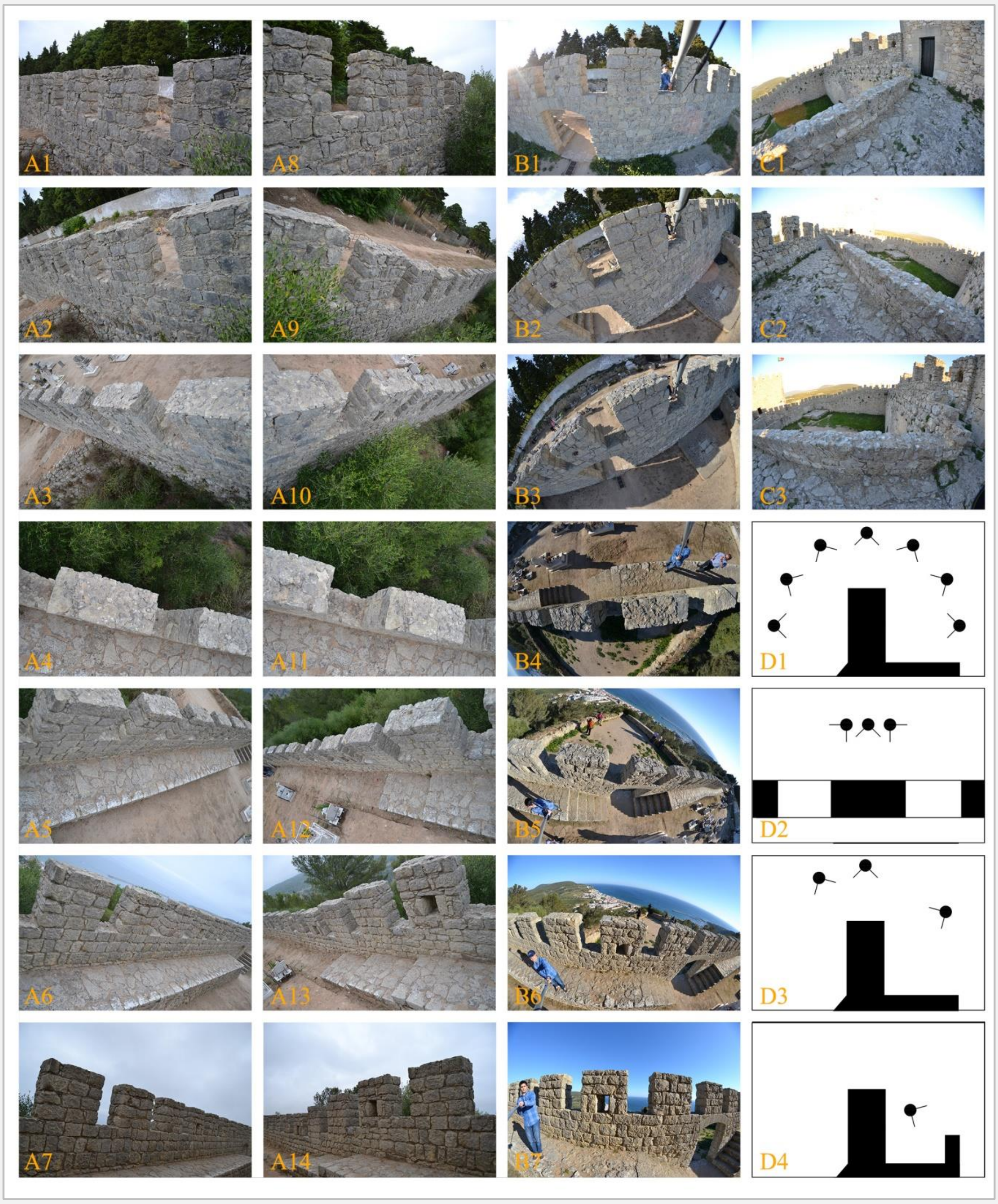

Figure 24: Strategy and sample images taken in the Castle of Sesimbra. Group A: 18mm wide-angle lens. Group B and C: 8mm fisheye lens. Group D: Camera positions.

It is important to note that each set of images, from each battlement, does not represent said battlement but adjacent ones. Therefore, if a specific battlement is to be reconstructed, the surveyor must photograph 3 adjacent battlements from each side. The reason for this is related to the FOV granted by the 18mm lens. If perpendicular photographs were to be acquired, the side faces of adjacent battlements would not be captured. Otherwise more photographs would be needed. Moreover, since battlements are made of random rubble masonry it would be hard to captured irregular features of every stone. Therefore, by obtaining images obliquely fewer images are needed and higher coverage is achieved.

Exercise - 8mm for Recording Battlements:

For the 8mm lens only 1 perpendicular image per position was required, that is, 7 images in total per battlement. See Figure 24, all images identified with the letter B, image D1, and middle camera position in image D2. Unlike the 18mm images, each fisheye image captured the lateral surfaces of adjacent battlements. The final 3D model was fully reconstructed and presented more coverage than the 3D model generated with the 18mm lens. Moreover, less care is needed to position the photographic camera in the estimated positions. Indeed, for the 18mm lens, the surveyor must be in a constant effort if a digital reconstruction is to be successful. In short, for the fisheye lens less than half of the images were needed to produce the same results and with less effort, revealing to be more user-friendly and time-saving.

Exercise - 8mm for recording Battlements Efficiently:

Even though the previous study resulted in extremely positive outputs, it was decided to further investigate the potential application of fisheye images. The previous tests were executed while having in mind the 7 specific positions, however, as fisheye images offer a lot more coverage it was opportune to study how far the operator can benefit from the FOV provided by the fisheye lens. Thus, after a few attempts, it was determined that 3 positions are enough to create the same results as obtained before, in terms of coverage. *See Figure 24, images B2, B4, B5, and D3.* However, the surveyor required 2 to 3 parallel images per position instead of 1 image per position, that is, a total of 6 or 9 images per battlement. By decreasing the number of positions but at the cost of increasing the number of photographs, it becomes more user-friendly and time-saving. The aluminium telescopic pole is locked to a specific position and the photographs are acquired swiftly. With this method, a 3D model was created successfully. It is important to note that all images must be obtained with the camera facing slightly downwards so there may be overlapping area between images. It may be noticed that in all fisheye images the operator and the telescopic pole are represented. This is not problematic because the software interprets such information as spurious and a clean reconstruction is achieved unless more than 2 images are obtained approximately from the exact same position.

Exercise - 8mm for Surveying Parapets of Chemins de Rondes:

Another study was conducted to include parapets of the chemin de ronde. The Castle of Sesimbra and Castle of Tomar have parapets and the available width for walking on the chemin de ronde is very short – between 70cm and 90cm, sometimes even 50cm of width. If a person stumbles upon another, each person must move through sideways.

Such occurrence illustrates how complicated it may be to execute a recording project in such conditions with conventional lenses or TLS. It would be possible to use conventional images, although at least 15 times more images would be obligatory to acquire to compensate for the lack of coverage. The application of TLS is impossible because a minimum distance for scanning operation is required. Therefore, fisheye images are applied and studied to overcome the identified challenges.

Two dissimilar approaches were studied. The first approach consisted of acquiring convergent images. *See Figure 24, images C1, C2, and D4.* The second approach consisted in shooting images perpendicularly. *See Figure 24, images C3 and D4.* Both approaches yielded positive results, although the last approach used half the total number of images. No approach is the best, depending on the physical configuration of the object to record. Particularly, the first approach, in which oblique images are obtained, is best applied for extremely narrow spaces, while the second approach, in which perpendicular images are obtained, is indicated for narrow spaces.

Exercise - Camera Settings:

An important question, particularly from users who own photographic equipment and/or generated photogrammetric models, is related to the sharpness of the images.

Irrefutably, photographic camera lenses with long focal distances have an increased chance or added difficulty to acquire sharp images, which is related to the shortening of the range of focus. The studies executed in the context of the current thesis make use of extremely small focal distances that provide with extreme range of focus. For that reason, acquiring sharp images is unproblematic because adjustments are considered irrelevant as all objects in the scene are in focus, from ~30cm to infinity while utilizing the highest aperture value.

In addition, other advantages include the use of the photographic camera in automatic mode to control the shutter speed as it is the remaining feature affecting the sharpness of the images - during the recording of the battlements Sports Mode was selected to counter the inevitable shakiness of the telescopic pole. However, for indoor applications or low lighting conditions, sports mode significantly decreases shutter speed and generates blurry images. However, for outdoor applications automatic mode, is the solution to adopt because images are acquired while moving and obviates the need to adjust the camera settings for each image.

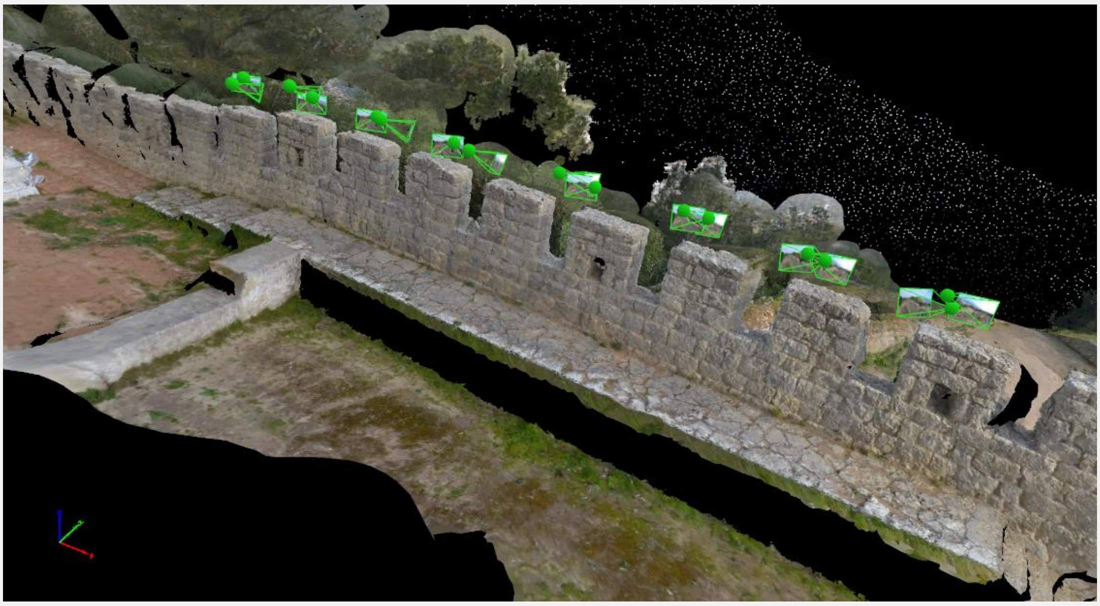

Figure 25: An example of reconstruction using merely 2 divergent 18mm images (wide-angle lens) from one specific position. Many surfaces are reconstructed but require too much effort to position the camera at the right position, otherwise side surfaces are not reconstructed.

RESULTS

The studies executed in the Castle of Sesimbra brought forth valuable results regarding the accomplishment of the main objective on the use of fisheye images to provide greater coverage and faster processing time, as opposed to the study executed in the Castle of S. Jorge.

3D models have been generated for both 18mm and 8mm images.

DISCUSSION AND CONCLUSIONS

Following a thorough analysis of the outputs, it is concluded that fisheye images are valuable to record complex elements when compared to conventional imagery, in which the recording of the battlements would have been hardly achieved even with the application of other surveying instruments such as TLS. The surveyor would need to station the TLS equipment for each battlement, not to mention the difficulty to capture exterior surfaces and substantially increased amount of time for data acquisition. The use of fisheye imagery accelerates the process of data acquisition compared to other surveying instruments.

The use of a telescopic pole obviated the employment of UAV in low flight conditions to capture information of the battlements. If UAV were needed, the pilot would require: outstanding piloting skills to counter winds while maintaining the drone in specific positions and require batteries beyond count since each flight duration is approximately 15 to 20 minutes.

Telescopic poles offer greater control and higher confidence during the photographic acquisition, thus increasing the likelihood of delivering high-quality outputs. Fisheye imagery allows greater flexibility and positive results because fewer images are acquired thus accelerating computing processes.

The execution of the study to record battlements, chemin de ronde, and parapets of the pathways, proved that fisheye imagery is a reliable source to execute photogrammetric projects with reduced total number of images, in addition to facilitating and reducing the time of photographic acquisition and processing of information.

Summary

i) The application of fisheye lenses is valuable to overcome specific challenges such as complex elements difficult to record and reduces the total number of photographs to generate a 3D model.

ii) The use of a telescopic painter pole with an adapter for photographic cameras is a good complement to allow photographing from specific POV while obviating the use of low flight UAV.

3.6.2. Exercise B - Igreja de Stº André

To further study the application of fisheye images to record complex elements at extreme close-range, it was decided to record the portal of the Igreja de Stº André, located in Mafra, Portugal.

This roman-gothic style church is one of the oldest buildings in the parish of Mafra and is considered a national monument (DGPC, n.d.-c). The main objective of the current study, as in the previous one, consists in the comparison of the efficiency between fisheye images and conventional images.

The portal of the church, which is architecturally composed of 4 nested arches supported on columns with few carvings, indicates the main entrance of the building. The portal has no tympanum nor a mullion, the shape is simple yet complex to gather information for it contains several recesses and corners. Therefore, two hypothesized approaches are presented.

EMPLOYED EQUIPMENT

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)
Wide-angle lens	(18mm focal distance)

Software:

Pix4Dmapper

METHODS AND CONDITIONS

The conditions to acquire and analyse the information of the portal are as follows:

i) The photographic camera must be mounted on a tripod with the purpose of acquiring photographs from stipulated positions due to the physical configuration of the portal.

iii) The stipulated positions must be parallel to the wall of the church, for each position the lens is changed, and a photograph is obtained with each lens.

iv) For a fair comparison of the results, the same software must be used to analyse the differences between every photogrammetric model.

THE HYPOTHESIZED APPROACHES

In the first approach, perpendicular photographs were acquired while having the photographic camera mounted on a tripod and positioned approximately 2m away from the wall. For each position, two images were acquired with each lens to minimize differences in POV. Proceeding in this fashion, it is possible to focus on analysing the coverage that each lens has to offer instead of questioning if potential differences existed due to the double positioning of the tripod on the same POV.

After acquiring and processing the photogrammetric models it is concluded that the model generated with fisheye images offers, as premeditated, higher coverage at the margins of the model than the model generated with wide-angle images. For example, the model generated via the use of fisheye images captured information of the floor.

Regarding the total number of reconstructed points, the fisheye model has 1,4 million points and the model generated with the use wide-angle images has 2,7 million points. The difference in the total number of points is due to higher FOV provided by the fisheye lens, that is, the GSD value is higher affecting the total number of detected homologous points. Stating differently, the wide-angle lens provides images with higher pixel resolution, resulting in a denser point cloud that is visually better because more details are detected. *See Figure 26, the two images on top.*

For the second approach, no tripod was utilized with the objective to mimic a typical photographic acquisition by handling the photographic camera and to determine if good outputs are obtained. For that purpose, 9 camera positions forming a convergent arc that is extremely close to the door were determined. Photographing at such distance allows studying if fisheye imagery offers the possibility to deliver outputs more efficiently relative to those outputs generated with conventional imagery.

To study reconstruction differences it was defined the computation of four models. The first model used 9 wide-angle images as input, the second model used 9 fisheye images as input, the third model used 4 fisheye images from the originally 9 calculated positions, and the fourth model used 4 wide-angle images acquired from the same POV as the third model. Due to the lack of overlap between images, the last model was unsuccessfully generated. *See Figure 26, the bottom 4 images.*

After a thorough comparison of the outputs, it is notorious that the models generated with fisheye images require fewer images – 4 images in the third processed model - to achieve a successful reconstruction of the same area of interest. However, on close inspection, minor geometric inconsistencies are visually detected.

The experiments, performed at extreme-close-range distance to study the performance of fisheye images versus the application of wide-angle-images, reveal that the operator has the possibility of utilizing fewer images to generate a model of a specific area with the use of fisheye images. However, taking such practice to extreme extents, in which too few images are utilized,

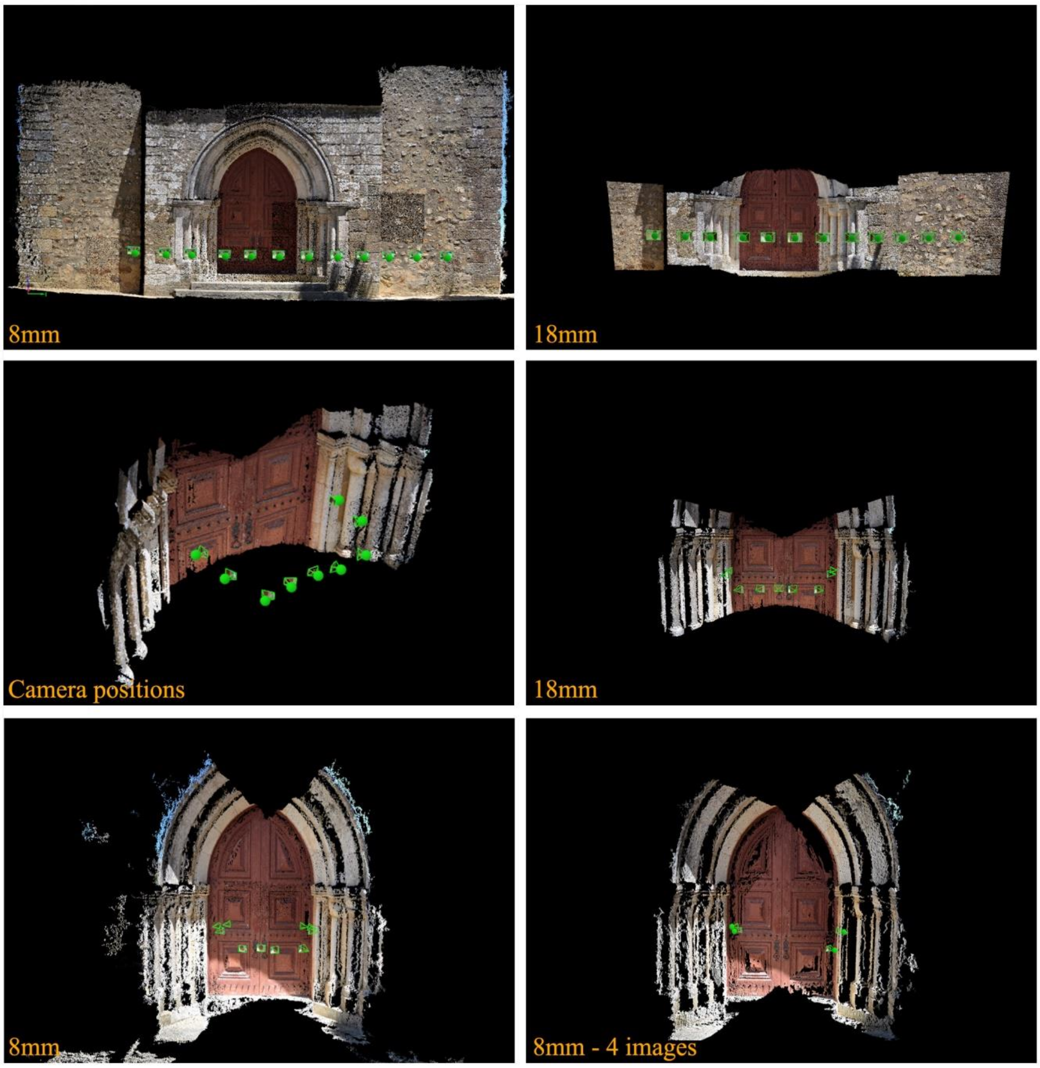

Figure 26: Igreja de Stº André. Comparison of the photogrammetric models generated with images acquired with 18mm and 8mm lenses.

as expected, a model with low geometric consistency is generated, as in the case of the third model computed with 4 fisheye images. Quasi-equivalent quality of outputs is obtained when utilizing too few conventional images as well. However, models generated with conventional imagery have lower coverage but higher geometric consistency near the margins of the model due to the lower variance of the GSD values, as opposed to fisheye images, whose GSD values decrease significantly the closer the pixels, are to the margins of the image.

In sum, to generate a model with higher coverage and fewer images as input, geometric consistency and density is sacrificed due to inevitable high GSD values mainly on the margins of fisheye images. Nonetheless, models with lower geometric consistency only occur in the current study because it is purposefully studied the limits of photogrammetric applications. Differently stated, in typical photogrammetric projects numerous images of the object of study are obtained that contribute to reconstructing a more geometrically correct model. Yet, models generated with fisheye images provide with lower density when compared to models generated with the use of wide-angle images. For example, the point clouds of the battlements *presented in the current section* were generated with fewer images and have the equivalent geometric consistency to the point clouds generated with wide-angle images.

RESULTS

The execution of the current study in the Igreja de Stº André resulted in the processing of several small-scale photogrammetric models of the portal from which the potential application of fisheye images to record complex elements is examined. Simultaneously, it is inspected the density and coverage provided by each type of images in use.

DISCUSSION AND CONCLUSIONS

From the study, it can be concluded that it is possible to use fewer fisheye images when compared to wide-angle images so to benefit from higher coverage in close-up situations but at the cost of point cloud density, which is directly related to the differences in GSD provided by each type of imagery.

When comparing the second approach to the first one, it is evident that while photographing farther away, approximately 10m, the use of a fisheye lens is not efficient due to lower pixel resolution. For that reason, another type of lens is preferred, such as wide-angle lens.

The execution of the current study brought to light one of the best uses that fisheye images are suited for to acquire divergent images due to its high FOV. Since the Igreja de Stº André required mostly convergent images, a wide-angle lens is the best solution to perform the recording. However, fisheye images offer other remarkable advantages. For instance, during the recording of the battlements, in which fisheye images were obtained perpendicularly to the surfaces, said images are the equivalent of two to three divergent images acquired with a wide-angle lens – considering coverage merely in the horizontal plane, and disregarding the vertical direction.

It can be concluded that for common applications fisheye images are utilizable, or as the distance from the surveyor to the object decreases the usability value of fisheye lenses increases relative to other conventional lens types, majorly due to increased FOV. Evidently, the usability of fisheye lenses is only plausible if images are within established GSD of the project, as fisheye images offer higher values of GSD and thus lower point cloud density.

Despite all advantages and disadvantages, a study on the geometric quality of point clouds delivered via the sole use of ultra-wide-angle images must be executed. Such study is crucial to determine if the advantages of fisheye images outweigh the lower geometric integrity of the outputs, if that is so. The pix4d team demonstrated through their own studies the validity of utilizing ultra-wide-angle images, whose geometric accuracy is within a range of 10 cm for an acquisition distance of up to 15m from the object. Pix4D further notes that accuracy values tend to be lower when not utilizing tripod or lenses that provide with increasingly higher FOV (Strecha et al., 2015). In the context of the current experiments, fisheye lenses are used at extreme close ranges up to 50cm, in which GSD values are lower thus contributing to more accurate reconstructions.

Summary

i) The application of fisheye lenses is valuable to overcome specific challenges such as complex elements difficult to record, or even impossible to record with conventional surveying equipment.

ii) The most positive application of fisheye images is the possibility to replace divergent photography taken with other types of lenses, thus reducing the total number of images for modelling. Able to convert at least 2 divergent images to 1 image.

iii) Although photogrammetric point clouds are visually consistent, even at close inspection, a study on the geometric consistency is required to understand if fisheye images deliver outputs with minimum accuracy. Pix4D performed experiments in which images were acquired up to 15m of distance from the object, while in the current thesis images are acquired down to 50cm of distance.

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3.7. RECORDING OF NARROW OR HARD-TO-REACH SPACES

RESEARCH PURPOSE

Executing photogrammetric projects of morphologically complex constructions can be an arduous task, particularly when the surveying equipment is unable to record surfaces of interest from spaces that are seemingly impossible to record.

Previous experiences highlight positive aspects and the potential application of fisheye images to record complex elements, to photograph at extreme close range, or to replace the use of conventional lenses when acquiring divergent images. Nevertheless, it is hypothesized if the application of highly distorted images is plausible to acquire information of narrow spaces or hard-to-reach spaces. In previous experiments, such as the recording of the parapets of the Castle of Sesimbra, the issue related to the proposed hypothesis was lightly addressed.

In the current study, a thorough study is presented to discover the limits on the application of fisheye images to record extreme close-range spaces or objects up to 50cm of distance from the surveyor. To test the proposed hypothesis 2 sites that are exceptionally difficult to record were selected: *(EXERCISE A)* A spiral staircase of The Convent of Christ; *(EXERCISE B)* and the Convento dos Capuchos, in Sintra, Portugal. The latter exercise was executed after the staircase case study. Not only it was selected to test the use of fisheye lenses to record narrow spaces but also for logistic purposes, that is, to execute a recording session as fast as possible of all interior spaces in one day.

The results of the study demonstrate the true limits of utilizing fisheye images to record not only morphologically complex constructions but also constructions whose lighting conditions are extremely poor. Most importantly, it is revealed how constructions that apparently seem impossible to record are, in fact, possible to record. It is also brought to light the pressing need of disseminating and making known the use of the current photogrammetric methods for it allows to better premeditate actions of conservation, restoration, and rehabilitation of constructions.

Research Question

The application of fisheye lenses provides with reliable information of hard-to-reach and/or narrow spaces that are exceptionally difficult or even impossible to record with other surveying instruments?

Key-Words

Close-range-fisheye photogrammetry; Close-range-photogrammetry; Fisheye Lenses; Wide-Angle Lenses; Narrow Spaces; Hard-to-reach spaces.

General Methods and Conditions

With the objective of evaluating the application of fisheye images to record narrow or hard-to-reach spaces, some conditions are imposed:

i) During the fieldwork phase, it must be considered the total number of photographs, the time for recording, and, above all, if the photogrammetric methods for acquiring the images are user-friendly.

ii) In addition to the previous point, during the office phase, a 3D virtual reconstruction should be executed from the acquired images not only to verify the possibility of generating outputs but also to visually verify the geometric integrity of the model.

iii) While recording it should be noted patterns on the application of fisheye images in close-range fisheye photogrammetry that may lead to new hypotheses.

iv) The recording must be applicable to other photogrammetric projects and must also be quantity-efficient to prevent processing delays during office work phase.

3.7.1. EXERCISE A - SPIRAL STAIRCASE OF THE CASTLE OF TOMAR

To test the proposed hypothesis the spiral staircase of the Castle of Tomar was selected. The staircase, being a typical example of other spiral staircases in The Convent of Christ, completes two full 360º turns and is so characteristically narrow that only one person can climb it at a time. Two experiments with distinct approaches were considered.

Considering the physical configuration and the possibility to acquire an incomplete photogrammetric model or no model at all, the first experiment was executed without much forethought or planning. Surprisingly, a successful reconstruction was achieved. During the second recording phase images were acquired methodically and a full reconstruction was calculated.

EMPLOYED EQUIPMENT

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)

Software:

Pix4Dmapper

METHODS AND CONDITIONS

The methods and conditions for acquiring and analysing the information of the spiral staircase:

i) The photographic acquisition must be swift and user-friendly.

ii) In addition, the least number of images should be captured to avoid generating a time-consuming photogrammetric model.

iii) Not only there should be a successful reconstruction of a photogrammetric model, but also said model must have full coverage.

THE TWO EXPERIMENTAL APPROACHES:

During the first immethodical recording session, one row of images was acquired while climbing down the stairs and with the photographic camera pressed to the body of the surveyor.

One image was obtained for each step climbed down. The space is so narrow that the leg of the surveyor and the tip of the shoes are present in some of the images.

It is important to stress that images were acquired without considerable caution since time was limited, and no reconstruction was expected. The ideal method to record should be photographing while climbing up to capture the ceiling, the risers of the steps, and the spiral column. An incomplete 3D model was generated. For that reason, another recording session was of pressing need to discover the limits on the application of highly distorted images.

During the second recording session, the images were acquired while climbing up the stairs. Three rows of images were obtained: one with the camera pointing a little to the right to capture the wall; another with the camera pointing to the left to capture the column and stairs;

Figure 27: Spiral staircase of The Convent of Christ. Images on the left represent a digital reconstruction. On the right side are the sample images to compute the reconstruction.

and a last row of images to capture the ceiling. Specifically, 3 images were acquired for each climbed step. Additional images were obtained at the transition areas in a convergent pivot around the jambs of the door.

A total of 131 photographs were captured and a complete 3D model was successfully generated. *See Figure 27*. The recording and processing were easily achieved because efforts were brought forth to produce a plan for photographic acquisition. Furthermore, neither the legs nor the shoes of the surveyor were captured as opposed to the first photogrammetric acquisition.

RESULTS

Contrary to initially expected, the use of a fisheye lens to record objects from 50cm or 1m of distance - in a typical extreme close-range situation, such as a spiral staircase in the Convent of Christ - yielded a reconstruction with full coverage and considerable high level of detail.

DISCUSSION AND CONCLUSIONS

During the beginning of the experiment, it was highly doubted that a successful reconstruction, even with fisheye images, could be achieved. Such prediction proved to be false.

It can be stated that narrow spaces, such as the one presented in the current study, are possible to be recorded using a wide-angle lens, but at the cost of increasing, theoretically, the total number of images by at least 15 times to generate a 3d model with the same coverage. Similarly, the use of TLS would be ineffective, considering that the legs of the tripod would require adjustment for every station, not to mention lack of manoeuvrability, the total number of stations, and minimum distance for scanner operation. Stated differently, capturing information in extremely narrow spaces proved to be highly efficient with the application of fisheye images.

It is vital to bring to light how impactful the application of fisheye images is to capture information of constructions that are seemingly impossible to record. Beyond that recognition, it is important to bring forward a topic of interested related to the normal expectations of the average surveyor, who makes use of conventional surveying instruments: if in the current thesis it is purposefully utilized highly distorted imagery to capture objects at extreme close-range, and the surveyors are surprised as to how information can be obtained at such extreme close range situations, what are the expectations of the average surveyor when attempting to record objects at extreme close-range scenarios. In short, the use of fisheye images is beyond expectations even for those who make use of said images.

For this reason, as it is discovered new possibilities to record morphologically complex elements with fisheye images, it is thought of the responsibility to diligently bring to light the whole range of applications of fisheye images that are, to some extent, not considered to its full potential, even though its application is known not to be new. In other words, the perceived value of the application of fisheye images, at least from our experience and related case studies, seems to be lower when compared to the true value of its application.

SUMMARY

i) The whole potential that fisheye images have to offer is yet to be fully explored.

ii) The application of fisheye images for photogrammetric purposes is beyond expectations and provides with positive results, particularly for exceptionally narrow spaces.

iii) The application of fisheye images for close-range fisheye photogrammetry should be disseminated and recognized by other surveyors for it offers the possibility of recording vital information of spaces thought to be impossible to record.

3.7.2. Exercise B - Convento dos Capuchos

After the discovery of potential applications of fisheye images by recording a spiral staircase of The Convent of Christ, it was decided to take the application of fisheye images to the very extreme. For that purpose, the Convento dos Capuchos, located in Serra de Sintra, Portugal, was recorded as it is well known for its remarkably small-sized interior spaces, and extreme-narrow corridors. It is also known as “Convento da Cortiça” (Convent of Cork) because it uses cork to protect and decorate its spaces.

The primary objective of the study consisted in confirming if fisheye images are utilizable to record exceptionally narrow spaces, that cannot be recorded efficiently with other surveying instruments. In addition to the main premise, a secondary objective consisted in executing the recording in only one day for logistic purposes and to refine the planning skills of the surveyor.

Due to the secondary objective, the major challenge was time management, in which the surveyor, having merely 4 hours, had to study the site, look for potential problems, estimate camera positions, prepare a good plan, and execute the recording. Bearing such in mind, the first four steps would need to be completed as fast as possible, so more time could be spent on executing the recording. It is essential to stress that incomplete information was expected, apart from the impossibility to acquire images of the roofs for a UAV would be required.

Employed Equipment

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)

Software:

Pix4Dmapper

METHODS AND CONDITIONS

The methods and conditions to acquire and analyse the information of the Convento dos Capuchos are as follows:

i) At first, a study of the site must be carried out to identify its characteristics, as well as eventual difficulties and disadvantages with respect to the application of the photographic equipment.

ii) In the next phase, solutions must be proposed for all detected problems and estimate spaces possible to record given the time-constraint of 4 hours.

RECORDING OF THE CONVENTO DOS CAPUCHOS

Located in a forested and mountainous area with massive rocks, The Convento dos Capuchos is isolated on the slopes of the Serra de Sintra and is extremely integrated with nature, and thus shaped according to the topography of the terrain while also incorporating local large stones, sometimes sculpted to shape its indoor spaces.

Observing the complexity of the environment, the first step of the recording session consisted of discovering the site, while noting imposing limitations for the execution of the recording. From experience, first-time visitors may feel lost as the building develops longitudinally, encompassing a main narrow zigzagging corridor shaped according to the elevation of the terrain, and that connects to most of the irregular shaped interior spaces positioned at roughly 3 different levels of altitude. *See Figure 28, bottom image.* The main corridor leads to secondary corridors and exterior pathways and halls. All indoor spaces are indistinguishably tiny, particularly the doorways of the bedrooms of the monks that must be crossed while kneeling and with the head lowered - yet, it is required to squeeze through uncomfortably. Such physical configuration portrays the withdrawn living style in a shadowy atmosphere with rooms poorly decorated with cork (DGPC, n.d.-b; SIPA, n.d.). The height of the doors is approximately 1,3m, and the dimensions of the bedrooms are approximately 2m per 1.5m. All other doors, still small, vary from 1.6m up to 1.8m in height. In the remaining indoor spaces, it is possible to stand up comfortably, although the ceiling is low, and the corridors are extremely narrow. From the exterior, the complexity of all indoor spaces is noticeable by observing the multitude of roofs. *See Figure 28, top image*.

The most logical approach to record the site within a limited time-window is to hold the photographic camera against the body of the surveyor while taking advantage of the high coverage provided by the fisheye lens. For this endeavour, the surveyor needed to lean against the wall to photograph perpendicularly the opposite wall. Though, for exceptionally narrow spaces the photographic camera must be placed obliquely to guarantee enough coverage and

Figure 28: Convento dos Capuchos. Illustration altered from the original leaflet of The Convento dos Capuchos created by Anyforms. Top image represents the configuration of the site. Bottom image illustrates the interior spaces.

overlap between images. On close inspection of the collected data, the body of the surveyor is sometimes visible in the images, revealing how narrow spaces are.

To minimize the total number of images, the acquisition followed a structured method. The photographic camera was pointed to the 4 specific positions: pointing to edges of the corridor, that is, to where footers and crown-mouldings would exist. In general, for each small step, approximately 30 cm, 4 photographs were acquired to have full coverage. It can be thought as the acquisition of images fitting in a plane perpendicular to the longitudinal axis of the path to follow. *See Figure 29, images identified with the letter A.*

It is significant to point out that before starting the recording, not only the acquisition of the images followed a structured approach, but also photographs were acquired in the same pattern to ease the organization of said images in groups during the office phase. Therefore, each group of images contains images of one room or transition images. By adopting such method, quality assessment of the data and detection of problematic images is executed faster.

However, some challenges were found that compromised the execution of the plan and are related to the lighting conditions of the site. Low light enters the spaces due to small windows. Some spaces are dark or even pitch black. This was a critical problem to address because there must be light to acquire images. However, since the site is open to tourists, the Convento dos Capuchos is equipped with hose lights for guidance in most of its indoor spaces. Although not that great, the hose lights provide with enough light to obtain photographs without a tripod.

Nevertheless, due to a high dynamic range of the scene, even within the same room, the photographic camera had to be configured to be fully automatic. This way additional time is unneeded to manually adjust the settings constantly. Most of the hose lights emitted a yellowish to reddish light and are distributed along the floor thus making the ceiling darker. For this reason, when photographing, the camera should not be pointing at the hose lights, otherwise, the dynamic range is adjusted for that light intensity creating images with said hose lights well represented and the remaining surfaces with very dark tones. The same logic should be practised when photographing windows. See Figure 29, images identified with letters B and C. Therefore, the camera is pointed at areas that are with mediocre light intensity. The most difficult images to acquire were those corresponding to the transition between rooms with distinct light intensity.

Considering all the previously mentioned aspects, more than 2000 images were collected, most of which depicting interior spaces. The roofs were not photographed for they were a difficult task, only achievable with the use of a UAV.

During the office phase, and before processing, the images were sorted into folders, each of which corresponding to a specific room. Next, a backup copy is done. From each folder, redundant and unsuitable images are removed. After the clean-up procedure, the total number of images decreased to 1891. The clean-up process is convenient if the time invested in reduces greatly the photogrammetric processing time. The major advantage is a quality assessment of the recorded data, in addition to: having information organized; facilitating the workflow; to detect which images failed to reconstruct; and to easily revisit the data by other operators.

Figure 29: Sample images of the Convento dos Capuchos and images of the digital reconstruction. Group A: Camera positions - note the slight lighting variation and the body of the surveyor; Group B and C: Hose lights and the problem of pointing the photographic camera at very dark or very lit areas; Group D: D1, dense reconstruction; D2, a plan view of the sparse reconstruction including camera positions.

It should be noted that many of the collected images are blurred because the photographic camera was held by the surveyor instead of being mounted on a tripod, in addition to the shutter speed being approximately 0.5 sec. To capture with sharpness a tripod should be used, although such operation would increase the time for data acquisition. If time was not of the essence, a tripod would have been used to capture HDR imagery thus providing high-quality data. However, since the images are within an acceptable range of sharpness the proposed approach is disregarded.

Once all images were organized and categorized, they were processed. A digital reconstruction of a global model failed perhaps due to a lack of transition images or due to clipping of highlights and shadows in several images. Yet, multiple attempts were made to create a global project with the maximum possible images. Seeing that it would be counter-productive, merely photogrammetrically decent images were selected, which corresponded to corridors, hallways and halls that were lit by hose lights or natural light. From 642 images 533 were used to create a successful reconstruction. Visually, the model displayed geometric congruity and good coverage. *See Figure 29, images identified with the letter D.*

All aspects considered, such as the extremely narrow and small sized indoor spaces, the execution of the current study proved to be a valuable source of experience for the surveyor, and a fundamental case study, if not the most important case study to confirm the plausibility on the application of fisheye images for close-range fisheye photogrammetry.

RESULTS

Given the conditions to proceed with the recording, and even though much of the collected data is of medium quality, it was possible to photograph most interior spaces and generate a partial photogrammetric reconstruction of the Convento dos Capuchos. In the end, results are positive and within expectations, providing with valuable information on how to proceed with future photogrammetric data acquisition.

DISCUSSION AND CONCLUSIONS

The recording of The Convento dos Capuchos, being an extension of the study of the spiral staircases of The Castle of Tomar, proved that fisheye images are a valuable source to obtain information of exceptionally narrow spaces in large-scale projects, even when lighting conditions are unfavourable.

Reconstruction of a 3D model was successful while using slightly blurred fisheye images. In this sense, and from experience, a complete photogrammetric model is possible to compute with imagery of higher than average quality, obtained with the use of a tripod or with a more careful approach.

Furthermore, the recording of The Convento dos Capuchos demonstrated to be a fundamental study to exponentially increase the experience of the surveyor, since it improved logistic skills to detect problems, find solutions, engineer a plan, and understand thoroughly the performance of photographic cameras.

SUMMARY

i) It is believed the major advantages of using fisheye images for close-range fisheye photogrammetric purposes have been explored.

ii) The application of fisheye images proved to be outstanding, particularly to record exceptionally narrow spaces, even under unfavourable lighting conditions.

iii) Recording the Convento dos Capuchos provided with valuable experience to be used in the main case study, The Castle of Tomar.

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3.8. Proposal of Contiguous Transitions and Remote Transitions

Research Purpose

A significant issue mostly present in photogrammetric projects is related to the alignment or correct geometric contiguity between features of a point cloud. Despite the desire from the surveyor to process a single global project containing all photographs as input, there will always and inevitably be complications, thus sub-projects must be generated and merged into a single project. Said complications may be related mostly to the physical configuration of the site that impedes standard recording procedures. The problem of merging sub-projects is increased risk of higher geometric inconsistencies, such as curved models, misalignments, and so on. Therefore, it is discussed two methods of proceeding with the photographic recording, "Contiguous Transitions" and "Remote Transitions", to increase the likelihood of generating a photogrammetric model in one run instead of merging several sub-projects.

The situation of processing multiple subprojects may occur due to how the images were acquired; hardware limitations; threshold limits associated with the software settings; or a combination of any. Ergo, when merging "contiguous" or "remote" sub-projects, proper alignment may not occur because of erroneous point reprojections, lack of overlap between images, or no image matching because of high difference in GSD values. Such a topic is of great concern when surveying equipment is not able to acquire contiguous overlapping information thus requiring other approaches and methods to generate results with quality.

The Castle of Sesimbra and The Castle of Tomar are used as examples for discussing "contiguous transitions" and "remote transitions".

Research Question

Is it possible to process a consistent photogrammetric project using scattered sets of images instead of contiguous sets of images?

Keywords

Contiguous Transitions; Remote Transitions; Digital Photogrammetric Reconstruction.

General Methods and Conditions

The execution of the current study must follow the current conditions:

i) The photographs must be acquired in a methodical way to obtain different sets of images to facilitate the office work phase.

ii) Reconstructions must be executed to corroborate the proposed photogrammetric recording approaches.

Employed Equipment

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)
Wide-angle lens	(18mm focal distance)

Software:

Pix4DMapper Discovery

3.8.1. Proposal for Contiguous Transitions and Remote Transitions

To discuss the possibility of generating a photogrammetric point cloud in a single and global computation, it is desirable to distinguish two conceivable types of connections between data sets. Stated differently, it is vital to know if the collected datasets are scattered or neighbouring to consider the possibility of applying a "remote transition" or "contiguous transition". It is possible to have a dataset defined as both categories as it can have one or more parts connecting contiguously, and another part connecting remotely. Note that by datasets it is conveyed the idea of groups of photographs containing information of a single surface, or even information of a whole area containing several surfaces. For convenience purposes, sub-datasets will be used for single surfaces and datasets for groups of surfaces.

From experience, and apart from features present in the site that may difficult the acquisition of images, such as recessed spaces, complex volumes, or inaccessible locations, the site may present with accessible locations to the surveyor but that is inaccessible photogrammetrically due to FOV limitations. For this reason, two distinct types of transition are discussed: i) "contiguous transition" - overlapping images photographed side by side and with little to no variation in the focal length values, thus resulting in images with the same GSD values or progressive changes in the GSD values; and ii) remote transition - overlapping images acquired at varying distances and from the same line of sight or close to the same line of sight, that is, with the use of different focal length values.

Particularly, when recording two adjacent walls in an indoor room, the surveyor photographs each wall separately and then acquires "regular transition photographs" that contain information of both walls. The "regular transition images" act as a connecting element for the two adjacent sub-datasets. Such occurrence is within the definition of "contiguous transition", that corresponds to overlapping of images side by side as mentioned in the 3x3 photogrammetric rules (Waldhäusl, P., Ogleby, C. L., Lerma, J. L. & Georgopoulos, 2013; Waldhäusl & Ogleby, 1994).

Per contra, "remote transition" is the merging of scattered datasets and/or sub-datasets, instead of merging neighbouring information. Such type of transition is achieved by utilizing diverse focal lengths incrementally, forming a chain of photographs with progressively higher or lower GSD values.

Figure 30: Top images, 8mm, 18mm, and 50mm respectively, represent a remote transition between two discontiguous datasets with the use of the keep as an element of transition. Bottom images represent a remote transition to capture information with higher detail.

For example, situationally during the recording of the Castle of Tomar some paths unallowed the acquisition of contiguous images due to inaccessible direct connection between adjacent paths or spaces. For that reason, the keep was used as a reference to attempt a transition between two image datasets. *See Figure 30, top three images.* In addition, performing remote transitions allow the possibility to lower the GSD to capture construction details. For example, a longer focal length lens, 55mm, was used to capture in higher detail the rope elements on the walls, which are typical Portuguese late Gothic architectural decorations. *See Figure 30, bottom 2 images*. It is fundamental to note that in the second example the recorded information is not used as transition element to combine scattered datasets but is the main target objective instead.

It is conveyed the idea that remote transition method can be utilized for diverse purposes. Stated differently, the break in the chaining of images that impede the reconstruction of a photogrammetric model in one processing is overcome via the use of remote transition method to produce a global model, and thus higher geometric integrity as camera values are better calculated.

From experiences performed on the field, the ratio between focal length values should not be higher than 2.5 times approximately, while taking as reference the lower focal length lens. Specifically, to combine a set of images acquired with an 18mm lens, the surveyor must use a lens not higher than 45mm of focal length. If higher focal length values are utilized, such as experienced with the use of a 55mm lens, the surveyor must step backwards from the same POV to increase the GSD and thus allow image matching algorithms to process with positive results. Studies have to be executed to further verify with a high level of precision the limits on the application of remote transitions, that is, the difference of the focal length values. For now, the 2.5x ratio should be taken as a suggestion.

The proposed remote transition method is a good solution to generate outputs with higher geometric integrity. That is, the typical solution to combine scattered image datasets is to generate separate models and posteriorly merge by selecting homologous points. The problem of such an approach is the possibility of generating models with lower geometric precision, and the possibility of having misaligned models not detected through visual inspection. In short, processing a global project with all datasets as input, the software synergistically corrects image calibration parameters to generate a model with higher geometric accuracy.

In the context of the current thesis, one of the most interesting aspects of the use of fisheye images is their flexibility. That is, images can be used simultaneously to make contiguous

Figure 31: Sample images taken in the tower of the Castle of Sesimbra. Group A: 8mm fisheye lens; Image B: Point cloud generated with fisheye images. Group C: 18mm wide-angle lens.

and remote transitions due to its high FOV. *In Figure 31* it is illustrated the acquisition of images to perform a transition from an outdoor space to an indoor space in the keep of The Castle of Sesimbra. Images acquired with the 18mm lens did not generate a reconstruction of the transition space via the use of contiguous images. *See Figure 31, images identified with the letter C.* Acquiring remote transition images proved to be impossible because the FOV did not allow the recording of both the remote background surface and the transition surface of interest. However, the use of a fisheye lens allows to successfully reconstruct the transition area in two distinct methods. For example, contiguous images can be obtained while pointing the camera perpendicularly to the transition surface of interest. *See Figure 31, images identified with the letter A and B.* Alternatively, due to high FOV, the same fisheye image can contain the transition surface of interest and a remote surface to ease the reconstruction.

In short, the application of several types of lenses with varying focal length values creates the possibility to generate a global model in one processing if considering the two proposed transition methods. Furthermore, having in mind the two types of transitions during a photogrammetric recording, the surveyor is mentally equipped to record more efficiently as he is encouraged to deconstruct the objects into its simple parts.

RESULTS

Two transition methods – "contiguous transition" and "remote transition" - were experimented and significant results are noted. While the two transition methods can be used to connect surfaces or areas with ease, particularly with the application of fisheye images both in close-range and extreme-close range situations, lower flexibility is noted when utilizing wide-angle images. Even though fisheye images provide greater flexibility, higher and lower GSD values are obtained.

Partial digital reconstructions were successfully obtained by using fisheye images while transitioning from outdoor spaces to indoor spaces. However, the same scenario was incomputable for the group of wide-angle images due to lower FOV.

DISCUSSION AND CONCLUSIONS

It is beyond uncertainty that acquiring numerous images of a morphologically complex construction decreases greatly the possibility of generating a single global model in one computation. Complexity, in this context, not only relates to the difficulty of acquiring information about specific construction elements but also relates to the image matching between distinct data sets that may be scattered or contiguous.

For projects of considerable size, the probability of creating sub-projects increases, either due to hardware limitations or low image matching. Generating several point clouds requires posterior alignment thus increasing the chance of producing incongruent geometric data. Therefore, the application of the two proposed connection methods are advisable to obtain outputs with higher quality by processing all data in one operation, that is, the image parameters are refined more accurately.

For that reason, it is recommended to execute a well-structured photogrammetric acquisition, having all image datasets - scattered or contiguous – well interconnected. By well-structured it is referred to the idea of deconstructing the objects or buildings hierarchically into areas, sub-areas, and surfaces, to facilitate the surveying operation. The major advantage of applying such method is having a clear mindset, that in turn increases confidence as to the acquisition of positive results. Furthermore, Pix4D proved to be an efficient software as good quality outputs were generated.

Summary

i) Two transition methods are presented: “contiguous transitions” and “remote transitions” that are usable to connect surfaces or datasets of areas.

ii) When recording the site, the two transition methods should be taken into consideration for they allow to structure the site hierarchically thus increasing the likelihood of generating a geometric congruent model in one computation, instead of several sub-projects.

iii) Pix4Dmapper software offers high flexibility in regard to the alignment of several sub-projects and detection of correct image distortion parameters.

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3.9. Coverage and Topographic Recording

Research Purpose

The application of fisheye images is efficient to obtain information of narrow spaces, hard-to-reach spaces, and complex elements that seem practically impossible of recording at first inspection. Nevertheless, in the current study, it is evaluated the coverage of fisheye lenses to record medium-sized areas, such as indoor floors or exterior surfaces mainly for topographic purposes.

The idea of executing such exercise occurred as recording ground surfaces are atypical or uncommon in close range photogrammetric applications, mostly due to the low FOV provided by the lenses and impracticality of execution. Alternatively, TLS or aerial photogrammetry are frequently utilized to obtain information about the features in question. Therefore, the main objective consists in studying if it is plausible the use of fisheye images to generate photogrammetric point clouds of ground surfaces due to its higher FOV and when no other survey instruments are available in the inventory or are hardly utilized due to the physical configuration of the site, such as narrow spaces.

To confirm the proposed hypothesis, a comparison between photogrammetric models generated with fisheye images and wide-angle images is executed. The Igreja de Stº André was selected to proceed with the study due to its small perimeter, convenient to be used to control the acquired data.

It should be noted that other survey instruments such as TLS and aerial photogrammetry are better suited for recovering information of larger ground surfaces, as indicated in a guide by English Heritage (English Heritage, 2011), and that the main purpose of studying the current hypothesis is to determine if it is convenient the use of fisheye imagery to record, for the most part, indoor spaces and/or small ground surfaces in outdoor areas due to high FOV. For that purpose, it is compared the total number of reconstructed points vs the total number of images for the reconstruction. The scaling of the model is not considered in this exercise because the main scope is to corroborate the flexibility on the use of unconventional imagery vs conventional imagery.

RESEARCH QUESTION

The use of fisheye images to generate a photogrammetric model containing information on floors is an efficient or plausible approach when compared to wide-angle images and when no other survey instrument is available such as terrestrial laser scanning?

KEYWORDS

Topographic Surveying; Close-Range-Fisheye-Photogrammetry; Fisheye Images; Wide-Angle-Images.

GENERAL METHODS AND CONDITIONS

To evaluate the efficiency and efficacy between fisheye lenses and wide-angle lenses for recording ground surfaces, the next points are considered:

i) Obtaining images with the fisheye lens or wide-angle lens must be within the same conditions for an effective comparison between the results.

ii) As ground surfaces are to be recorded in close-range-photogrammetry and close-range fisheye photogrammetry, the photographs must be acquired with the use of a telescopic pole to offer higher coverage.

EMPLOYED EQUIPMENT

Hardware:

Nikon D3100	(with APS-C sensor)
Fisheye lens	(8mm focal distance)
Wide-angle lens	(18mm focal distance)
Wired remote shutter release	
Straps for the wiring	
Aluminium telescopic pole	(adapted painter pole)

Software:

Pix4Dmapper

3.9.1. Igreja de Stº André

Considering the experiences thus far relative to the application of fisheye images, it can be stated that recording pavements while holding the photographic camera at conventional height – of a person - generates images with low coverage. For this reason, the use of a telescopic pole to position the photographic camera at a higher altitude is mandatory to achieve higher coverage.

Yet, in the first approach, in which no telescopic pole is used, it is possible to execute a recording but at the cost of increasing the number of images beyond count. However, more than processing a point cloud with the intended coverage, it is crucial to discover an efficient photographic acquisition method to reduce the total input-data and, consequently, the computing time. The use of a telescopic pole is preferred.

To compare the results within controlled conditions, and identical to those typically experienced while recording, the Igreja de Stº André was selected to execute the recording due to its short perimeter that can be utilized as a path-guideline to acquire a unique row of contiguous images. Merely one row of images allows to better analyse the performance of the surveying equipment versus the outputs computed by the photogrammetric software.

To achieve such goal, two datasets were acquired, one with an 18mm lens and the other with an 8mm lens. As expected, the most evident difference between the two datasets is the total number of images mainly due to different FOV offered by each lens. The set of images acquired with the 18mm lens has 145 photographs, and the set of images acquired with the 8mm lens has 74 images. The difference in the total number of images is roughly equal to a factor of 2, meaning that the distance between photographs reduced by half when utilizing the fisheye lens. It is noted that even fewer images could have been acquired, however, the main objective is to study apparent differences while mimicking the standard application of surveying techniques. In other words, to mimic how a surveyor usually proceeds during a recording session. In praxis, more images are acquired than necessary to avoid revisiting the site and as the operator has the possibility or organized the acquired data during the office phase.

The reconstructions with the use of a wide-angle lens and fisheye lens originated 3D models with noticeable differences. Objectively, for the fisheye model 10 million points were reconstructed and with moderately higher coverage. By contrast, the model generated with wide-angle images reconstructed 26 million points, with lower coverage, and thus higher density. *See Figure 32.* The reason for higher density is related to lower FOV, and processing of double number

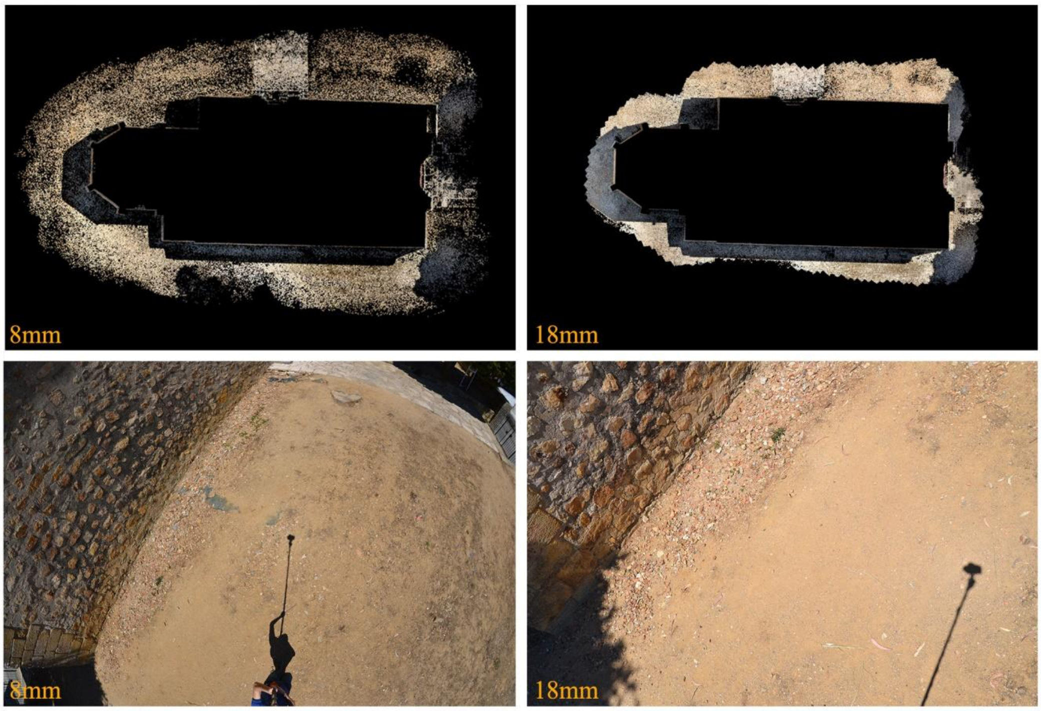

Figure 32: Pavement of the Igreja de Stº André. Top images: Digital reconstructions of images generated with 8mm and 18mm lenses. Bottom images: Sample material used for the digital reconstructions.

of images. Subjectively, interpretability of the information is higher for the outputs generated via the use of wide-angle-images. Depending on the final outputs to produce, the point cloud generated with the use of fisheye images provides with enough detail to compute contour lines for instance. Per contra, if details of ground surfaces are of pressing need, a denser point cloud is preferred.

Considering the experiment, the application of fisheye lenses in close-range fisheye photogrammetry provide with essential data even to record ground surfaces when mounted on a telescopic pole to increase coverage. The resulting models offer a high potential to generate various information at small scale: for topographic purposes; to create a local context; to record indoor spaces with lower to medium detail; and other applications. It should be noted that in aerial photogrammetric applications, fisheye lenses are frequently mounted on UAV to record extensive ground surfaces. Interestingly, such application may sound counter-intuitive because objects represented in the images are extremely small as fisheye lenses record objects at reduced size and are mounted on UAV to be used at high altitudes, thus representing objects and surfaces with tiny dimensions. It should be noted that the use of terrestrial laser scanning is one of the solutions to recover ground information when compared to the photogrammetric methods.

Results

The execution of the current study brought to light once more the positive impact of utilizing fisheye images for photogrammetric purposes.

Digital photogrammetric models were generated with the use of 18mm and 8mm images and were compared to allow studying other potential applications: topographic purposes; to create a context with surrounding terrain; etc.

Discussion and Conclusions

In this exercise, it was presented the use of a photographic camera mounted on a telescopic aluminium pole to record ground surfaces. In general, the execution of such a task seems simple to accomplish, although the simplicity depends on the surveying instruments under use and the scale of the site. Particularly, if information of small ground surfaces is required, a photographic camera mounted on a telescopic pole is sufficient. However, as the area to record increases other instruments are preferred to increase user-friendliness and ease the workflow on site. For example, TLS and UAV provide with greater flexibility to record ground surfaces of considerable size.

The identification of the current dissimilarities allows predicting workflows of future projects. For instance, if stereotomy of ground surfaces are requested, a wide-angle lens is preferred as it provides with higher detail but at the cost of processing time due to a higher number of images as input. Per contra, for topographic purposes, fisheye lenses are suitable because fewer images - less than half - are required to process a 3D model with enough detail.

For clarity, it is reiterated that the application of fisheye lenses mounted on a telescopic pole should only be utilized to record small to medium sized areas, such as indoor spaces, or surfaces along the perimeter of the construction. If information about large areas must be acquired, then other surveying equipment proper for recording those areas should be utilized.

Summary

i) The application of wide-angle lenses mounted on a telescopic aluminium pole allows acquiring high detailed information of ground surfaces. Such an approach is ideal for small to medium-sized areas as it requires a considerable quantity of images.

ii) The application of fisheye lenses mounted on a telescopic pole allows acquiring low to medium detailed information of ground surfaces while utilizing less than half the images needed for a reconstruction with wide-angle images.

iii) Both points i) and ii) are valid when recording small surface areas or along the perimeter of a building. If large areas are to be recorded other instruments should be utilized, such as TLS or UAV.

4. PROPOSAL OF POINT CLOUD PROCESSING ALGORITHMS

4.1. RESEARCH PURPOSE

Generating point clouds with the highest accuracy and precision, without exceeding moderately the demanded point cloud density to produce the requested drawings or 3D models, is one of the most desired characteristics when executing a project. By way of explaining, for efficiency and efficacy purposes it is preferred to record information in which the level of detail is slightly superior to the established one while avoiding unnecessary overwork that causes over-detailed information and additional processing time.

Such an idea is of utmost importance mostly due to time constraints, disk space usage, computing power, software capacity to process large amounts of information, and so on. Moreover, it is desirable to manage computing times in such a way to anticipate setbacks that may emerge during work and provide with extra time to reprocess the results if needed.

When generating a point cloud using digital photogrammetric techniques, spurious points are frequently computed. Such results occur mainly along the edges of reconstructed features, particularly if photographs have sky represented in them. The projection of points of the sky to near the edges of the elements in the point cloud is referred to as "sky densification". Generally, it is consisted of bluish to whitish points, the colours of the sky. Consequently, cleaning the point cloud becomes unquestionably a "must do" step, if minimally acceptable results are to be achieved, apart from being a recommended step to produce visually satisfying results, and to study in detail the generated point cloud. From experience, manually cleaning sky densification and spurious information is a task requiring incalculable dedication (and which may incur troubled boredom to the operator). Per contra, processing and creating information rapidly may increase the chances of not detecting missing details or spurious information. Middle ground is desirable. We have the maxim of "looking is not enough, one must see". Stated differently, some details are only perceived when studying the 3D model.

In addition to the presence of spurious data in the point clouds, other factors increase the time to deliver outputs, such as tools not freely available or non-existing in free and open source photogrammetric software. The absence of the "right" tool for executing a specific step fuels the need to use other less effective tools that in turn increase by a large amount the total time to deliver outputs.

For these reasons, python programming language was self-taught to develop scripts to overcome time-constraints and increase workflow speed. For that purpose, the file format of point clouds had to be studied as well. In the end, writing python scripts alleviated the workload, not to mention the possibility to use said scripts in future projects.

RESEARCH QUESTION

The time used to write scripts to execute specific operations on point clouds is an advantage to increase workflow speed and a suitable method to overcome the unavailability of free and open source tools?

KEYWORDS

Python Scripting; Point Cloud Processing, Outputs, and Tools.

GENERAL METHODS AND CONDITIONS

For the development of algorithms to process point clouds, the following conditions must be considered:

i) A programming language, such as python, should be learnt as quickly as possible with the main objective of writing scripts to process point clouds, apart from being a skill valuable to apply in future projects.

ii) In addition, the file formats of point clouds should be learnt as well to write a code able to process the point cloud format files.

iii) To avoid bloated scripts, the scripts should be written for specific purposes.

iv) The cause for writing a script should be clearly identified before defining the mathematical solution.

v) Scripts must be tested on small sample data sets and if the results do not meet the established criteria or expectations, the code is rewritten to match the defined criteria or expectations.

vi) Scripts must be executed in streaming mode (line by line) instead of loading all information to the RAM, which may crash the computer if the file is heavy.

vii) Once it is verified the scripts run correctly, scripts are run to process the main point clouds.

EQUIPMENT AND DATA

Point clouds

Python 2.7 (run in Python Shell or PyCharm)

THE ".PLY" FORMAT

Before presenting the proposed algorithms, the file format of the point clouds should be discussed as it is one of the crucial elements for which the programming language must be written and adapted to.

The file format containing information of point clouds, which was originally designed for output data of laser scanners, is named "Polygonal File Format" with the corresponding file extension ".ply". The file format can contain a variety of information, including colour, surface normals, texture, coordinates, data confidence values, and other parameters. The file format can either be written in ASCII language or binary.

```
ply
format ascii 1.0
comment Author: CloudCompare (TELECOM PARISTECH/EDF R&D)
obj_info Generated by CloudCompare!
element vertex 7825
property float x
property float y
property float z
property uchar red
property uchar green
property uchar blue
end_header
21.265 39.2806 -2.89388 187 173 143
20.2832 39.0994 -2.76887 163 164 157
15.8435 39.9315 -4.45586 136 136 142
31.9413 43.4687 -2.00486 107 112 122
31.9 43.3701 -1.99323 145 152 157
```

Table 7: Example of an ASCII Polygon File Format. In this case each point has X, Y, Z, R, G, and B values associated to it.

To achieve the established purposes, the ASCII format is preferred because the information in the file is human-readable once opened. The header has approximately 15 lines and specifies the types of information stored and that are associated to each point. After the header, a list of the points is presented, in which each line corresponds to a point with assigned values. In other words, a point cloud containing 1 million points has a file with 1 million lines plus the header. Given that each line corresponds to a point, the information is stored in columns, facilitating the programming of a script.

4.2. Python Scripts: SkyRemover Buildings and SkyRemover Vegetation

The major reason for investing time on writing a python script to clean point clouds is related to the pressing need for cleaning heavy sky densification in the point clouds of The Castle of Tomar. Before proceeding with a detailed explanation, some particularities should be noted.

The photogrammetric software selected for processing the photographic datasets of The Castle of Tomar was Pix4Dmapper. Many tools are available in this software and provide the operator with increased flexibility when processing the point clouds. One of the tools is "Image Annotation". Image Annotation is a semi-automatic approach designed to remove spurious data from the processed point clouds by masking the images used for the densification. The masking process involves the selection of specific images and painting of areas in said images with quick "selection tool" or a simple brush. The masked areas are then processed to remove from the point cloud the points that were projected into the 3D space from that corresponding area selected in the image. The advantage of this tool, besides saving a considerable amount of time when compared to manual clean-up, is that the points selected in one image are homologous in other images, therefore it is not needed to mask every single image to obtain satisfying results. In addition, spurious points located near the edges of features are easily removed when compared to the manual approach.

However, due to the project size of The Castle of Tomar, containing over 400 million points and approximately 7000 images for the first processing, or 700 million and approximately 8000 images for the second processing, the Image Annotation tool was taking up to 30minutes per image to process masked areas. A quick calculation revealed that cleaning the project by masking 3500 images would require approximately 1728 hours, that is, 72 days non-stop. Not including the time for masking images. Thus, the cleaning process would take up to 6 months, a workload to be avoided. It is important to note that due to the vast sky densification it was not possible to verify for the geometric consistency of the photogrammetric model, meaning that if any geometric inconsistencies were found after cleaning the point cloud it would be necessary to reprocess the project ex-nuovo along with another 6-month cleaning process. Do note that in this case masking was execute post-processing.

As the approach would be an unpleasant and strenuous task to complete by any surveyor, researching for a plausible and trustable solution was a must. Therefore, few ideas were considered before writing a python script. First, a completely automatic approach that is both time-saving and user-friendly is the ideal solution. If such is not possible to achieve then a semi-automatic approach is to be considered. In the semi-automatic approach, most of the spurious points are removed and the remaining areas are cleaned manually, saving up tremendous amounts of time. In addition, to remove the spurious points resulting from sky densification, it was determined that the selection of points should be via colour instead of coordinates. Identifying by colour is faster because the colours of points corresponding to the sky, bluish to white, are infrequently present on the dense reconstruction of the surfaces of interest.

For that purpose, the Python programming language was studied. Two versions are available, Python 2.7 and Python 3.x. The former version was recommended since it still is used by most current users and has greater library support than Python 3.x. This approach meant that we had to learn in very short time basic programming and technical RGB values. In two weeks, the basics of python programming were learnt, and with the help of a fellow PhD student (Mosab Bazargani), with experience in programming background, the python code to remove spurious points was run in the servers of the university, as soon as the code was ready by the fourth week. Trial and error were constant during the first three weeks, particularly for determining specific RGB range values.

The reason for selecting points through their assigned RGB values relates to the fact that reprojected points in the sky are bluish to white, and old construction, such as castles, frequently do not have the same colours as the sky. In fact, depending on the weather conditions, the castle can be more distinguishable relative to the sky. For instance, during sunny days the castle tends to present colours with a shade of yellow, while on cloudy days the castle is greyish to bluish. The most difficult part of coding is related to the range of grey colours because both the sky and the castle have grey colours. In other words, however much work is invested in determining the RGB values, it was concluded that running the script will always and inevitably remove non-spurious

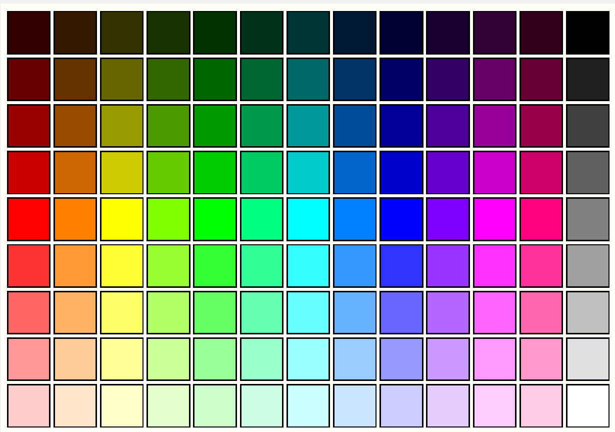

Figure 33: RGB chart. Image from *"http://www.rapidtables.com/web/color/RGB_Color.htm"*

points. Yet, the script would still be an extremely time-saving approach to clean the point clouds when compared to Image Annotation tool of Pix4D or manual cleaning.

The python code was written and tested in an average state of the art laptop - ASUS K56CB. It was noticed that running the code would take quite some time, approximately 1 week to filter all the point clouds. The total number of points was around 400 million. For faster processing, the python code was run on the server of the Faculty of Architecture. It took approximately 1 hour to filter all point clouds. The results are very positive. However, some improvements to the RGB range values had to be done because there still was a lot of sky densification. A more thorough study that lasted a week was conducted to specify with more precision the RGB range values. The python code was re-run and even better results were obtained.

Concerning the python script, there still existed some unremoved patches of spurious points. As such occurrence was expected, the python script was written to generate two PLY files for every filtered original PLY file, one file for accepted points and another file for rejected points. This method allows selecting points that are in the rejected file and reinsert back in the accepted file. In addition, it is also possible to calculate if any point is missing by adding the total number of points from the rejected file with the accepted file and compare to the original point cloud file.

In the end, the python script is a semi-automatic approach. Its application is advantageous as a quasi-cleaned point cloud is obtained, and if manual cleaning is needed it is executed swiftly. Yet, to achieve better results a second python code was written. The coding structure follows the same as the first code. The differences are in the assigned RGB values. The purpose is to apply in the cleaning of vegetation area as these still presented with some greyish points. Before running the script, the operator must separate building volumes from vegetation volumes, otherwise, the second python script removes valuable information from the buildings. In short, the first python code, named “SkyRemover Buildings”, is executed to make a general clean-up, and the second code, named “SkyRemover Vegetation”, is executed to clean spurious points in the vegetation.

In the end, one month and a half were needed to: learn basic python programming language, to learn and understand RGB colour chart values, to write and run two python codes that worked very well, and to clean all point clouds manually. This approach proved to be time-efficient and, above all, self-didactic.

Figure 34: SkyRemover Buildings – python script. Top image: Original point cloud; Middle image: Accepted points; Bottom image: Rejected points.

Figure 35: Another example of SkyRemover Buildings – python script. Top image: Original point cloud; Middle image: Accepted points; Bottom image: Rejected points.

Figure 36: Yet another example of SkyRemover Buildings – python script. Top image: Original point cloud; Middle image: Accepted points; Bottom image: Rejected points.

4.3. PYTHON SCRIPTS: "CONTOUR LINES" AND "PLAN"

Another important reason for investing time on writing a python script is to create a tool to facilitate the creation of orto-drawings or contour lines. Both python scripts are included in this section due to the coding format and identical requirements to execute the scripts.

As aforementioned, even though free and open source software for processing point clouds exists, there is the pressing need for tools allowing the manipulation of point clouds to deliver the desired outputs. From experience, there are two tools that are a must for creating architectural orto-drawings: a tool to generate contour lines; and a tool to generate plans. Both require the point cloud to have its altitude defined -georeferenced - because executing the scripts requires reading the Z coordinate values.

Regarding the contour lines script, when running, the operator is prompted to input a range value to filer the points falling within the user-defined input range. Setting a range discards information that should not be computed thus decreasing computation time. The input point clouds must be in one folder for the script to run. A subfolder is created with one point cloud containing a copy of the accepted points. In addition, contour lines are coloured depending on their corresponding altitude value: one colour for multiples of 5m; a second colour for multiples of 1m; and a third colour for multiples of 0.5m. The reason for colouring is to increase the intelligibility of the outputs as it may be confusing to follow or count the lines if vertical stacking occurs. Note that the script calculates if a point is acceptable if it falls within a range of 3cm for every specific altitude.

Concerning the script for creating plans, the original point clouds must be in one folder with a TXT file containing the name of the output files and a z coordinate value. The z coordinate value is accepted as the maximum altitude value to filter the point cloud, that is, the script accepts points whose value is smaller or equal to the z coordinate value and appends to a temporary file. The temporary file containing all points is a solution to merge points of the same surfaces that are in several PLY files. Next, points in the temporary file are copied to the final output files corresponding to 10m intervals. The reason for executing such operation is to decrease the weight of the files and be able to open in point cloud software. To produce plans, in the final step a manual selection of features is executed, where occluded background surfaces are removed to produce good outputs.

However positive the results are, the python script for generating plans has a major disadvantage: large space disk is required to store the final outputs.

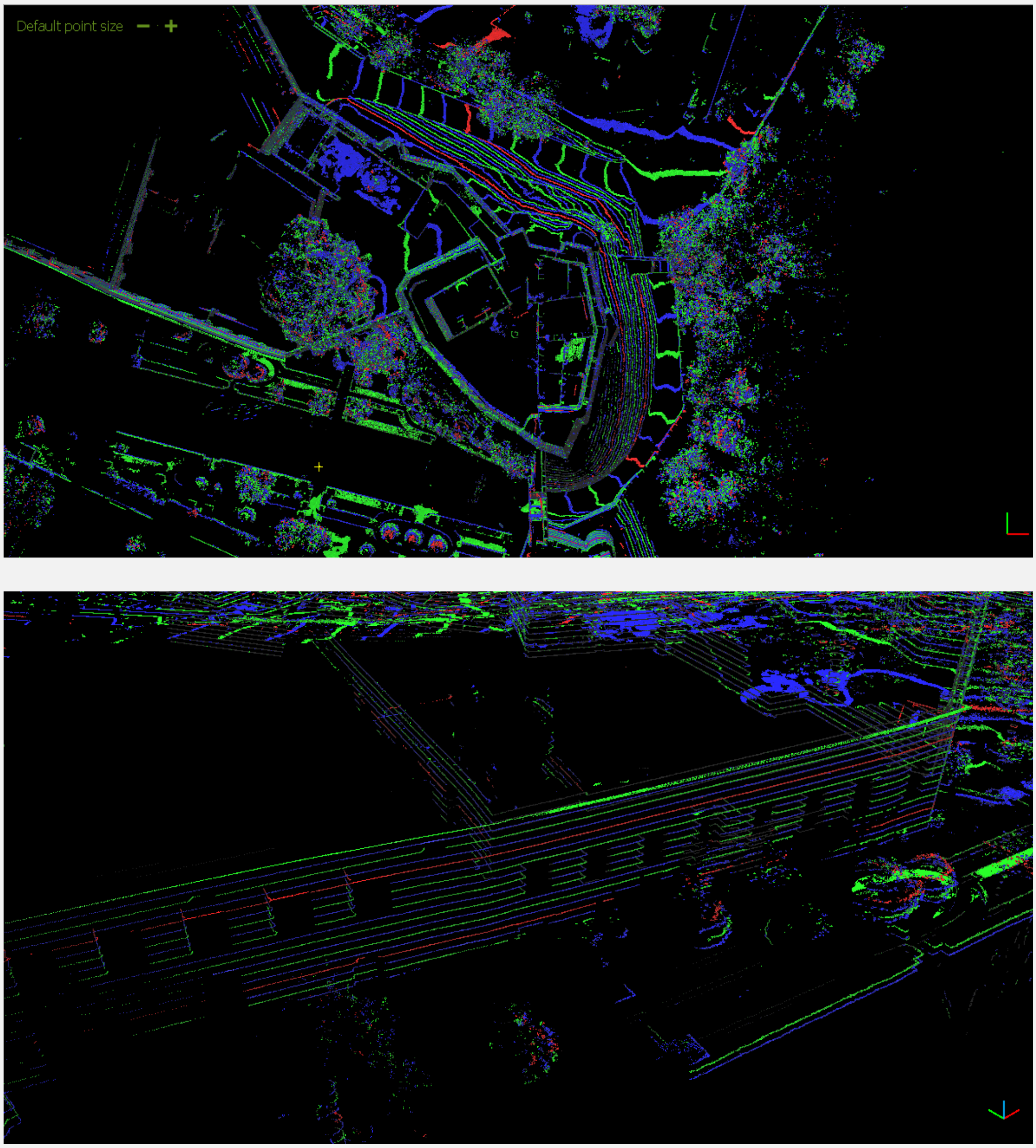

Figure 37: Contour Lines – python script. Top image: Plan view of the contour lines; Bottom image : Perspective view of the contour lines.

4.4. Python Scripts: "Cross Sections and Elevations"

In addition to the two scripts presented previously, it is also presented another script to allow the production of cross sections and elevations as CloudCompare and MeshLab software do not offer tools with to calculate cross sections and rotation via specific selection of points.

A method to generate cross sections or elevations parallel to the front view - or facial plane- is to print an image from the top view in the point cloud editing software and determine the angle of rotation using another software, such as AutoCAD. Next, the value of rotation is inserted in the point cloud software. The undesirable aspect of performing such workflow is related to the acquisition of imprecise rotation values, resulting in a point cloud that is not exactly parallel to one of the orthogonal views and thus leading to imprecise drawings. Theoretically, after rotating, the operator segments the point cloud to remove non-visible information and occluded points in background surfaces. The processed point cloud is saved for posterior reprocessing in case that the subsequent generated outputs are non-satisfying.

The proposed algorithm follows approximately the same semi-automatic approach but with higher control on the rotation of the point cloud. To run the script a ".txt" file is created by the operator containing: i) the name for the output point cloud; ii) x and y coordinates of A, B, and C points; iii) and a value for variable E. Points A and B correspond to the vertical cross section plane. Point C is selected above or below the cross section plane to indicate the viewing direction. Variable E is the offset for the cross section, that is, to translate the cross section above or below the initially selected position. Instead of selecting points A and B approximately parallel to the surface of interest, points A and B are selected on the surface and variable E specifies the offset value. This method delivers an accurate rotation and placement of the cross section relative to the surface of interest.

On a thorough explanation of the script: The Pythagorean equation is computed to calculate the hypotenuse of the triangle formed by points A and B in a cartesian coordinate system. The hypotenuse value allows to calculate sin and cos values to rotate other objects. The application of a rotation matrix model for the computation depends on the angle of the cross section, and the location of point C relative to said cross section. To determine if C is below or above the cross section, it is rotated and compared to the rotated line segment $\overline{AB}$ (parallel to x axis). If C is positive it is above, if C is negative it is below and requires an additional 180° of rotation.

If positive angle and point C is positive, then a clockwise rotation is applied:

$$R(\alpha) = \begin{matrix} cos\alpha * x & + & sin\alpha * y \\ -sin\alpha * x & + & cos\alpha * y \end{matrix}$$

If positive angle and point C is negative, then a clockwise rotation is applied with an additional 180°:

$$R(\alpha) = \begin{matrix} -cos\alpha * x & - & sin\alpha * y \\ sin\alpha * x & - & cos\alpha * y \end{matrix}$$

If negative angle and point C is positive, then a counter-clockwise rotation is applied:

$$R(\alpha) = \begin{matrix} cos\alpha * x & - & sin\alpha * y \\ sin\alpha * x & + & cos\alpha * y \end{matrix}$$

If negative angle and point C is negative, then a counter-clockwise rotation is applied with an additional 180°:

$$R(\alpha) = \begin{matrix} -cos\alpha * x & + & sin\alpha * y \\ -sin\alpha * x & - & cos\alpha * y \end{matrix}$$

Once the type of rotation matrix is defined, it is applied to subsequent points of the input point clouds. Note that no matter the position of the cross-section, the resultant rotated point cloud will always be positioned to be observed from the front view - or facial plane. Next, every rotated point having its $\boldsymbol{y}$ coordinate value positive is accepted and appended to the temporary point cloud file. The rotated points with negative y coordinate values are discarded.

The following step consists of filtering the points from the temporary point cloud file into segments of 10m to break down the oversized file.

Identical to the python script to generate plans, the cross-section python script requires a considerable amount of disk space to store the temporary files and to store the final outputs. The reason for saving a rotated and segmented point cloud is the fact that, if any errors are detected while producing the final drawings, it is not required to execute again the time-consuming operations. Therefore, from experience, it is preferred to save time during the production of the final drawings at the cost of disk space.

Relative to the writing efficiency of the code itself, the script is inflated containing 500 lines of coding. In the future, the script should be compacted, unnecessary variables removed, and computation of an octree included so to increase processing speed.

Figure 38: Cross sections and elevations – python script. Top image: Point cloud after manual-clean; Middle image: Mesh model; Bottom image: Mesh model with vegetation.

Results:

The application of python scripts to automate work or to increase the quality of the output data provided with positive results.

Discussion and Conclusions:

Digital photogrammetry is a method that provides the user with digital outputs in the form of point clouds and in which the points are the 3D reprojection of pixels identified across multiple images. Each point contains at least 6 values: x, y, and z coordinates; and Red, Green, and Blue colour values.

For that reason, having information stored in the digital format increases the flexibility to deliver varied types of outputs. Such occurrence opens doors and opportunities to study the underlying mechanisms or codes that lead to the representation of the information as is. Therefore, learning programming languages equips the operator with powerful skills in which he can manipulate the digital information to increase the quality of the information or to derive new types of information.

Consequently, impediments have been identified and that would exceptionally delay by a great amount of time the delivery of the intended outputs, python programming language has been learnt to write scripts and overcome such difficulties.

Yet, as programming is an ever-developing skill that is honed with experiments and experience, it is possible to ameliorate the python scripts to decrease the total number of calculations and, subsequently, processing speed. In fact, if such is to be executed it is best to learn a more efficient language such as C++.

Summary:

i) Python programming language is easy to learn.

ii) Python programming language allows creating tools to accelerate the workflow during the office phase.

iii) When free and open source tools are unavailable, and a task requires months to complete, it is best to write a tool to overcome such a setback.

iv) Four python scripts have been written: i) SkyRemover for Buildings and Vegetation; ii) Contour Lines; iii) Plans; iv) Cross Sections and Elevations.

5. THE CASTLE OF THE CONVENT OF CHRIST

5.1. Context and Background

Having researched several potential applications of fisheye images and acquired vital experience for executing photogrammetric projects, the main case study of the thesis is presented: The Castle of Tomar of the Convent of Christ in Tomar, Portugal.

The main purpose for recording relates to the pressing need of acquiring detailed information to proceed with further works of conservation, restoration, and rehabilitation. After a research that included personal consultation with the administration of the Convent of Christ,

Figure 39: Location of The Convent of Christ: Tomar, Portugal. Image from Bing Maps.
URL: < https://www.bing.com/maps >

it is verified that documentation of the Castle is scarce. The collected information includes material in the drawing scales of 1:1000 down to 1:100. The latter material corresponds to partial drawings of a few parts of The Convent of Christ and not of the citadel, the main objective of the project.

For this reason, the administration of the Convent is interested in obtaining information on the citadel at a drawing scale of 1:100 to proceed with thorough studies. In addition, stereotomy information is highly desired not only to increase drawing interpretability but also to study the construction technique used in the building under examination: random rubble masonry. Therefore, the recording of The Castle of Tomar was executed as if drawings were requested at a drawing scale of 1:50. Such objectives are accomplished effortlessly due to the inherent advantages from the main application of photogrammetry and complementary application of terrestrial laser scanning to verify the geometric integrity of the points clouds.

Figure 40: A drawing of The Convent of Christ. Image from SIPA.
URL: < http://www.monumentos.gov.pt/site/app_pagesuser/SIPA.aspx?id=4718 >

For the execution of the task, the best approach to define the objectives, methods, and conditions to execute the project is the establishment of a specific GSD value by the client, with which the level of detail is defined and calculated for the application of the surveying instruments. In this case, specific drawing scales were requested, and GSD is calculated by the surveyors. Bearing in mind the objectives defined previously, and the fact that the site to record is considered a world heritage by UNESCO since 1983 (World Heritage Committee (UNESCO), 1984), the approaches to obtain the requested data must be thought thoroughly to acquire high-quality information. For that purpose, several surveying techniques were utilized, such as close-range-fisheye photogrammetry (as proposed in this thesis); close-range-photogrammetry; aerial photogrammetry; terrestrial laser scanning; and GPS equipment.

The reason for considering such surveying instruments is related to the inevitable setbacks that occur in every project. Thus, all problems, solutions, advantages, and disadvantages are presented and discussed. It is crucial to note that most of the setbacks were presented and researched *in chapter 2*. Yet, no matter how carefully a project is planned, there are always and inevitably adverse occurrences that must be dealt with as the project progresses. Flexibility is one of the key elements. As a result, several recording sessions are necessary to fully record the site within established requirements.

The main challenge of this project is to compute a full 3D model using, for the most part, photogrammetric techniques. GPS and terrestrial laser scanning are also used as complementary instruments to georeference and to verify the geometric quality of the point clouds generated via photogrammetric processes, respectively.

The recording of The Castle of Tomar is organized according to two survey periods, as illustrated in *Table 8*. The cause for having two survey periods is strictly related to the experience of the surveyor and the application of solutions to overcome the identified setbacks. Particularly,

Figure 41: The Convent of Christ. Image altered from the leaflet designed by AnyForms.
URL: < http://www.anyformsdesign.com/ >

Surveying of Tomar	First Surveying period		Second Surveying Period		
Surveying days	14-11-2013	21-11-2013	9-4-2015	30-4-2015	26-6-2015
Terrestrial Laser Scanning					
Terrestrial Photogrammetry					
GPS					
Aerial Photogrammetry					

Table 8: Survey instruments used for each survey session. The vertical dashed line separates two survey campaigns: first survey period in 2013, second survey period in 2015.

during the first survey period challenges were enumerated and solutions researched to be applied during the second survey period that was executed ex-nuovo.

Relative to the structure of the current section, first a brief historical background is presented followed by information relative to the two survey periods. Each survey period is subdivided into field work and office work. Note that for the second survey period, due to a considerable amount of information to bring to light, the fieldwork phase is further subdivided into field work days to explicitly reveal the amount of work allotted for each survey day. Furthermore, office work phase is subdivided into 3 parts: a) the first part corresponds to the first attempt at generating a photogrammetric model in Pix4Dmapper, and georeferentiation of TLS data to GPS data followed by transformation of photogrammetric data to said TLS data. The final model contained major errors; b) For that reason, the second part is the second processing of photogrammetric data in Pix4D software with changes to the workflow established during the first part. Both photogrammetric and TLS data are georeferenced to GPS data; c) Finally, the third part includes information about manipulation of point cloud data to generate various outputs.

5.2. SUCCINCT HISTORICAL BACKGROUND AND PHYSICAL CONFIGURATION

One of the key aspects to consider, before advancing with the project, is the collection of information that prepares the surveyor. Such information allows to identify, examine, and study the construction elements. A brief historical background and a physical description are presented to reveal the cultural impact of The Castle of Tomar and its predominant features. The referred information is mostly focused on the Castle even though it also relates to The Convent of Christ.

The Castle of Tomar is but only a minor portion of The Convent of Christ for which much can be revealed relative to the numerous constructions, changes, improvements, and additions implemented throughout the centuries. The site is characterized by containing diverse architectural elements and styles such as Romanesque, Gothic, Renaissance, and others. The construction of The Castle started after D. Afonso Henriques, first king of Portugal, passing to the Knights Templar the defence of a vast strategic territory, ranging from Rio Tejo (Tagus River) to Rio Mondego (DGPC, n.d.-. Accordingly, the Castle of Tomar started to be erected in 1160, as written in an epigraphic inscription on the main keep and by the orders of the Master of the Knights Templar in Portugal, D. Gualdim Pais, during the territorial formation of Portugal. The

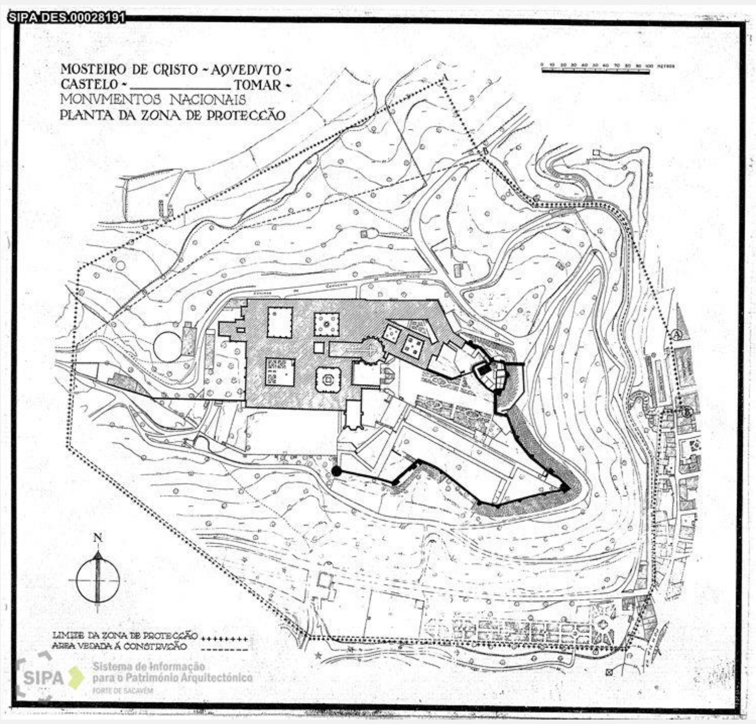

Figure 42: Non-Aedificandi Area of The Convent of Christ – 1982. Image from SIPA.
URL: < http://www.monumentos.gov.pt/site/app_pagesuser/SIPA.aspx?id=4718 >

castle, along with other castles from the same region such as Almouroul, Idanha, Pombal, Zêzere, and Monsanto, formed a defensive line named “Linha do Tejo” (Tagus Line), which contributed to the shaping and defence of Portuguese lands from the moors (Bento, 2013; DGPC, n.d.; SIPA & Nós, n.d.).

The constructions composing The Convent of Christ are implanted on the steepest hill to the West of Rio Nabão (Nabão River), in the city of Tomar and in the region of Ribatejo. In the same year that the castle started to be erected, the construction of the church started as well, which encloses an oratory and is considered one of the most significant and unique buildings of the Templars in Western Europe.

The connection of the Knights Templar to the History of Portugal is undeniably recognized and culturally impactful. For instance, instability was faced during the extinction of the Knights Templar due to a papal bull issued by Pope Clement V in 1312. By virtue of D. Dinis (King Denis I), the possessions of the Knights Templar were provisionally safeguarded as Portuguese property until 1321, when the King established “A Ordem dos Cavaleiros de Nosso Senhor Jesus Cristo” (The Order of the Knights and Our Lord Jesus Christ), simply known as “Ordem de Cristo” (Order of Christ). Infante D. Henrique (1394-1460), being the governor of the Order of Christ, has resided in the Castle of Tomar. In fact, The Convent of Christ was highly considered by kings as D. Manuel (1495-1521) and D. João III (1521-1557), who performed numerous interventions to restore and expand The Convent of Christ. However, from the XVII century to current days, few works have

Figure 43: Speculative image. (Bento, 2013). Observe the walls and village.

been executed: restoration works of the various chemin de ronde in 1934; reconstruction of walls in 1939 and 1944; construction of stairs leading to the keep of the castle and repairs of the entrance of the keep in 1960; placement of lights in the exterior of the castle in 1961 (Bento, 2013).

Regarding the general physical configuration of the Castle of Tomar - of military architecture, see *Figure 41* and *Figure 42* - it is located on the eastern side of the construction for being topographically favoured for strategic and military purposes. Such militarized area is composed of a citadel from where extensive exterior and interior walls part from and encompass most constructions of the Convent of Christ. Both interior and exterior walls are shaped as an irregular polygon due to the steepness of the terrain. See *Figure 41.*

The exterior wall, see *Figure 43*, which used to start from the West side of the church, incorporated the citadel, and ended at the South part of the same Church, used to shelter the population until 1499 when it was forced to move out by order of D. Manuel. In current times, the space that used to function as an infirmary is located between the church and the citadel, where once part of the northern wall existed. In fact, the area adjacent to the northern wall was the target of several changes throughout the centuries (Oliveira, 2010). In addition to the exterior walls, interior walls section the site in four distinct areas: the area where once the village existed, which is currently gardened; the citadel; the promenade or mall; and the quarters of the knights (Bento, 2013).

The citadel includes the keep, a construction of value for its remarkable defensive purposes, and the first of its kind to be introduced in Portugal by the Knights Templar - a construction style brought from the crusade missions in the East. The keep is the innermost defensive mark constructed at the highest altitude of the hill, and from that central post, the remaining positions of the castle were commanded. The tower has no access from the ground floor as typically observed in other castles. The access to the construction is performed in an unconventional manner, from the superior floors with narrow openings leading to the chemin de ronde. However, in time, such openings were configured into windows, transforming the initial morphological configuration. Such alterations also occurred in the towers of other castles (Bento, 2013).

Another feature introduced by the Knights Templar, and is present in all walls, is the batter: a steep volume at the base of the walls angled in such a way to not only bounce stones off onto the enemy but also to increase structural stability of the walls. In addition, the batter prevented the employment of offensive battle techniques such as tunnel excavations, climbing of the walls or the use of stairs by invading forces (Bento, 2013).

Other notable features include the cruciform arrow slits in the extensive merlons, and the circular wall towers protruding from the walls that provided with greater defence by allowing to flank and crossfire over enemy forces (Bento, 2013).

Even though the castle includes exterior and interior walls, the recording of the information focuses on the citadel of The Castle of Tomar. Here, the wall is of scutiform configuration, which includes: windows resembling loveseats in the North and East side; two wall towers, one on the South in a similar shape of a rectangle and the other one on the East side in the shape of a truncated pentagon. Both towers overlook the entry transition zone – a barbican constructed during the XVI century -, which is controlled by two small gated walls: the “Porta de Santiago” and the “Porta do Sol”. The main and only access to the citadel is performed on the North side. In current times, remains of constructions in the citadel are observable, indicating living spaces and a portion of ulterior wall foundations. The wall foundations, due to its thickness, bring forth the hypothesis that the defensive wall was aligned with the second entry door – Porta do Sol – and the citadel was of smaller size than it is currently. Such a hypothesis is in need of archaeological corroboration. (Bento, 2013; Oliveira, 2010).

The keep is of rectangular shape with 3 vaulted floors and a roof accessed area. The floors and roof are connected in unconventional ways: the first floor, speculatively a calaboose or a warehouse for it has no openings, connects to the second floor via a trapdoor; the second floor is disconnected to the third floor; the third floor is connected to a smaller intermediate floor and then to the roof. The third floor is accessible by a door via the chemin de ronde. The second floor is accessible via an opening on the southern façade by using a movable ladder from the ground floor. Note that on such opening, a commemorative epigraphic inscription of the foundation of

Figure 44: A few features of The Castle of Tomar. From left to right: The keep with entrances at different levels; Hollows in the wall; The batter; Cruciform arrow slits.

Figure 45: Two perspective views of The Castle. Images from DGPC and SIPA, respectively. URL: http://www.patrimoniocultural.gov.pt/pt/patrimonio/patrimonio-imovel/pesquisa-do-patrimonio/classificado-ou-em-vias-de-classificacao/geral/view/70473 http://www.monumentos.gov.pt/site/APP_PagesUser/SIPA.aspx?id=3390

the castle is visible. Lastly, small hollows are observable on the interior face of the walls and are traces of the use of wooden framework to sustain other constructions that no longer exist (Bento, 2013; Oliveira, 2010).

All in all the Convent of Christ can be viewed as the home and headquarters of the Knights Templar, that contributed to a series of well-known historical events, such as the territorial formation of Portugal and the Portuguese discoveries, to name a few. From 1910 the site is considered a National Monument, by decree of 1910 (Diário do Governo, 1910), and from 1946 it is included in a "Zona de Especial Protecção" (ZEP – Special Protection Zone) and in a "Zona Non Aedificandi" (ZNA) (Diário do Governo, 1946, cited in DGPC, n.d.), Figure 42, to maintain its exceptional historic and cultural values. Since 1983 (World Heritage Committee (UNESCO), 1984), The Convent of Christ is in the list of UNESCO world heritage sites.

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5.3. First Survey Campaign

As aforementioned, the first recording campaign was executed during the year of 2013 and comprised of two recording days for the acquisition of data: days 14 and 21 of November. At the time, due to the low experience of the surveyor in the recording of constructions with the use of photogrammetric techniques, the acquired data was of minimally exceptional quality, even though the surveyor was under professional guidance. Multiple mistakes occurred, particularly due to the morphological complexity of the construction. The issues, problems, and solutions are described in detail and consubstantiated. For that purpose and intent, the information concerning the first recording period is subdivided into field work and office work.

Employed Equipment:

Hardware:
Nikon D3100 (APS-C sensor)
Wide-angle lens (18-55mm lens)
Faro Focus 3D Laser Scanning

Software:
VisualSFM + CMVS/PMVS
MeshLab
CloudCompare
Adobe Photoshop
Autodesk AutoCAD

5.3.1. Field Work

During the photogrammetric recording, great assistance was provided by the ARCHC_3D research team on how to proceed with the photographic recording, such as how to photograph, where to position, where to look at, and other criteria. However, the photographic data is of low quality due to the low experience and skill at recording. Low experience and skill from the few tests and experiments executed on small scale objects such as shoes, statues, diffuse and specular surfaces, and other experiences. More experience was required. In fact, no matter the level of proficiency (while comparing our present experience to the experience of that time), it is difficult to know even with average precision the information being recorded by the photographic camera being utilized by another person, even if the settings and characteristics of the photographic camera are known.

For this reason, excessive and redundant data were acquired due to an unsystematic approach. The best-recommended approach involves photographing in a hierarchized structure: i) first, the construction is disassembled to its essential elements, and each element is further subdivided to surfaces; ii) Surfaces are further subdivided taking into consideration the area covered by each photograph, that is, the number of rows and columns; iii) then the inverse procedure is thought by discerning the type of connections to perform between the various image data sets (contiguous or remote transition photographs as proposed before).

Executing such a hierarchized structure not only eases the photographic acquisition, but also the office work. As implicitly expressed, such approach was not considered at the time of the recording as it was not experienced or thought of before by the surveyor, or the surveyor did not fully understand the strategy suggested by the professional guidance.

A total of 1776 images were captured, representing: the citadel; the promenade; the path between the main doors; and the exterior wall from the parking lot. No indoor spaces nor transition areas were recorded, such as bridges, the interiors of the walls, and the keep.

Of all the collected information, the images representing the exterior side of the wall were within the limits of what is considered good photogrammetric information. Specifically, the images were captured having the photographic camera pointed perpendicularly to the pathway and for every two steps along the pathway two images were recorded: one pointing horizontally towards the batter to include foreground information, and the other pointing upwards to include the wall on the background. See *Figure 47*, the two images on the left.

Regarding the citadel, images were acquired from the chemin de ronde. For every four steps, a pseudo-panorama of images was captured to include the main tower, the surfaces of the wall, the battlements, and ground surfaces in the citadel. The objective consisted of a “shotgun approach” to include all the information at once. For the calculation of photogrammetric models, panoramas should be avoided to generate successful reconstructions. Such a statement is verifiably true if acquiring a single panorama, but if several panoramas are acquired an accurate digital reconstruction is computable. Yet, such a method for acquiring photographs proved to be very inefficient for there were countless redundant and inadequate images, thus increasing the computing time. In addition, when accessing the images on the computer to organize the data, the operator easily loses track of work. Organizing the collected data is a vital step before initializing computations.

Another challenge when recording is related to the poor acquisition of the images of the southeast and southwest surfaces of the keep due to insufficient FOV of the lens. Consequently, extremely redundant images were captured, and the density of the generated point cloud varies greatly. The reason for this occurrence relates to the distance of the surfaces to the lens versus the need to acquire fewer images as the surface is farther away from the lens. Furthermore, transition photographs connecting the tower surfaces with the chemin de ronde were equally difficult to capture due to insufficient FOV, thus impeding the calculation of a single and global point cloud. See *Figure 47*, the two images on the right. However, the major problem identified that would demand the computation of sub-point clouds instead of a global point cloud, is the connection of the sets of images acquired from the exterior of the castle with the images of the citadel. A method to overcome this is to use the main tower as a remote transition element, which is identifiable in multiple sets of images. For that purpose, several photographs with varying focal length values were acquired from both the citadel and exterior of the castle. Such an approach proved to be inefficient as well due to the use of varying focal length values instead of fixed progressive focal length values.

Figure 46: How the photographic data of The Castle of Tomar was acquired. Image acquired from the initial laser scanning operation.

The objective of obtaining a homogeneous GSD was not prudently premeditated. For example, it was assumed due to the high MP count of the photographic camera that the superior surfaces of the walls would have enough density. The calculation of the GSD was not executed at the time, not only because the surveyor was a novice in the application of photogrammetric techniques but also due to the pressing need of acquiring the most information for the time available to execute the recording. In addition, the maximum density the photogrammetric software can deliver relative to the GSD of the project was not considered as well.

Another problem with the photographic acquisition relates to the acquisition of the photographs by the surveyor. As previously mentioned, 1776 images were captured within a short time limit and it was noted that breaks are needed to recover arm strength to proceed with the recording. However irrelevant such aspect may be, it affects the total time for recording and should be accounted for in future recording projects.

Overall, the collected photogrammetric data, in our experience, is estimated to be within satisfactory quality, if insufficient skill during the photographic acquisition is considered and that affects the workflow during the office work phase. All the challenges and identified problems are the result of the main problem: the absence of a photogrammetric surveying strategy that, at the time, was elaborated as the recording progressed paired with low experience in recording.

In addition to the photogrammetric recording, during the second surveying session, TLS was utilized by the research team. A total of 6 stations were completed: 1 between the Porta de Santiago and the parking lot; 3 between the Porta do Sol and Porta de Santiago; 1 on the mall; and the last one on top of a battlement to make the transition between the citadel and the promenade.

Figure 47: Example of the recorded data. The two images on the left meet the standards for efficient photogrammetric processing. The remaining images represent the FOV problem.

The main reason for utilizing laser scanning is to provide with crucial and complementary information that is non-existent or associated to the point cloud generated via photogrammetric processes, such as scale, information of virtually unreconstructed areas, and to verify the geometric quality of the outputs. Ideally, to perform the latter action a loop of scans around the object is required to guarantee that all the TLS point clouds are accurately and precisely aligned. Nonetheless, if all 6 scans are aligned carefully, the geometric quality assessment is executed effortlessly.

SUMMARY OF THE FIELD WORK PHASE

i) The photographic acquisition was executed as the site was examined and with professional guidance from the research team.

ii) GSD not calculated.

iii) Excessive and redundant images acquired in a non-methodical approach.

iv) Low photogrammetric experience of the surveyor

v) Several setbacks identified that set-in motion the need for researching new surveying approaches.

vi) TLS was utilized by the research team to record the areas between Porta de Santiago and Porta do Sol, and the exterior area of the Castle.

5.3.2. OFFICE WORK

After the photogrammetric recording on the 14th of November and knowing the next recording session was in a week, work in the office to identify potentially missing information progressed in the meantime. Objectively, results had to be obtained in less than 1 week. However, it was necessary a total of 1 week and 3 average state-of-the-art computers to process an incomplete Match Matrix of the images in VisualSFM, which is a representation of the correlation-strength between images. See *Figure 48*. The more images are introduced, the more matches are calculated per image, that is, the total number of matches increase exponentially, following the formula:

$$m = \frac{x(x-1)}{2}$$

x is the total number of images

m is the total number of matches

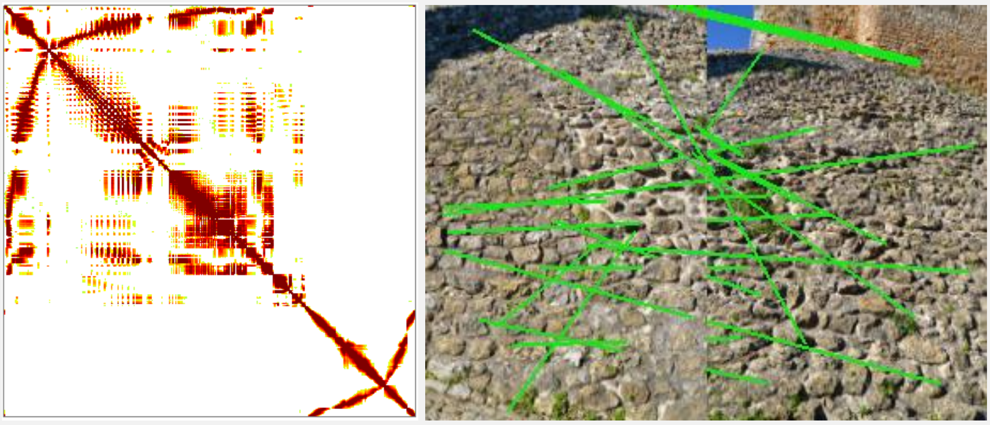


Figure 48: On the left: Image matching matrix with VisualSFM + CMVS/PMVS. On the right: Green lines representing detection of homologous points between images.

Having 1776 images, 1,576,200 matches are calculated. The processing time is estimated if the time to complete one match is known, which varies from computer to computer due to hardware differences. Since 3 computers were available and results had to be achieved within 1 week, images were processed in portions. This method proved to be effective, even though results were obtained not in time. However, one of the downsides relates to the 100% usage of computer hardware, which is inconvenient if other tasks must be executed simultaneously. For that reason, after processing for 1 week, the computer available at the faculty, specifically built for computing large data sets, was utilized for processing the remaining matches to ensure maximum image correlation.

As the image Match Matrix was not computed within the established time-frame, the identification of problems that could be corrected in the next recording session on 21st of November was not achieved. For that reason, during the second recording session TLS was utilized by the ARCHC_3D research group and no photographs were acquired.

Concerning the processing of the data after the two recording sessions, the most evident problem is related to the connectivity between the scattered sets of images acquired at different locations. The issue is related to the one presented in “Contiguous Transitions and Remote Transitions”. Although images with different focal distances were used to provide with varying values of GSD to ease the image matching between the sets of images of the citadel and the mall, a single 3D model proved to be inexecutable. For that reason, 3 distinct point-clouds were computed: one of the citadel; another of the mall; and the last one of the exterior.

In the following step, the 3 point-clouds are aligned by selecting homologous points manually. A 20 cm deviation is noted. After multiple attempts to merge the point-clouds, it was determined that no better results could be achieved. It is possible that the reprojections were not accurate due to the use of images captured with different focal length values. For that possible cause, the point clouds were reprocessed with no problematic images as input. Yet, similar results were obtained. Consequently, it is concluded that to generate a geometrically consistent point cloud transition images are as important as images representing the object or scene.

Other major issues were detected that inevitably resulted in an incomplete point cloud reconstruction due to the impracticality of acquiring: i) information with conventional surveying instruments in the pathways and chemin de ronde; ii) transition images between dark and bright areas, and between sets of images; iii) and, lastly, information of indoor spaces.

Relative to TLS data, the point clouds were decimated to 2cm of distance to reduce the file-weight. If the operator loads approximately more than 3GB in MeshLab, the software interrupts. Therefore, an alternative method consists in aligning all the light-weight point clouds to determine matrix transformations. In this case, to determine rotation and translation as TLS delivers information in true scale. The matrix transformation values are stored and ready to apply to the heavy point clouds. Next, as a closed loop of scans is inexistent, the medium deviation between point clouds is checked in CloudCompare. The software returned the value of 2cm. This value is within acceptable limits because the point clouds were decimated to 2cm and the precision level should be no less than 2cm. See *Figure 49*.

To create material at a drawing scale of 1:100, 2cm of density is within acceptable limits. Specifically, 2cm offers outputs in which the distance between each point at a drawing scale of 1:100 is of 0.2mm. A value of 0.2mm corresponds to the highest value of accuracy that has been established for graphical representations, even though the human eye is capable of distinguishing lines for every 0.1mm of distance. Specifically, due to the very nature of graphical representations and human vision combined, it is not possible to distinguish lines falling within less than two or three-tenths of a millimetre. Therefore, graphical "errors" can be considered within a threshold from two to three-tenths of a millimetre (Docci & Maestri, 2005; Mateus, 2012). Should the drawing scale be 1:50, point clouds must be decimated to 1cm of spacing. Ideally, for optimal alignments point clouds are not decimated and homologous points are selected, but such method is discarded due to software and hardware limitations.

Due to time constraints, no further attempts were performed to enhance the results. Given that drawings are possible to be created at a drawing scale of 1:100 using TLS data, which have higher coverage, the final drawings from the first recording period were completed having TLS data as main input and photogrammetric information as complementary input. An objective opposed to that established in the current thesis.

Nonetheless, for testing purposes, the drawings were completed to determine a conceivable and efficient workflow. See *Figure 50*. Therefore, the photogrammetric point clouds were aligned with the terrestrial laser scanning point clouds using CloudCompare software. If no terrestrial laser scanning existed, incorrect information of the exterior areas would be prevalent nor drawing scales could be defined correctly as photogrammetric data provides unscaled outputs.

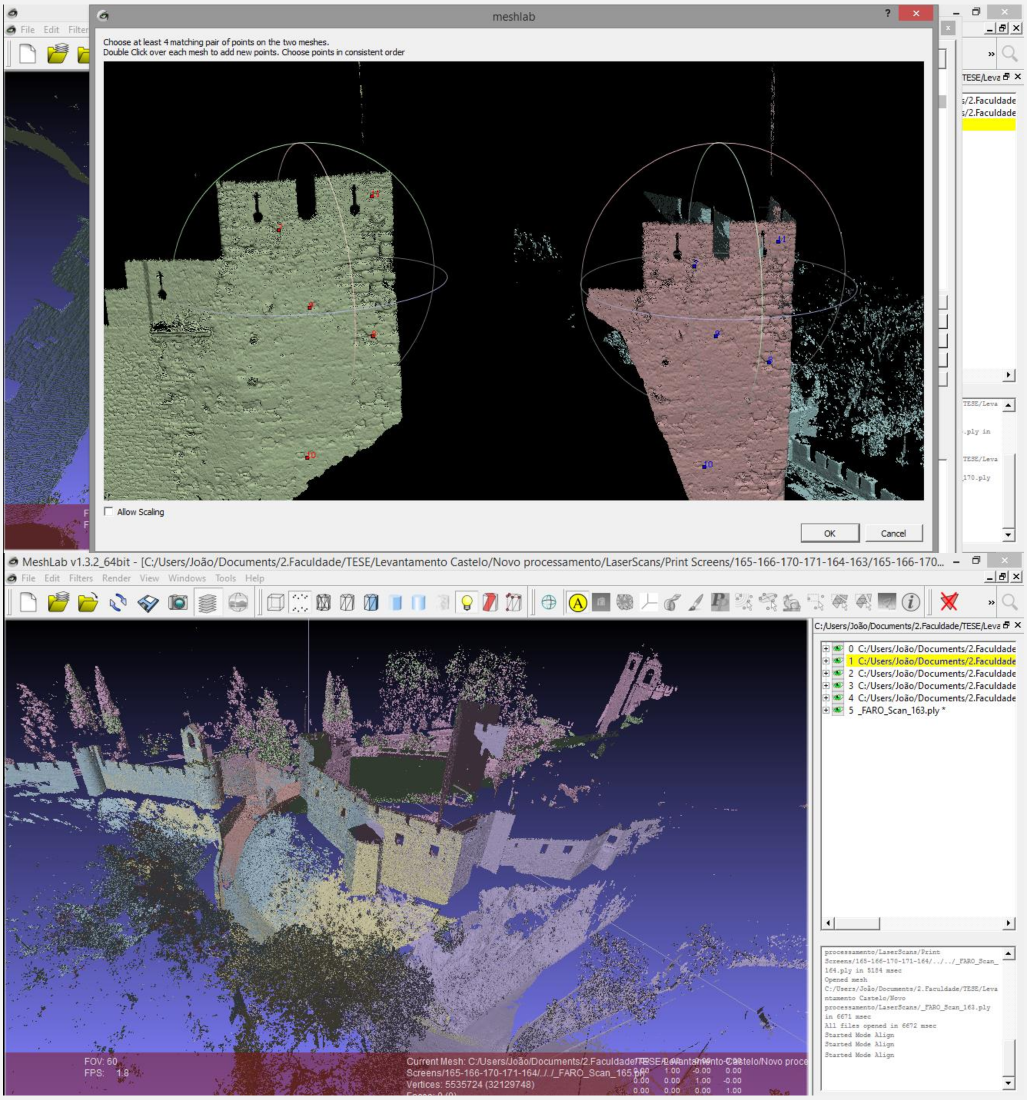


Figure 49: An example of point cloud alignment in MeshLab software. Top image: Example of the alignment procedure. Bottom image: All 6 laser scanning point clouds aligned.

In the following step, every point cloud is prepared to generate orto-images. To execute such step MeshLab and CloudCompare offer image capturing tools that instead of capturing the current resolution of the screen, a multiplier of the resolution of the screen is specified. Yet, before capturing images with high resolution (greater than value 1), the size of the points of the point cloud must be indicated. The point cloud allows the operator to visualize occluded surfaces through the foreground surfaces, which should be avoided when producing final drawings. To solve this, the size of each point is increased to occupy interstitial areas as best as possible.

However, as the density of the point clouds varies, positive results are scarcely obtained. Background surfaces are removed manually, despite being a labour-intensive work. In addition, point clouds cannot be simultaneously visible in MeshLab software. As a result, several screenshots are captured and merged in an image editing software by removing the background of the workspace. The problem of proceeding with this method is that, if the point clouds are not merged and segmented, points in overlapping areas will be above or underneath other homologous points when such should not occur.

Despite the point cloud displaying the correct scale, the final image must be scaled. Autodesk AutoCAD software is used to scale the image by using as reference the grid projected in the background of the point cloud editing software. Lines and hatches are created and sorted into different layers. The colours of the lines and hatches are irrelevant as they can be manipulated in the image editing software. For each layer a PDF file is created and imported as a raster image in the image editing software, that is, each PDF file corresponds to a layer. After adjusting and manipulating the raster images, the final product is exported as a JPEG or PDF.

The outputs of this workflow are vast. The final drawings are one plan and one section displaying various information at a drawing scale of 1:200: only point cloud; schematic drawings with shades to represent altitude differences; merely lines (traditional drawing); amongst other types of representative data. See *Figure 51*, *Figure 52*, and *Figure 53*.

Summary of the Workflow of the Office Phase

i) Processing images to acquire dense point clouds;

ii) Decimate point clouds to acquire light-weight versions to deliver outputs faster;

iii) Align light-weight point clouds to determine matrix transformations;

iv) Geometric quality assessment of the point clouds. If outside acceptable threshold limits redo step iii) any times necessary. If non-promising results are achieved, redo from step i);

v) Cleaning of the point clouds;

vi) Produce screenshots and merge into a singular image in an image editing software;

vii) Export and open in AutoCAD software to draw lines, hatches, solids, etc. and organize in different layers.

viii) Export each layer as a PDF file or raster image and open in Adobe Photoshop software for final touches.

ix) Lastly, quality assessment of the drawings and export the results.

5.3.3. Discussion and conclusions

After performing the first recording of The Castle of Tomar, it is unmistakable that a firm amount of field experience is required to be able to overcome setbacks. For this reason and from experience, it is recommended to perform several exercises to hone the skills. In our case, most of the skills for executing the second recording period were acquired by executing secondary case studies presented in the previous sections.

Relative to the recording of The Castle of Tomar, a few problems are identified. The use of an 18mm lens for a photographic camera with APS-C sensor does not grant enough FOV for recording narrow and hard-to-reach spaces. In addition, if different focal lengths are utilized, they must be fixed and previously calibrated. Moreover, the images used for making the transition between photographic datasets are as important as the photographic data sets, and images must be acquired methodically to ease the office work phase. Concerning the work during the office phase, unexpected software errors or problems may occur, for which surplus time should be assigned. Lastly, forethought and planning are of the essence to record more efficiently.

Figure 50: Office workflow to produce drawings during the first survey campaign.

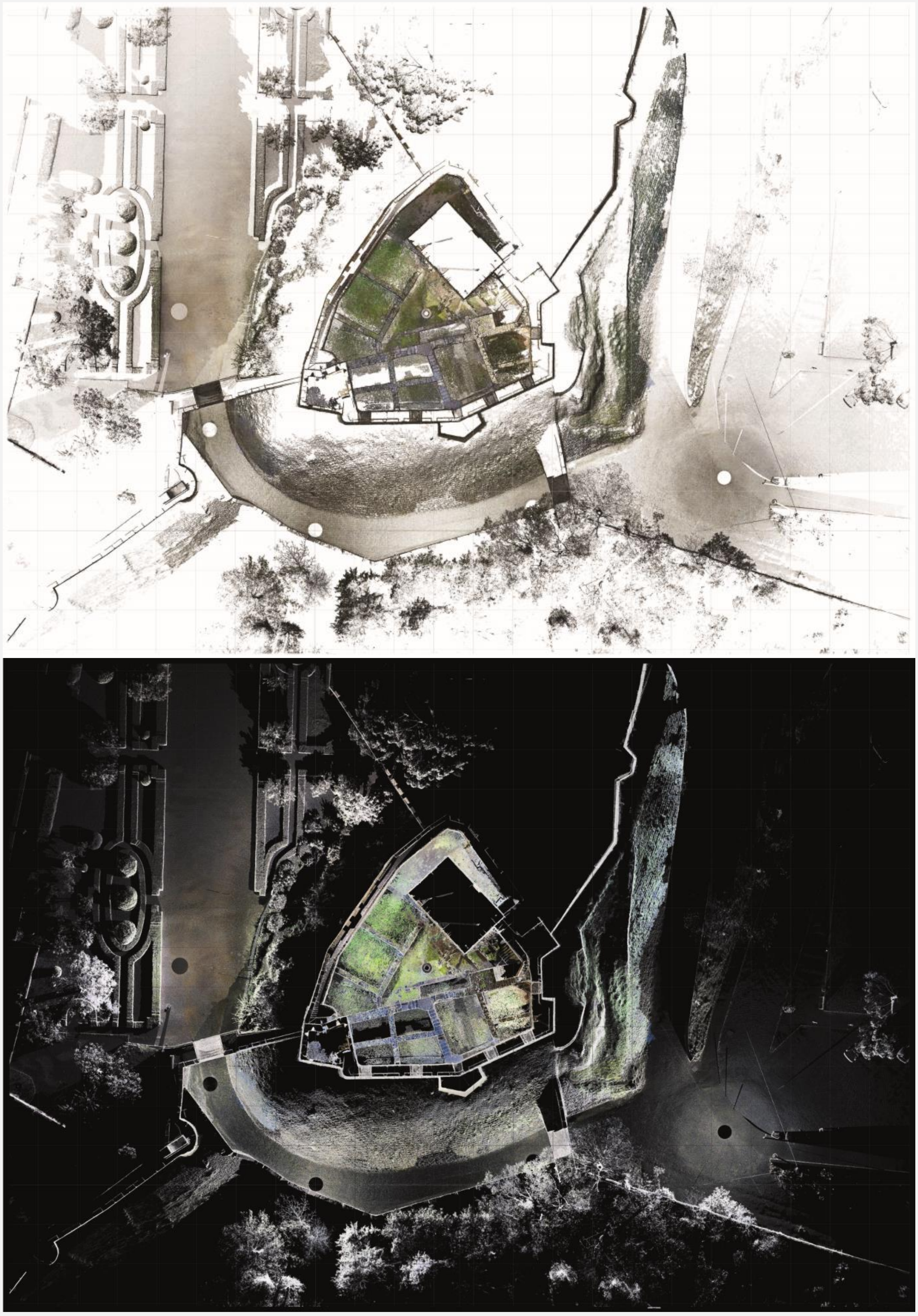


Figure 51: Plan view of The Castle of Tomar. Top image: Image exported from MeshLab software. Photogrammetric and laser scanning point clouds merged. Bottom image: Inverse background colour of the top image.

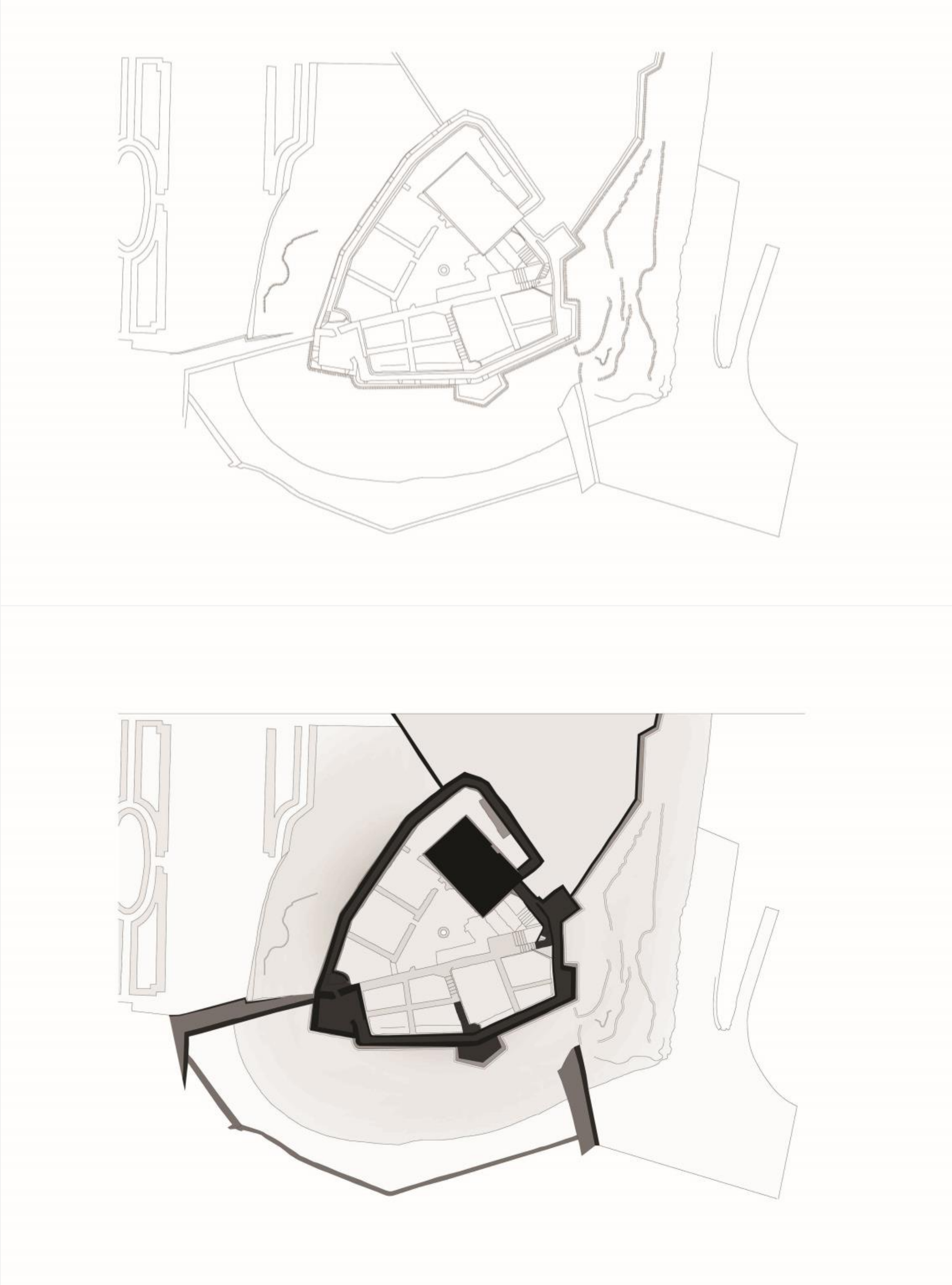


Figure 52: Examples of plans. Top image: Traditional 2D drawing of the Castle of Tomar. Bottom image: Schematic drawing. Darker colours correspond to higher altitudes. Information created from the TLS and photogrammetric point clouds.

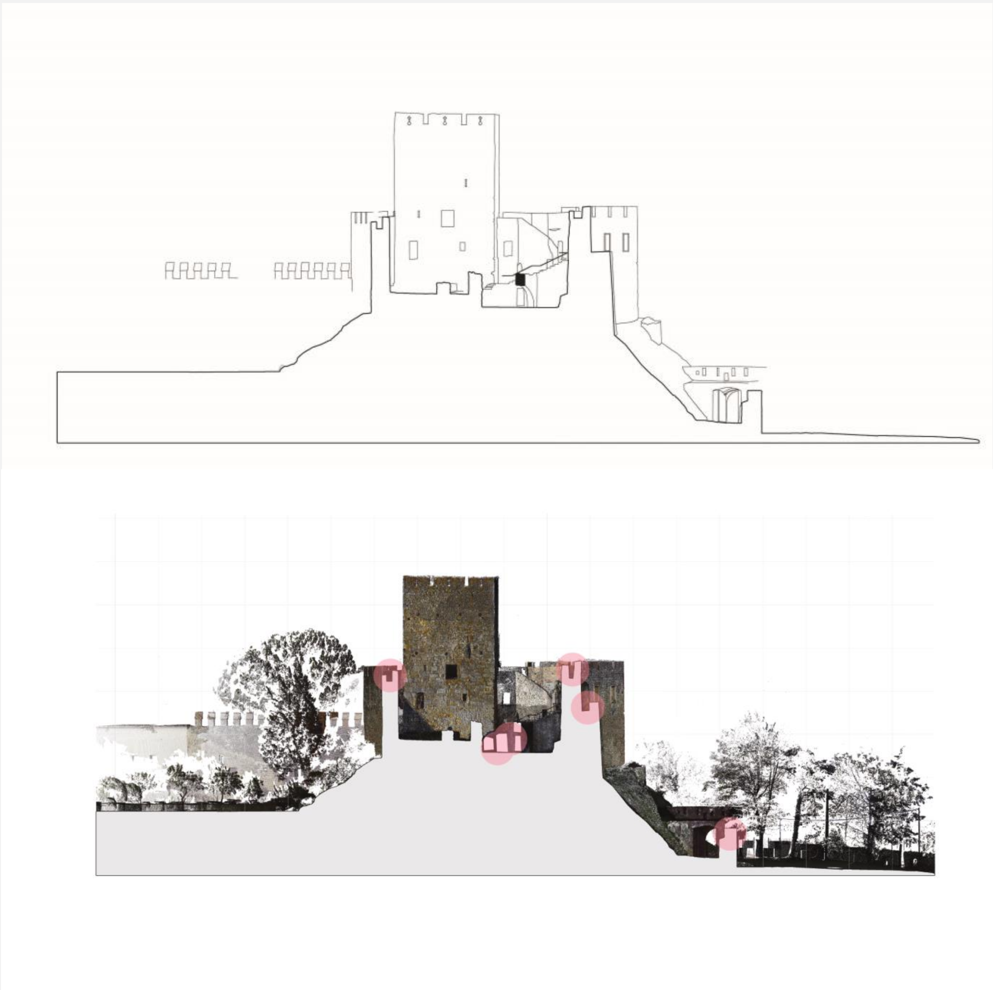


Figure 53: Examples of section cuts. Top image: Traditional 2D section cut drawing of the Castle of Tomar. Bottom image: Typical"2.5D" drawing using TLS and photogrammetric point clouds. Red circles display areas with missing information.

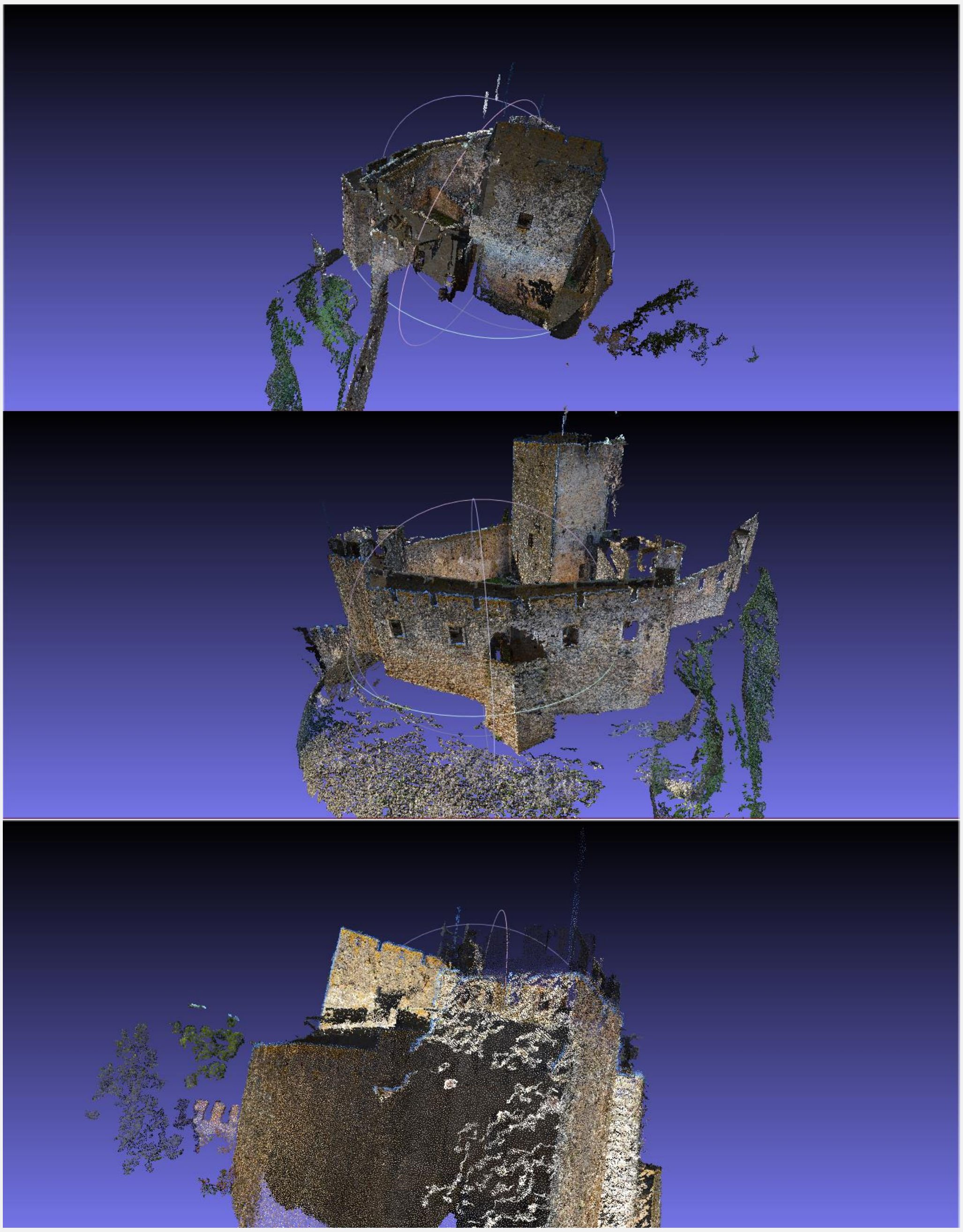


Figure 54: The quantity of information missing from The Castle of Tomar with the use of photogrammetric methods with conventional equipment.

5.4. Second Survey Campaign

While the first recording of The Castle of Tomar yielded minimally satisfying outputs, the results were inadequate to produce material at a drawing scale of 1:100. Much information was missing from the final point cloud. Undoubtedly this was related to the great complexity of the castle and the little experience of the surveyor. Particularly, the most difficult elements to capture in this type of military architecture are the battlements, narrow spaces, indoor spaces, bridges, wide areas followed by small areas, the transition between areas, spaces lacking illumination, elements occluded by vegetation, and so on.

Considering the previous outputs and overall experience, another recording campaign had to be considered to fully reconstruct the castle digitally. With such main objective, secondary exercises were performed to acquire basic knowledge, skills, and new methods. Thus, all work presented henceforth is based mostly on experiences acquired from the research presented in *chapter II*. Chronologically: the first recording campaign was performed in 2013; during 2014 and the first months of 2015 all research mentioned previously was executed; lastly, in 2015 the second surveying campaign of The Castle of Tomar was performed. See *Table 8* in the introductory part.

It was due to the exercises presented in *section I* that the surveyor was able to perform the photogrammetric acquisition more efficiently during the second recording campaign. By "efficiently" we convey the idea of: acquiring fewer photographs but with higher coverage; less time working on site and office phase; the quality and density of the point clouds and its influence on the production of valuable documentation; and the tools and software programs to achieve all the goals during the office work phase.

In addition, TLS is utilized by the research group in the second recording campaign to acquire a closed loop of scans to perform an analysis and quantification of the geometric quality of the point cloud generated via photogrammetric processes. For this purpose, GPS points were captured to provide with a global reference in which the photogrammetric and laser scanning point clouds are aligned relative to.

EMPLOYED EQUIPMENT

Hardware:	
Nikon D3100	(with APS-C sensor)
18-55mm lens	(fixed at 18mm and 55mm)
8mm	(fisheye lens)
Telescopic aluminium pole	
Wire straps	
Remote shutter	
Faro Focus 3D Laser Scanning	
DJI Phantom 2 Vision+	(utilized but its use was unnecessary)

Software:

Pix4Dmapper

MeshLab

CloudCompare

Adobe Photoshop

Autodesk AutoCAD

5.4.1. FIELD WORK

The most marking and unusual aspect identified during the recording in the first recording campaign is the minimally acceptable quality of the input data for processing photogrammetric point clouds. In a review of this disparity, it is related to the experience which has since then increased by personal exertion. Knowing that most of the images of the first recording campaign would not be useful in the office phase of the second recording campaign, it was intently considered starting the photogrammetric recording anew. The final documentation previously produced still is useful as it allowed sketching plans and foreseeing potential problems.

Nevertheless, however well prepared one is, problems arise when least predictable. Small problems are expected since the major ones were addressed in *section I* and solutions have been proposed. Occasionally small and unpredictable problems will undeniably prolong the recording time or office work. For example, when surveying dimly lit indoor spaces the flashlight of the photographic camera takes 12 seconds to recharge between each shot. In the case of photographing without the need for a flash, in 12 seconds 6 photographs are acquired instead of 1.

To complete the new recording campaign three days were needed and a total of 8163 images were acquired through a rigorous and well-planned strategy, starting from the parking lot or exterior (one end of the loop) and towards the interior of the citadel (the end of the loop). It can be thought of a spiral path that does not close in on itself exactly at the starting point.

Performing the recording in a pipeline fashion, it is assured everything is executed and nothing is forgotten unwillingly. Indeed, progressing in an unmethodical approach much may go unrecorded. For example, one of the major mistakes a surveyor should avoid is relying on memory. The appropriate approach is to annotate everything down, as referred in the 3x3 photogrammetric rules (Waldhäusl, P., Ogleby, C. L., Lerma, J. L. & Georgopoulos, 2013; Waldhäusl & Ogleby, 1994). In the second recording campaign, a plan was printed and sketched over to be used as a check-list. See *Figure 55*, also available in the annex 2 along with additional

Figure 55: A schematic plan displaying the main paths to follow and surfaces to register.

information. The sketching involved the drawing of the main path in which the surveyor must follow while recording. In addition, parallel lines to the surfaces were drawn and numbered. Such a method is valuable not only to acquire images in an organized fashion and ease the workflow in the office phase but also to know if said surfaces have already been recorded. In addition, to preserve the intelligibility of the drawing it was defined that all the checkmarks and scribbles should be drawn in supplementary sheets of paper, that is, checklists. In practice, for a specific recording day, all the intended surfaces to record were written down, and as work progressed, they were checked. The checklists were prepared before travelling to the site and for that reason also contained a checklist for the equipment to take.

Regarding the accomplishment of the tasks assigned to each checklist, most of the items were executed for the assigned day, even though it was expected to accomplish more than what was written in the checklist. This is related to the issue of encountering problems that delay the work. Yet, the approach of making checklists proved to be very productive. Nonetheless, if the physical structure of the castle and possible challenges were not known beforehand, the planning phase would have not advanced expeditiously. Therefore, from what has been experienced during the first recording campaign it is preferable and desirable to visit the site beforehand to look, see, and study to anticipate undesirable setbacks.

We emphasize "looking" and "seeing" for one may be looking but not truly seeing what may be there to be seen. This occurs more frequently than one is aware of. Often, one tends to see more when surveying because the site is being observed intently. To find anything "new" unexpectedly can potentially delay the recording. For instance, on the keep, there are epigraphic inscriptions that had to be photographed up close to acquire detailed data. However, when an epigraphic inscription was found in a hardly accessible area, the surveyor was required to think of solutions. In this case, a 55mm lens for an APS-C sensor format was used to photograph the epigraphic inscriptions on the main tower from the chemin de ronde.

Relative to the execution of the plan, it is advised to read the annex 2 to observe how the sets of images are structured. As aforementioned, the ideal photogrammetric recording is to acquire two types of images: images of individual surfaces; and transition images that connect said individual surfaces. Maintaining this mindset while recording at the site helps to proceed with higher confidence and certainty, thus more productive.

The full recording of the citadel was executed in three days in 2015: 9th of April; 30th of April; and 26th of May. For having a considerable amount of time between the recording days, office work advanced meanwhile. Therefore, sub-projects were generated to detect any geometric inconsistencies and other possible setbacks. This strategy was of pressing need to obviate the need for revisiting the site and acquire new data if the processing should fail.

9TH OF APRIL

On 9th of April the exterior (a), the area between the Porta do Sol and Porta de Santiago (b), and the mall (c) were recorded. Specifically, the exterior was subdivided into 3 main contiguous pathways from where the surveyor photographs.

In the first path (denominated “A” in *Figure 55*), from the Porta de Santiago to the highest altitude of the ramp, the batter and exterior surfaces of the wall were recorded in a similar approach mentioned in the first photogrammetric recording campaign, though with a few additions: i) use of 55mm focal length to capture the upper part of the wall in order to decrease the GSD and facilitate the identification of homologous points in the point-cloud software; ii) use of an aluminium telescopic pole with an 8mm fisheye lens to capture the horizontal surfaces of the batter, and to capture the battlements between the Porta de Santiago and the Porta do Sol.

In the second path (Identified as “A2” in *Figure 55*), which is next to the wall and above the batter, an 8mm fisheye lens mounted on an aluminium telescopic pole was utilized. For every two steps, 1 image perpendicular to the wall was acquired, 1 vertical image to capture the ground surfaces and the superior part of the batter, and transition images between the two images captured previously.

In the third path (Identified as “A3” in *Figure 55*), which starts from the Porta de Santiago and ends at the asphalt road in the parking lot, perpendicular images were taken in the same fashion as in the first path to record the gardened area and slope between the first and third paths.

The three data sets are connected using contiguous transition and remote transition methods. Particularly, each path is connecting with a series of photographs and each path is also remotely connected by using different focal length values.

Regarding (b) the area between the Porta do Sol and Porta de Santiago, a single path was formulated. The same approach for surveying was used as in the first pathway of the exterior space. However, instead of 1 perpendicular 18mm image for each position, 2 oblique 18mm images were acquired because the stones of the batter are prominent and without vegetation. On the opposite side of the batter, there are battlements, which were photographed divergently using an 18mm lens. In addition, an 8mm fisheye lens mounted on an aluminium telescopic pole was used to photograph the battlements as demonstrated in *"Survey of Complex Elements"*. In addition, 55mm images captured the top part of the wall that continues further to the South. Knowing that 18mm and 55mm images would not be matched together due to high GSD differences, the 55mm images were acquired a bit farther away than those acquired with the 18mm lens to allow positive image matching.

In short, from this single path, two sets of images were recorded, each of which points at opposite directions. The set of 55mm images of the wall is connected to the set of 18mm images of the wall and batter. The set of 18mm images of the battlements is connected to the set of 8mm images of the battlements. The connection between the battlements with the batter and walls was accomplished by photographing vertical and oblique 8mm images of the batter to connect with the set of 18mm images. Summarily, images are hierarchically connected: 55mm with 18mm, and 18mm with 8mm.

Yet, it is needed to connect the sets of images between the exterior area (a) with the sets of images of the area between Porta do Sol and Porta de Santiago (b). See *Figure 41* to see where the doors are located. Between the two areas, there is the Porta de Santiago that is inserted on a small gated wall with battlements and that resembles a bridge, which emerges from the batter. To record such, the batter was carefully climbed while carrying the recording equipment. Next, the battlements were recorded as presented in *"Survey of Complex Elements"*. No transition photographs were needed as the wall of the citadel was also present in the images. To have information of the doorway, images were captured using 18mm and 8mm focal lengths. This approach was also used to record the transition to the mall as there is another gated wall.

Figure 56: Example of the recorded data. From left to right: An 18mm image of the exterior area; An 8mm image acquired on the exterior area and adjacent to the wall; An 8mm image to make the transition between the sets of images; The vegetation occluding the wall.

Relative to the promenade area (c), two paths are considered. The first path is along the longitudinal axis of the promenade, and the second path is perpendicular to the promenade and leads to the quarters of the knights through the door. In the first path, images of the wall and main tower were captured using 18mm and 55mm focal lengths. However, the base of the wall is not visible from this POV due to occlusive vegetation. For that reason, images had to be acquired up close along the second path. In the second path, images were obtained using an 8mm fisheye lens. This path is for making the transition between the mall and the area of the knights. In addition, it served as a link to the path adjacent to the wall to acquire images of the base of the wall occlude by vegetation and images of the battlements of the Porta do Sol.

Furthermore, TLS recordings were executed by the research group during the recording session in the parking lot and the promenade. No scans were executed between the Porta de Santiago and Porta do Sol because it had been scanned previously in the first recording campaign. Unlike the photogrammetric recording, previously acquired information in the first TLS campaign still is valuable. The advantage of TLS is its higher freedom of positioning and reusability of the outputs as opposed to close range photogrammetry.

30TH OF APRIL

On 30th of April, the area of the knights (a) and grand part of the citadel (b) were recorded with photogrammetric equipment.

Regarding the quarters of the knights (a), several challenging elements are identified, such as a narrow passage leading to the citadel, a narrow spiral staircase leading to the chemin de ronde of the exterior wall that encloses this area, and the ground surfaces to register. To overcome such challenges, the 8mm fisheye lens was used to register the features effortlessly, particularly the spiral staircase in which merely one person can climb at a time. The remaining

Figure 57: Example of the recorded data. From left to right: An 18mm image capturing the wall and the keep as a transition element; A 55mm image to record with higher GSD; An 8mm image of the spiral staircase.

features, such as walls, were quickly structured and recorded with the use of an 18mm lens, and the 55mm lens was utilized to photograph the upper distant surfaces of the wall and the main tower to acquire enough GSD during the digital reconstruction.

Relative to the citadel (b), the same strategy was utilized as in quarters of the knights. Objects, walls, and spaces were subdivided into surfaces, and for each surface and transition between surfaces, a set of images was acquired. Most outdoor surfaces of the citadel were fully photographed with the use of the 8mm fisheye lens. Specifically, for each position, while photographing the ruins at ground level, 3 photographs were taken: 1 perpendicular to the surface; 1 oblique looking downwards; and the last one looking upwards. Thus, a full reconstruction is possible to execute, except for the horizontal surfaces above the height of the surveyor that had to be recorded while recording the battlements by using a telescopic aluminium pole.

In addition to the exterior surfaces, the 3rd and 4th floors of the main tower were recorded. Some challenges were faced while recording the indoor spaces due to the great difference in light intensity. In other words, the dynamic range of the scene was greater than the dynamic range of the imaging sensor, thus resulting in clipping of the highlights or shadows of the images. It was decided to produce images with the highlights clipped while recording the interior surfaces, otherwise said surfaces would present dark shades. For this reason, to execute the transition between the interior and exterior spaces, several photographs were needed to provide a smooth and continuous transition with the intent of facilitating the image matching in the photogrammetric software.

During this recording session, additional TLS were executed by the research team, particularly in the quarters of the knights with spheres on the floor. The spheres are useful for making fast semi-automatic alignments when using TLS software, in which an algorithm is run to detect sphere shaped surfaces.

26TH OF JUNE

A few areas were missing from the previous recording sessions and it was crucial to have information, such as the 3 recessed indoor spaces inside the walls, the indoor space of the tower wall, the 1st and 2nd floors of the keep, and the remaining surfaces of the battlements. For this reason, a third and last recording session was executed to complement the information.

Figure 58: Example of the recorded data. From the top left to the bottom right: An 8mm image capturing the battlements; An 8mm image to record the arrow slits; Exposure latitude problem; An 8mm image to go through extremely narrow spaces.

Most of the missing information to record in this session were indoor spaces. It was expected to finish the recording quickly, however, a major setback was encountered. All the indoor spaces were dimly lit or even pitch black. A light source had to be utilized. A flashlight proved to be inadequate for it created images with uneven lighting, therefore the flash of the camera was used but at the cost of delaying the total time to accomplish the recording. Every image could only be registered for every 12 seconds of recharging time of the flash. Since most spaces to record were indoors, it became a low-time efficient task. This method was practised for every indoor space.

The photographic camera could have been mounted on a tripod to acquire HDR images in a shorter time frame and without the use of a flash. However, such a solution is not applicable to every situation because taking a photograph with the flash on the shutter speed is set to 0.5

Figure 59: Left image: An example of a photograph with flashlight and flash as the source of light. Right image: An example of a photograph with flash as the source of light.

seconds, whilst photographing with a tripod and with the flash off it takes up to 5 seconds per photograph. Employing the latter method would lead to an unsuccessful reconstruction since the contiguous transition images would be blurry from photographing in unreachable positions for the tripod. For example, at least 100 images were acquired for making the contiguous transition between the 1st and 2nd floor of the keep due to the very narrow passage on the floor (literally a hole on the floor, see *Figure 59*) and light intensity differences. The images were shot while climbing up a ladder and with the camera over the head of the surveyor because there was no space for transitioning with the camera pressed to the body (that is how extremely narrow the passage is). At the same time and for every photograph the surveyor would need to be motionless. Regarding the battlements, the external row of images was recorded once more because the arrow slits were not visible in the first set of images acquired on 30th of April. It is important to have the arrow slits evident enough for the photogrammetric software to match the images with the sets of images acquired from the exterior side of the citadel with the use of the 55mm lens. Proceeding in this fashion increases the likelihood of generating a global project, instead of reconstructing geometrically incongruent point clouds that misalign. In addition, the remaining missing sets of images of the battlements were acquired.

Besides the recording of photographic data, 61 GPS points were recorded by the research team with the use of a Trimble R4 synchronized to a Control Slate, while having in mind the data

Figure 60: Professor Victor Ferreira acquiring a GPS point and photographing its location.

AREAS		Nº Points
	citadel	28 (1-28)
	knights	11 (29-39)
	mall/promenade	4 (40-43)
	between doors	9 (44-52)
	exteriors	9 (53-61)
TOTAL		61 points

Table 9: Index table of the collected GPS data.

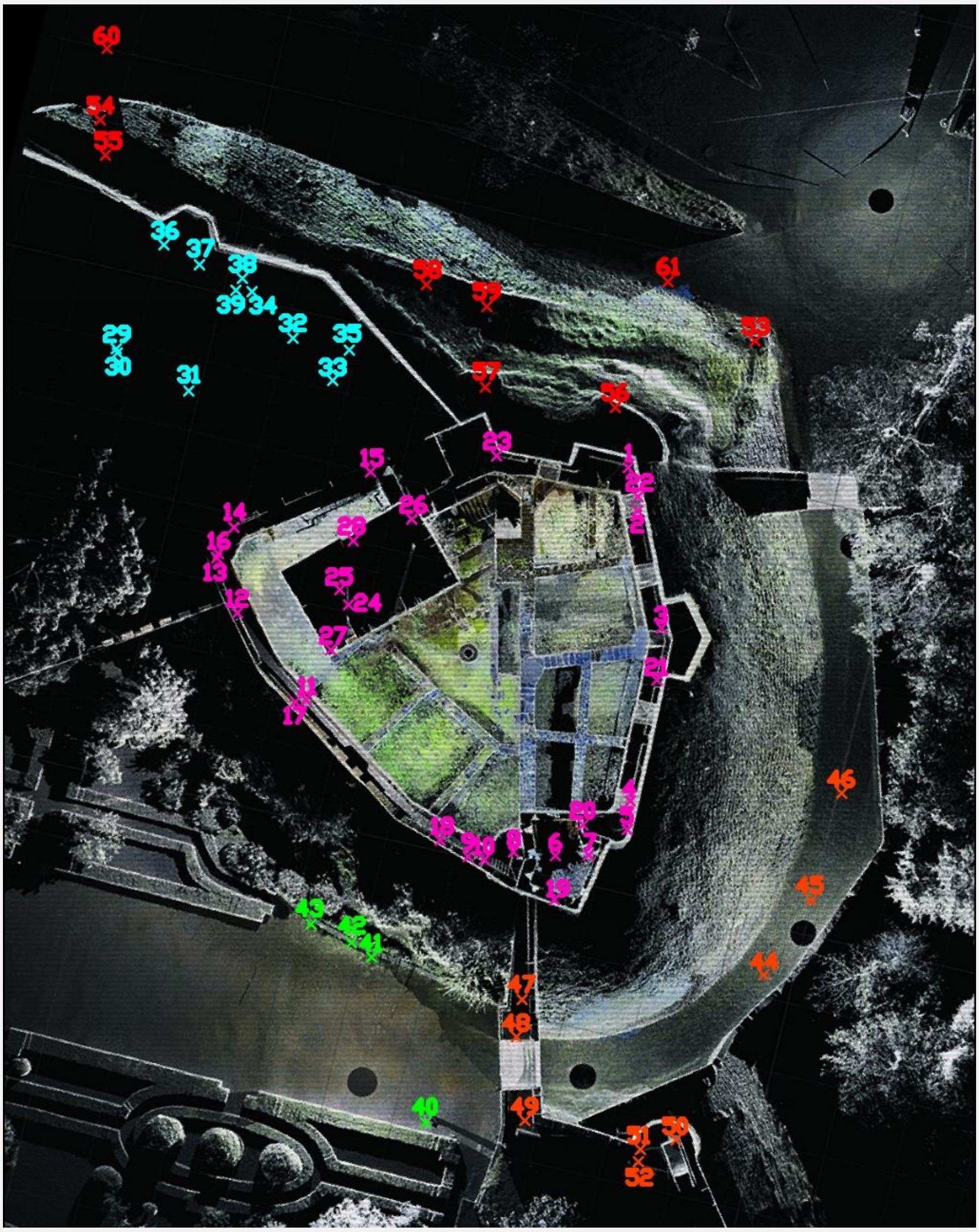


Figure 61: Planview of the GPS recording with the position of the GPS points.

~~captured by the TLS and photogrammetric equipment: 9 points in the exterior or parking lot; 3 in~~

the area between the Porta de Santiago and Porta do Sol; 6 at the Porta do Sol; 4 at the mall; 11 in the area of the knights; and 28 in the citadel. If both TLS and photogrammetric point clouds are aligned with the same GPS points, the probability of acquiring an accurate geometric overlap between the point clouds is higher, and thus allowing to easily study geometric discrepancies between the photogrammetric and terrestrial laser scanning point clouds.

In theory and idealistically 3 GPS points are enough to georeference. However, due to some factors such as inaccuracy and/or imprecision of the GPS surveying instrument, models generated through photogrammetric processes, manual selection of the homologous GPS points in the point cloud, and other occurrences, using 3 GPS points generates a model slightly larger or smaller than planned. For this reason, 61 GPS points were collected close to the edges of the 3D model and in as many different locations as possible, such as the battlements, the chemin de ronde, the last floor of the main tower, walls, pavements, and other features. Having coordinates as distant as possible from each other mitigates with maximum efficiency the error when scaling the point cloud. The inverse logic applies as the distance between the coordinates decreases since the inaccuracy and imprecision values remain equal. In addition, collecting more coordinates than necessary allows for greater safety in the workflow during the office phase because if the location of a coordinate is not legible or not precisely determined, there are other coordinates to resort to. Bearing in mind such potential problems, every GPS location was registered with a photographic camera to pinpoint the exact location.

In addition, a DJI Phantom 2 Vision+ was utilized during the recording sessions to capture aerial imagery. However, due to the application of the photographic camera mounted on an aluminium telescopic pole the photographic acquisition with the drone was obviated as there was full coverage of the site already.

Summary of the Field Work Phase

i) As opposed to the first photogrammetric recording campaign, the acquisition of photographic data followed a hierarchized plan in which The Castle of Tomar is broken down into areas, sub-areas, and surfaces, and paths to be followed meticulously by the surveyor. In addition, checklists were created for each recording session with the surfaces to record and the equipment to utilize.

ii) GSD was estimated to acquire material at a drawing scale of 1:50. For this reason, several focal lengths were utilized strategically.

iii) Images were acquired with high overlap to avoid any further additional recording sessions.

iv) The high experience acquired through the execution of secondary case studies reflected on the great quality of the recorded information in the main case study.

v) As expected, minor setbacks were encountered and properly countered given the experience and equipment available during the recording.

vi) For proper scaling of the photogrammetric model, the acquisition of GPS points was executed by the ARCHC_3D research team, in addition to the laser scanning recording to verify the geometric consistency.

5.4.2. Office Work Overview

The development of the tasks during the office work phase followed two similar approaches - referred as first approach *(a)* and second approach *(b)* -, executed in different periods of time, and focus mostly on the photogrammetric processing of the images to generate point clouds. It is noted that the second processing of the data generated optimal results beyond expectations. Afterwards, workflow relative to the production of outputs *(c)* is presented.

Before proceeding with photogrammetric computation, the collected data was organized in a hierarchized order as defined in *Figure 62*. Each subfolder is named after the area it corresponds to, in addition to the identified surface, and how the photographs were acquired. The photographs are renamed to easily identify which area they belong to and to solve problems

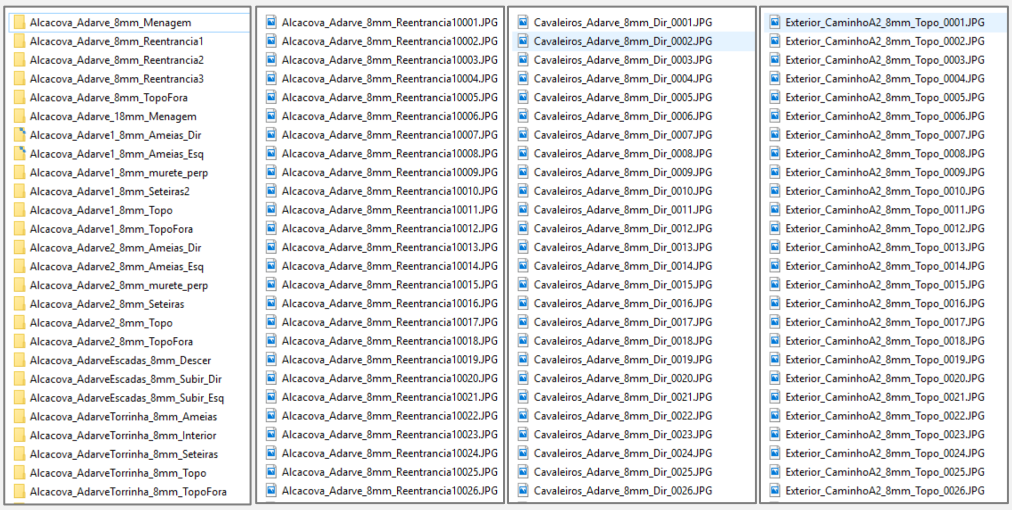


Figure 62: Example of how the photographic data is organized.

expeditiously. Such a strategy increases workflow speed without requiring the surveyor to dedicate additional time on identifying problematic images when software errors occur.

Independently of the first or second processing phases, imposing conditions were determined not only to control the quality of the data output but also to control the workflow. Being a photogrammetric recording in which 7919 photogrammetrically useful images were recorded, and due to hardware and software limitations that difficult the computation of a single and global project, imposing initial conditions for processing information proved to be a fundamental step to assure encouraging results.

Specifically, for a complete virtual reconstruction with geometric consistency, it is defined that the computation of the photographs must be executed in groups and said groups are merged in a posterior phase. For this intent and purpose, two major aspects are considered: i) verify if the sets of images from every defined area connect to each other; ii) and verify if the images recorded along the paths within each area interconnect. Depending on the possible connections between the various sets of images, an ad-hoc workflow is adopted.

5.4.3. Office Work First Approach

First approach – (a) -

As the recording of The Castle of Tomar was performed in three days separated by weeks in between, the first processing phase of the recorded images majorly focused on determining the interconnectivity between the sets of mages. It is confirmed, for the most part, the possibility to connect sets of images from contiguous paths and areas. However, such a condition is not positively verified for every adjacent area with no contiguous path to follow. For this reason, the interconnectivity occurs in a horizontal spiral, starting from the parking lot and ending in the citadel. The spiral follows the path a person walks to access the citadel.

In other words, contiguous connectivity of images between adjacent paths and areas is confirmed (between path “A1” and “B” as seen in *Figure 55*), but remote transition photographs between areas is not always confirmed (between the exteriors and the citadel) whilst it is confirmed between paths within the same area (between path “A1” and “A2” and “A3” as seen in *Figure 55*). Bearing in mind the previous information, manual tie points were selected in Pix4D software to merge the several computed point clouds to increase the geometric consistency. View *Table 10* to read the total number of processed sub-projects.

Almost 30 sub-projects were necessary to originate the final point cloud. Concisely, sub-projects containing information of a specific area were computed whenever a global project of that corresponding area was inconceivable. After generating projects for each designated area, said projects were merged into a single global project. During the merging process, the resulting point cloud was carefully examined to search for and identify geometric irregularities. If a geometric irregularity is observed, the merging process is recalculated for optimal results. In addition, the Pix4D software offers the user the possibility to view with precision the error associated to each selected homologous point utilized in the merging process. *See the reports of*

Area	Sub-Projects	Projects
Exterior	"torrinha_exterior"	"merge_exteriores2_good"*[3]
	"exteriores_caminhoa_murete_8mm"	
	"exteriores_a3"	
	"exteriores"	
Between Doors	"ponte1"	"merge_portas_pontes_2" *[1]
	"ponte2"	
	"ponte2_2"	
	"entreportas"	
	"_entreportas_atras"	"_ports_tudo"*[4]
	"merge_portas_pontes_2" *[1]	
Mall/Promenade &	"jardins"	"merge_jar_cav"*[2]
	"cavaleiros"	
	"espiral_bom"	"_merge_jar_cav_esp"*[5]
	"merge_jar_cav" *[2]	
Citadel	"adarve1"	"merge_alcacova"*[6]
	"alcacova_casas2"	
	"alcacova_casas3"	
	"_menagem_interior"	"merge_extalc_tor_intmen"*[7]
	"torrinha_exterior"	
Final	"__reentrancia1"	"tudo"
	"__reentrancia2"	
	"__reentrancia3"	
	"__torrinha_interior"	
	"__topofora2"	
	"merge_exteriores2_good"*[3]	
	"_ports_tudo"*[4]	
	"_merge_jar_cav_esp"*[5]	
	"merge_alcacova"*[6]	
	"merge_extalc_tor_intmen"*[7]	
Total Images	6769 enabled out of 6930 as input	

Table 10: The hierarchized structure to merge the several sub-projects in Pix4D software.

Pix4D in the annex 2. In total, approximately 400 million points were projected, including spurious points, and “sky densification” as revealed in *the annex 2 as well*.

It is crucial to note that during the first photogrammetric processing, the operator could have generated outputs with a higher number of points. See *Figure 63*. Specifically, Pix4D software allows to group images before exporting the outputs so to generate a denser point cloud for each group of images. Said feature is imperative due to hardware limitations. In other words, the same hardware is fully utilized to calculate denser reconstructions for smaller sets of images. For the first processing, the images were organized into merely one group as this feature was unknown. In addition, the point cloud was not georeferenced in Pix4D with relative to the GPS points, thus generating a model out of scale.

For this reason, and as approximately three-quarters of the images were acquired with the use of a fisheye lens, which contains high distortion values, an objective and rigorous analysis of the final point cloud was a decisive key point to confirm positive geometric consistency. Thus far, the point cloud was analysed visually by the operator. Therefore, for quality assurance, it was established an imposing criterion: the photogrammetric point cloud must be compared to the point cloud generated via the use of TLS, and after proper alignment with the GPS points. The reason for utilizing GPS points to georeference the models relates to the need for producing specific outputs, as the administration of The Convent of Christ requires orthogonal drawings of The Castle of Tomar. Georeferenced models are scaled and oriented correctly, allowing to study another phenomenon such as the relationship to other volumes or even relative to the Sun.

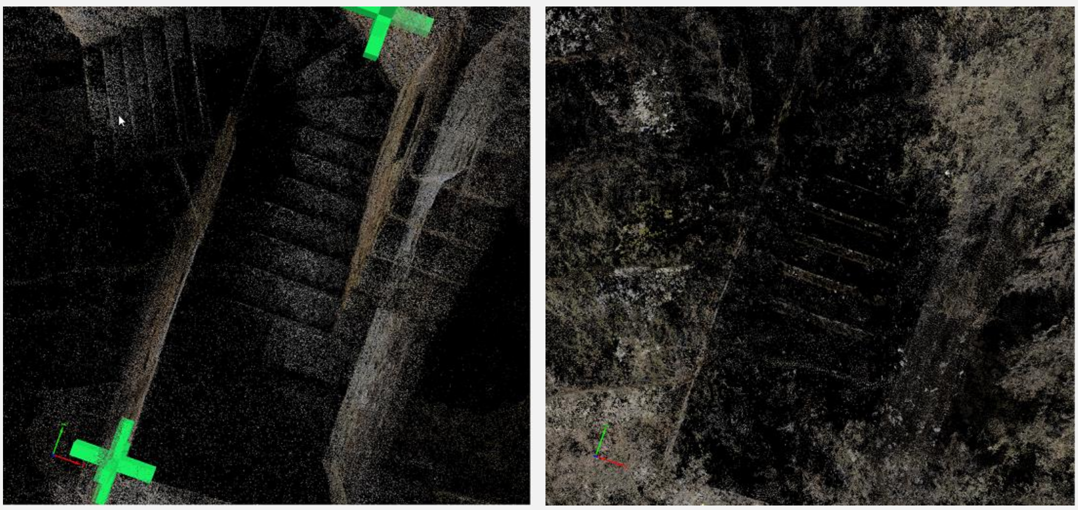


Figure 63: An example of output from the first processing using Pix4D software. The image on the left: Sparse reconstruction. The image on the right: Low dense reconstruction with a lot of spurious data.

TLS provides essential data to analyse the geometric integrity of the point clouds due to its more stable accuracy when compared to the photogrammetric processes. Although the use of fisheye images was tested during the secondary case studies, the use of TLS data ensures the verification of the quality of the 3D model. This proves essential due to the nature of the surveyed object, a world heritage construction. In addition, geometric abnormalities may not be detected even to a trained eye due to the nature of the point clouds themselves, in which points composing a volume are difficult to read due to other points presented in the background and foreground simultaneously.

To control the geometric regularity, the photogrammetric point cloud must be cleaned to enable an accurate comparison of the values when calculated in CloudCompare software.

Figure 64: First step of the office workflow to prepare the data for further post-processing.

Before the exportation of the photogrammetric point cloud, Pix4D software offers a cleaning tool in which images are manually masked and posteriorly processed to remove the reprojected points. The use of such a tool would prevent the delivery of results within a reasonable time-frame because each masking and respective processing takes on average 30 minutes for the magnitude of the current project. As a result, an algorithm was developed to exclude points falling within specific colour ranges. *See the annex 2*. The following step consisted of executing a manual cleaning of the remaining spurious points and reinserting points that were automatically excluded with the use of the algorithm.

Once all point clouds are cleaned and ready for subsequent processing steps, the georeferencing step is executed. The GPS points allow the operator to scale, orient, and georeference the 3D model. Nonetheless, the GPS data must be prepared as well. The information provided by the Trimble R4 is in the form of a DXF file format. The points are automatically positioned and visible in the Model Space in Autodesk AutoCAD software, and to acquire the x, y, and z coordinate values the user must input the command “ID” for each selected GPS point. Note that the values are of considerable length, and the GPS points are positioned far away from the Origin Point on the Model Space. In addition, coordinates with high values are not applicable as input in some software due to a limited number of characters input. Therefore, to

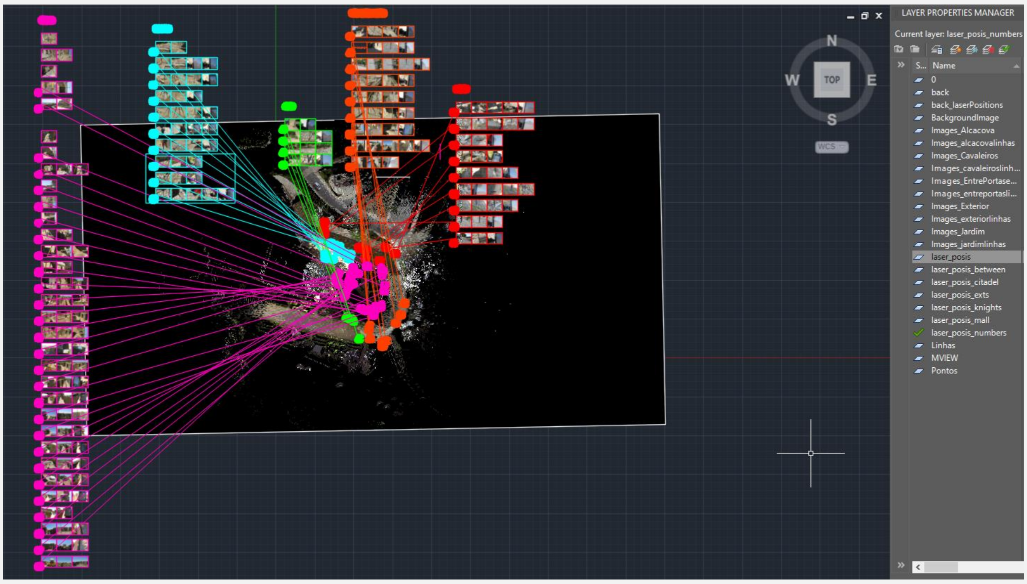


Figure 65: Preparation of the GPS data in AutoCAD Autodesk software.

avoid miscalculations and maintain the proportions, all points were translated in the x and y-direction to the first quadrant by issuing the command "UCS". The coordinates have positive and low values for x and y variables. The values for the z coordinates remain unchanged. For example, coordinate nº29 had the values: x = -24461.071; y = -7139.6082; and z = 120.6689; The values were changed to: x= 31.755; y= 65.3172; and z = 120.6689. The downside of modifying the values reflects on the untrue world position of the model. However, since the original GPS values are stored, the operator only requires undoing the translation operation once the model has been scaled and oriented. Furthermore, to facilitate interpretability, and not require the use of memory, the images of each GPS point were inserted in the AutoCAD file. See *Figure 65*.

After preparing the GPS data, the following step consists in georeferencing the point clouds originated via photogrammetric and TLS processes with the GPS points. See *Figure 66*. The operator must proceed with greater care to generate optimal results and thus outputs with correct proportions. The first step is to identify the location of at least 4 common GPS point locations present in the photogrammetric and TLS point clouds. Merely a few acceptable and common GPS points were identified, but less than 3 are considered within reasonable and acceptable limits due to low spatial resolution or difficulty to pick the exact position in the photogrammetric and TLS point clouds. The major problems are the location of most of the GPS points in areas visible in the photogrammetric point clouds but not visible in the TLS point clouds, such as battlements, and chemin de ronde. For georeferencing, at least 3 points are needed to perform translation, rotation, and scale transformations.

Figure 66: The ideal workflow to georeference photogrammetric and TLS point clouds.

For this reason, another approach was considered - view *Figure 67* - , but such approach only allows to georeference and does not provide with the necessary conditions to perform an analysis on the geometric consistency of the photogrammetric point clouds. To perform the latter, it is required an independent alignment of the photogrammetric and terrestrial laser scanning points clouds relative to the GPS data. The new approach requires the alignment of the photogrammetric point clouds relative to the TLS points clouds, after the alignment of the TLS data to the GPS points. For that purpose, JAG3D software is utilized for it provides the user with 4x4 matrix transformations, usable in software such as CloudCompare or MeshLab. Although the new approach is not ideal, it still allows a better alignment of the photogrammetric point cloud relative to the TLS point cloud. Therefore, the GPS data, in this context, has the main objective of georeferencing the model than exactly to perform an accurate and precise assessment of the geometric quality of the photogrammetric point clouds.

As laser scanning provides data with accurate zenith direction, the transformation parameters were calculated using 3 GPS points and in two sequential steps to avoid vertical misalignment: first, a transformation for both X and Y axis is computed with scale constriction turned on, then the translation is calculated for the Z axis. Next, the two matrices are multiplied resulting in the final one. Particularly, as the transformation values in the first and second matrices occur in non-homologous elements of the matrices, the non-transformed elements (same values corresponding to an identity matrix) in the first matrix can be replaced with the transformation values of the corresponding elements from the second matrix transformation. Finally, the ICP algorithm is executed to adjust minor misalignments between the sets of point

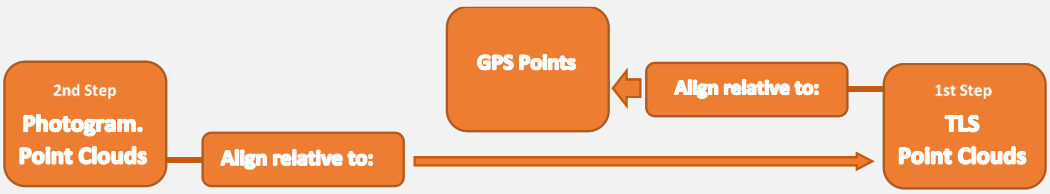


Figure 67: The workflow to georeference the data considering the encountered setbacks.

clouds. Such method avoids originating a 4x4 transformation matrix that tilts and scales the 3D model.

Regarding the photogrammetric point clouds, 8 points from the TLS point clouds were used to determine the transformation matrix parameters in one step for the X, Y, and Z axis, and scale constriction was turned off - that is, an operation that solves the scale and orientation in one step. The reason to proceed in one step relates to the lack of true scale and inaccurate zenith direction of the photogrammetric point clouds. Executing transformations along X and Y axis without activating Z axis results in a tilted model whose dimension is greater than the model in the correct location. Furthermore, posteriorly executing a transformation along the Z-axis in the same fashion as in the TLS point clouds merely translates the output and preserves the tilting. In other words, to perform a transformation in which scale constraint is turned off, the three axes, X, Y, and Z, must be calculated in one operation to maintain the proportions of the model. After calculating the 4x4 matrix transformation, ICP algorithm in MeshLab software is applied to the photogrammetric point clouds while having the TLS point clouds as a reference to accomplish minor adjustments. In short, translation, rotation, and scale were calculated in one operation.

Performing the formerly referred steps prepares the data to undergo a rigorous geometric analysis and determine if the point clouds are acceptable for further operations. Note that, as there was no independent alignment of the photogrammetric and TLS point clouds, the geometric analysis is considered more of an "estimation".

In the following step, an algorithm developed in the context of the current thesis and for the thesis of another student is executed for both the TLS and photogrammetric point clouds to produce contour lines. Contour lines, being thin horizontal slices, are the best method to search for any geometric incongruencies from the top view or by examining section cuts. Conventional contour lines are typically displayed in specific colours to indicate different altitude values in ranges. However, for the geometric analysis, the red colour is assigned to the photogrammetric data, and the green colour is assigned to the TLS data. Next, one high-resolution screenshot of each data is acquired in CloudCompare and blended in Adobe Photoshop, originating a third colour for overlapping areas: purple. Many incongruences are detected and measured in AutoCAD software. Idealistically, the perfect project would display every contour line in purple colour for the equivalent recorded areas. See *Figure 68*.

Particularly adopting the proposed workflow requires the operator to analyse from top view to detect parallel lines in areas containing slopes or ramps. As a rule of thumb, the farther

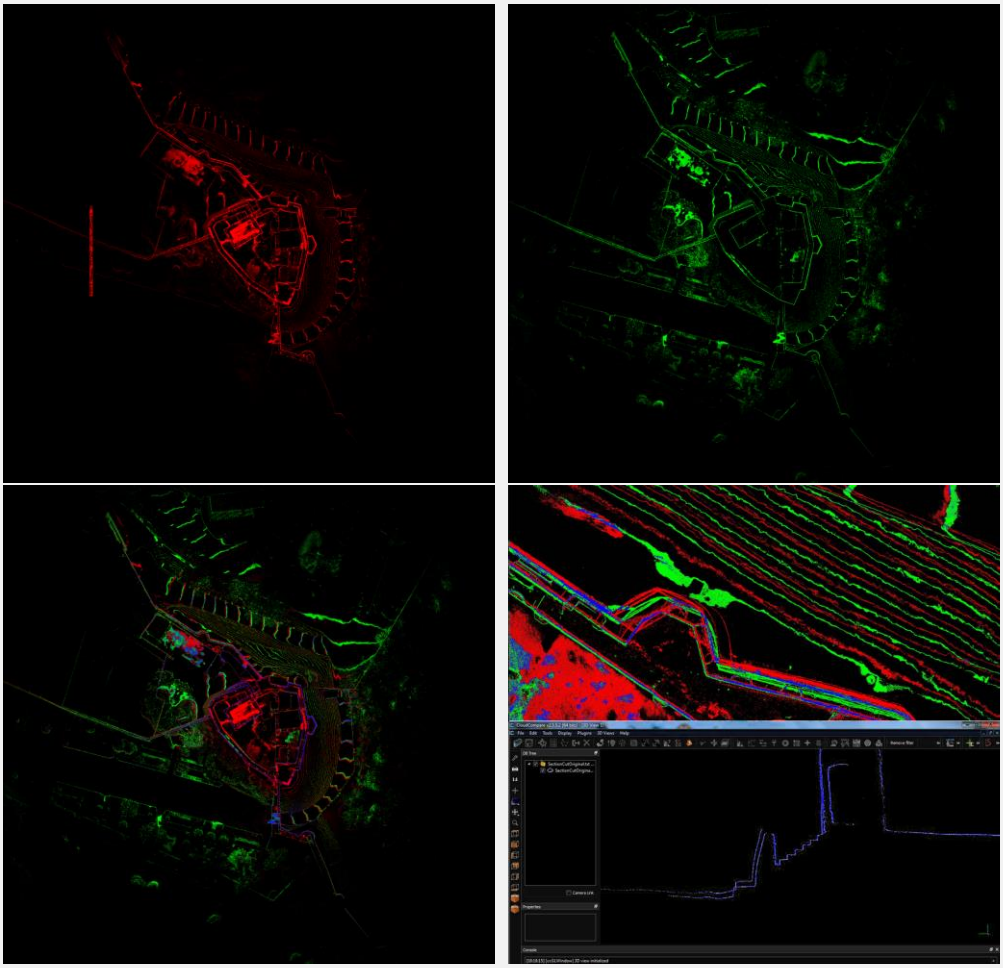


Figure 68: Analysis of the geometric quality of the photogrammetric data by comparing to the TLS data. From the top left to the bottom right: Photogrammetric data; TLS data; Overlapping of photogrammetric and TLS data displayed in purple; Errors detected.

apart the parallel lines are, the greater the geometric irregularity. Yet, even if the overlap is confirmed in vertical walls, proper alignment in the vertical direction is not guaranteed. For this reason, section cuts are executed to detect parallel lines on the top and bottom parts of vertical elements. To determine specific values, measurements are executed in AutoCAD by inserting the image and scaling said image relative to the GPS points.

There are other methods to proceed with the geometric quality assessment by applying tools readily available in point cloud editing software. For example, CloudCompare software

Figure 69: The workflow to execute the geometric quality assessment.

offers the possibility to run "compute cloud/cloud distance" and inserts a gradient map to the source cloud considering the distance values (using Haussdorf distance method) between said source cloud to the target point cloud. The tool runs after calculating an octree to accelerate the processing, but at the cost of accuracy. To maximize the accuracy the octree value is set to the highest computable value possible. However, due to the size of the point clouds, the tool is inexecutable even if said point clouds are further subdivided into smaller sizes. For that reason, calculating contour lines proved to be an expeditious method but at the cost of precision at determining the distance values between the point clouds. Such condition did not impede precision measurements down to 0,5cm of distance. The measurements are executed manually because projecting a gradient map over the photogrammetric contour lines proved to be difficult to interpret and compare to the TLS point cloud.

In the end, most deviation values were approximately 1cm, which is within acceptable limits to produce material at a drawing scale of 1:50. The remaining deviation values, like the ones visible in *Figure 68*, were up to 20cm. In addition, high inconsistency and critical problems were detected that obligatorily forced the processing of photogrammetric data ex-nuovo. Such critical problems include multiple parallel reprojections of surfaces in crucial areas, for example, the exterior wall; the pathways leading to the promenade; and others.

SUMMARY OF THE FIRST PROCESSING OF THE DATA

i) TLS point clouds decimated and inter-aligned using semi-automatic and manual approach.

ii) Photographs processed in Pix4D software in a structured fashion to generate point clouds. Several sub-projects created to overcome hardware and software limitations so to create a global project.

iii) Discovery of features that could have been used before starting the photogrammetric processing: grouping photos to increase the density of the outputs; inserting GPS points in the first sub-projects to georeference the model.

iv) Development of an algorithm to remove spurious points and sky densification in an automatic approach, followed by manual clean-up of the point cloud.

v) Georeferencing of the TLS point clouds relative to the GPS points, and alignment of the photogrammetric point clouds to the TLS point clouds.

vi) A few setbacks were encountered due to hardware and software limitations, which led to the search for solutions to increase workflow speed. Development of an algorithm to create contour lines from point clouds.

vii) Geometric quality assessment of the photogrammetric point clouds while taking as reference the TLS point clouds. Application of the developed algorithm to create contour lines to perform the geometric quality assessment.

viii) Detection of misalignments and critical problems such as “multiple parallel wall effect” – reprojection of the same feature around the same area.

ix) The decision to redo the photogrammetric processing as the quality of the point clouds does not allow the production of material with minimal quality.

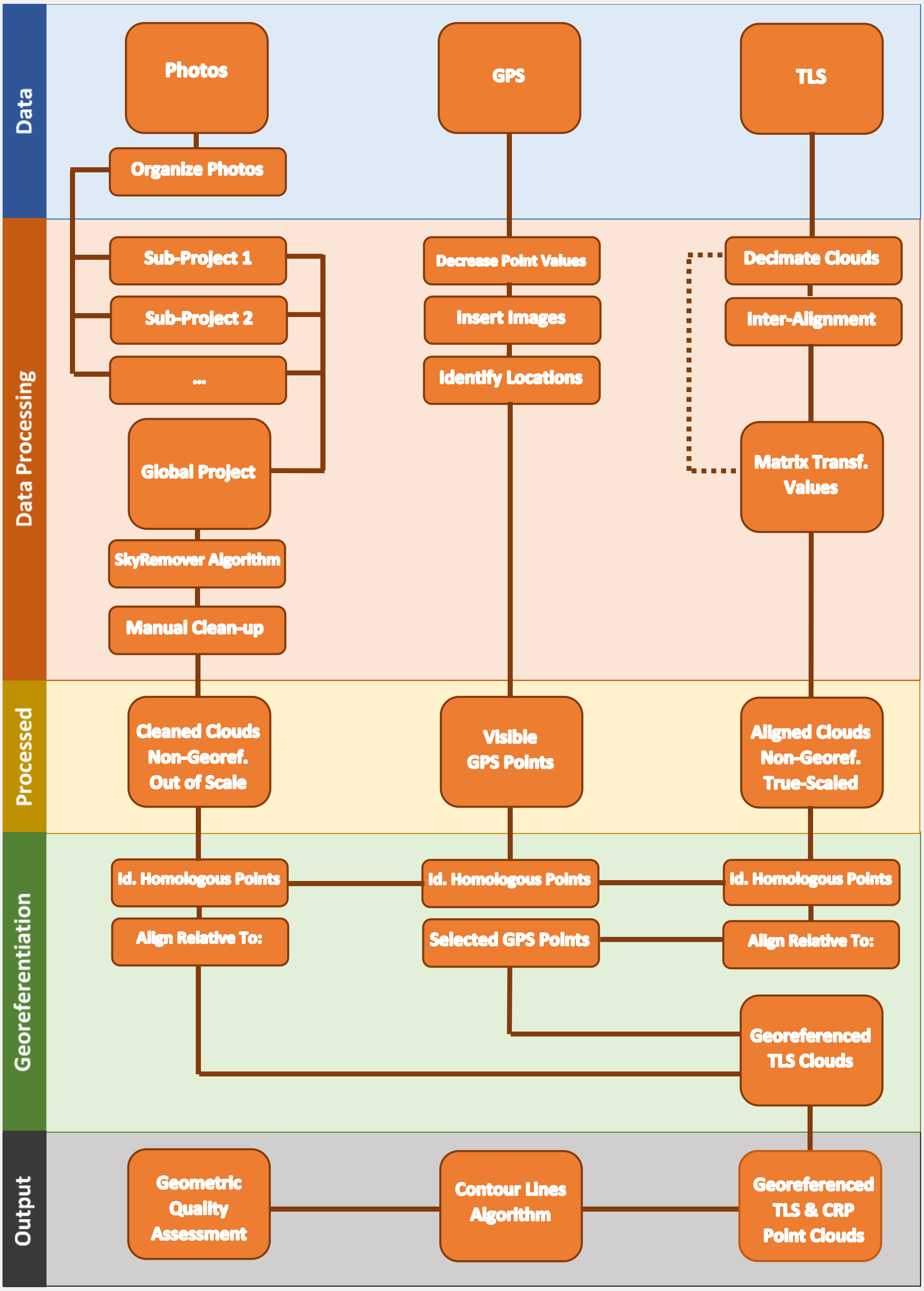


Figure 70: Workflow used in the first processing of the data

5.4.4. Office Work Second Approach

The second approach – (B) -

In the second approach of processing the acquired data, the workflow followed the formerly presented workflow structure but with a few minor changes to ameliorate the quality and speed of output delivery.

In Pix4D software, once more, the strategy consisted in creating sub-projects to be merged into a global project. See *Table 11*. This time, and from the start, images were selected into several groups and 19 GPS points, out of 61 points in total, were introduced – points nº 2, 6, 8, 9, 10, 11, 29, 30, 31,32, 43, 44, 45, 46, 49,55, 56, 57, 61. See *Figure 61*. See the annex 2 as well. Inserting GPS points in Pix4D proved to be the most efficient method to process the photogrammetric point clouds because, not only sub-projects are merged faster and with the right proportions for each segment, but also increases the geometric consistency of the data. In other words, on close inspection, no multiple parallel walls were detected, even when utilizing section cut tools from Pix4D software. Note that analysing the model in Pix4D proved to be difficult due to massive clusters of sky densification. Approximately 3 weeks were needed to process the model.

To introduce GPS points in Pix4D, the operator creates a "3DGCP - Tie Point" (3D-ground-control-point) and inserts the GPS coordinates. Next, the location of the point is selected across multiple images, which is advantageous for two reasons. First, the higher the GSD value, the lower

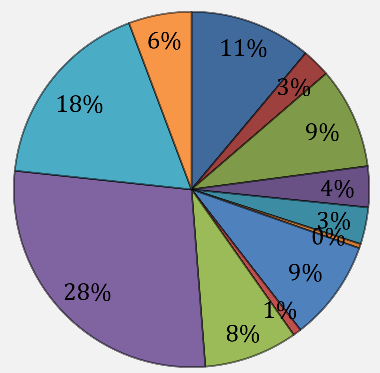
Area	Sub-Projects	Projects
Exterior Between Doors Mall/Promenade Knights battlements	"best_extna1na2ndoors"	"mer_test_battlsnext"*1
	"mer_best_ext_50mm""	
	"best_parklot"	
	"mer_battles2"	
	"mer_battles2"	"mer_test_battlsncavjar"*2
	"best_jarncavnponte"	
	"mer_test_battlsnext"*1	"mer2_extnjarncavnbattls"*4
	"mer_test_battlsncavjar"*2	
Citadel	"best_housing"	"mer_best_hous_ints"*3
	"best_indoor1"	
	"best_indoor3"	
	"mer_best_hous_ints" *3	"mer2_best_citnhouseints" *5
	"mer_best_citadel"	
Final	"mer2_extnjarncavnbattls"*4	"mer3_everything_GPStoprocess"
	"mer2_best_citnhouseints"*5	
Total Images	7176 enabled out of 7576 as input	

Table 11: The hierarchized structure to merge the several sub-projects in Pix4D software

the precision there is for determining the exact location of the GPS point. Therefore, selecting the same GPS point in more than one image mitigates the uncertainty value. Secondly, there is a small and unavoidable margin of error when selecting the pixel since the interpretation of the image is required and is affected by the GSD. Furthermore, the uncertainty of the GPS point location increases if considering the uncertainty value associated with the GPS survey equipment. For the prementioned reasons, almost all GPS points were selected with an accuracy of 2cm and yielded an RMS error of 4.7cm.

Pix4D generates reports for every processing allowing the operator to determine the quality of the computed data. For the second processing: approximately 700 million points were calculated from the 94% of processed images (7176 out of 7576); the GSD is 2,2cm on average.

The Castle of Tomar	Nº Photos	from which nº photos: 8mm Lens	18mm Lens	50mm Lens
exterior	889	351	420	118
bridge 1	208	118	90	
between doors	738	129	511	98
bridge 2	298	247	51	
mall	268	117	128	23
transition - mall to	32	32		
knights	732	263	455	14
transition – knights to	60	60		
citadel	682	682		
citadel – chemin de ronde and	2144	2144		
citadel – keep	1410	1410		
unsystematic	458	405	53	
TOTAL	7919	5958	1708	253



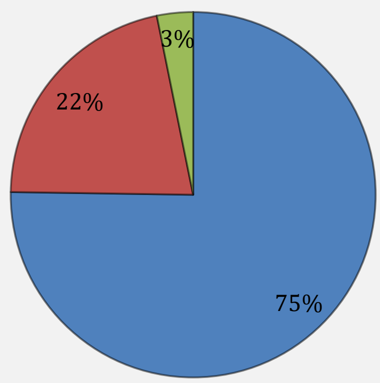


Table 12: Statistical data for the recorded images.

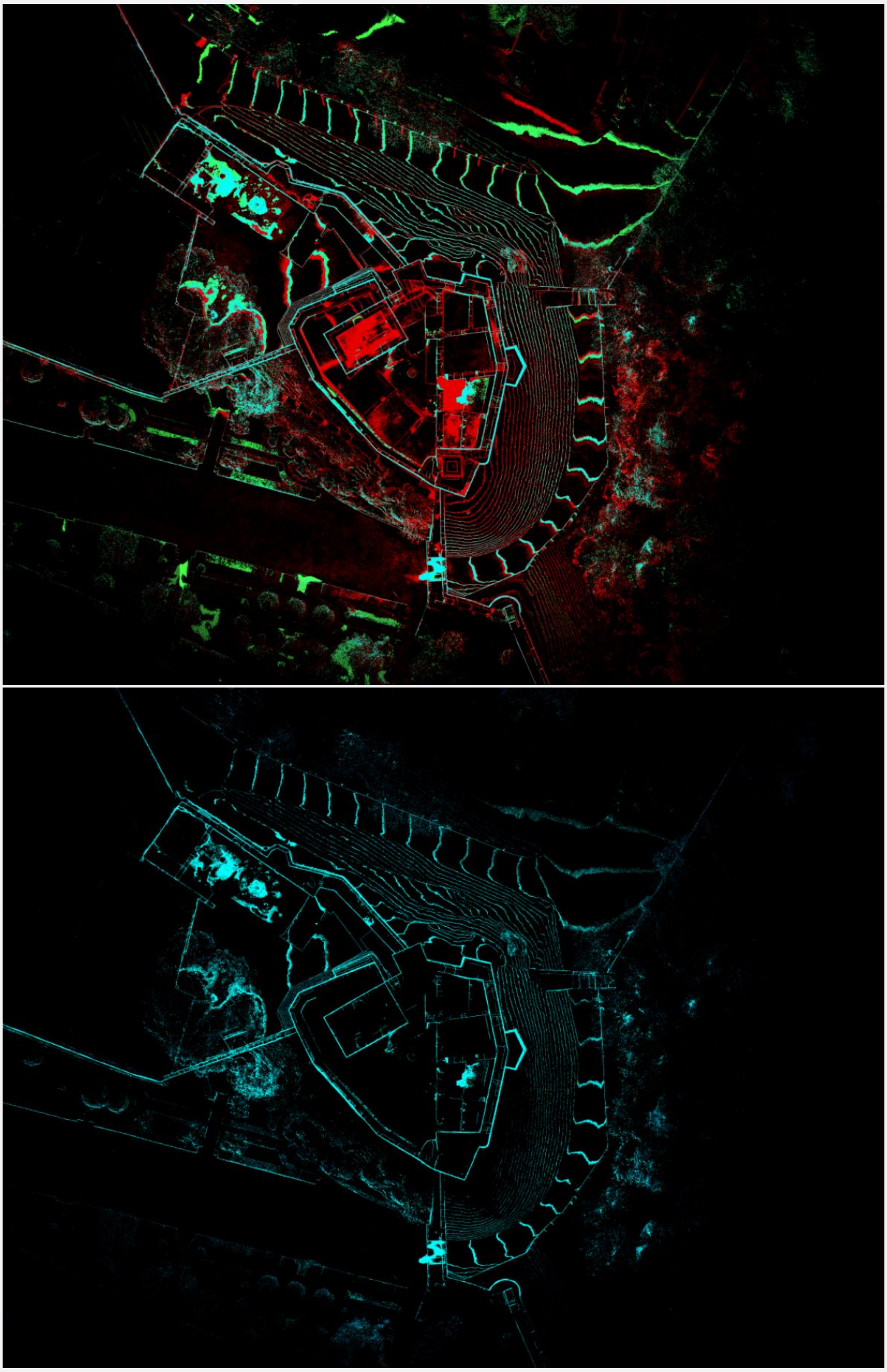


Figure 71:Geometric quality assessment. Top image: Overlapping(cyan) of TLS (green) with CRP (red). Bottom image: Overlaps only.

The GSD parameter should be interpreted as a guideline rather than as a true value. The reason is related to the fact that three-quarters of the images were recorded with an 8mm fisheye lens, in which the GSD value is predominantly higher for the pixels closer to the edges of the image plane. In addition, dense point clouds were populated by major clusters of sky densification at a fair distance from the castle, which contributes negatively to the calculation of the true GSD value.

Following the exportation, application of SkyRemover algorithm, and manual clean-up of the point clouds is executed, and CloudCompare was utilized to calculate the density of a few segments. Calculating point cloud density of the whole project proved to be a challenge due to hardware and software limitations. In other words, in CloudCompare an octree must be calculated and selecting extremely high values to allow accurate and precision acquisition of values requires resources beyond those that are available. For the calculated segments, CloudCompare yielded values around 1cm, or even 5mm in some cases. Bearing in mind that even though cloud density is not the same as GSD as not all pixels are projected, the fact that point cloud density is approximately 1cm or less means that GSD is at least less than 1cm for the areas of interest, as opposed to the 2.2cm in the Pix4D report.

To produce material at a drawing scale of 1:50, 1cm of point cloud density is within the acceptable limits bearing in mind that graphical "errors" can be considered within a threshold from two to three-tenths of a millimetre. In other words, for material at a drawing scale of 1:50, the point cloud density must be at least 1 cm (1cm : 50 cm | 0.1cm : 5 cm | 0.02cm : 1cm) (Docci & Maestri, 2005; Mateus, 2012).

The calculation of the point cloud density was achieved after executing the same process of cleaning the point clouds as in the first processing phase. First, SkyRemover algorithm is executed, then manual cleaning over a period of 3 weeks. One of the downsides of executing of a manual clean-up is the inevitable situation of appearing points when least expected while the operator may consider the clean-up process finished.

The last and most important step of the second processing of the photogrammetric data is the geometric quality assessment. Once more, the contour lines algorithm is executed providing with thin slices of the point cloud at specific intervals. Next, the TLS and photogrammetric point clouds are opened in CloudCompare, and orthogonal high-resolution screenshots are recorded from the same POV. The images are opened in Adobe Photoshop software, blended together to originate a third colour allowing the operator to study the

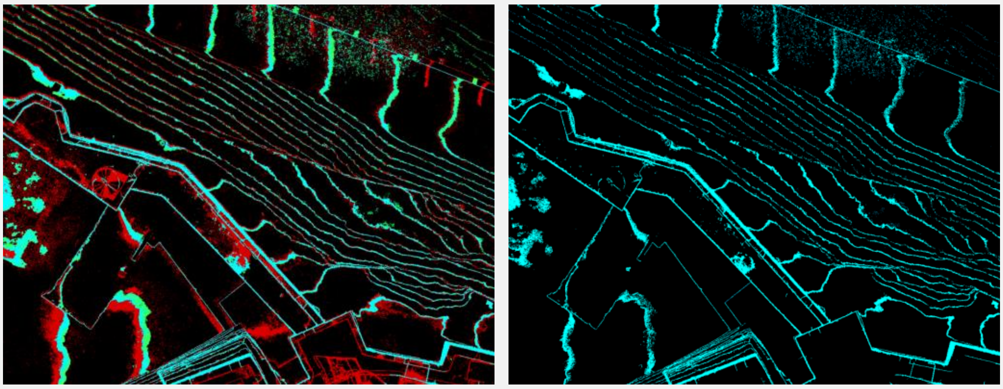


Figure 72: From the left to the right: Zoom to demonstrate the overlapping (cyan) areas of TLS (green) with CRP (red); Zooming image showing overlaps only.

overlapping areas. The final image is saved, inserted in AutoCAD, transformed relative to the GPS points, and measurements are executed. See *Figure 72*.

By the end of the second data processing, exceptionally positive results are obtained beyond expected. Most contour lines have the same thickness between photogrammetric and TLS points clouds, excluding horizontal surfaces that, due to the intrinsically lower precision of the photogrammetric processing, line thickness is predictably larger. The only area where geometric inconsistency is detected beyond the established 2cm threshold is the ramp at the parking lot. Observe the red lines between the cyan lines at the top right of the bottom left image of *Figure 72*.

SUMMARY OF THE SECOND PROCESSING OF THE DATA:

i) Workflow of the second processing followed most of the steps defined for the first processing.

ii) Photographs grouped, assigned GPS points, and processed in Pix4D software in a structured fashion to generate denser point clouds that are georeferenced once exported. Do note that for photogrammetric projects additional information is introduced to scale the final outputs. Several sub-projects created to overcome hardware and software limitations so to create a global project.

iii) Application of SkyRemover algorithm, manual clean-up of the photogrammetric outputs, and separation of buildings from vegetation point clouds.

iv) As opposed to the first processing, no need to align the photogrammetric point cloud relative to the TLS point clouds. The GPS points were fully utilized as common data for the georeferentiation step.

v) Geometric quality assessment, using TLS point clouds as a reference. Very accurate and precise outputs.

vi) Data ready to allow the production of material at a drawing scale of 1:50.

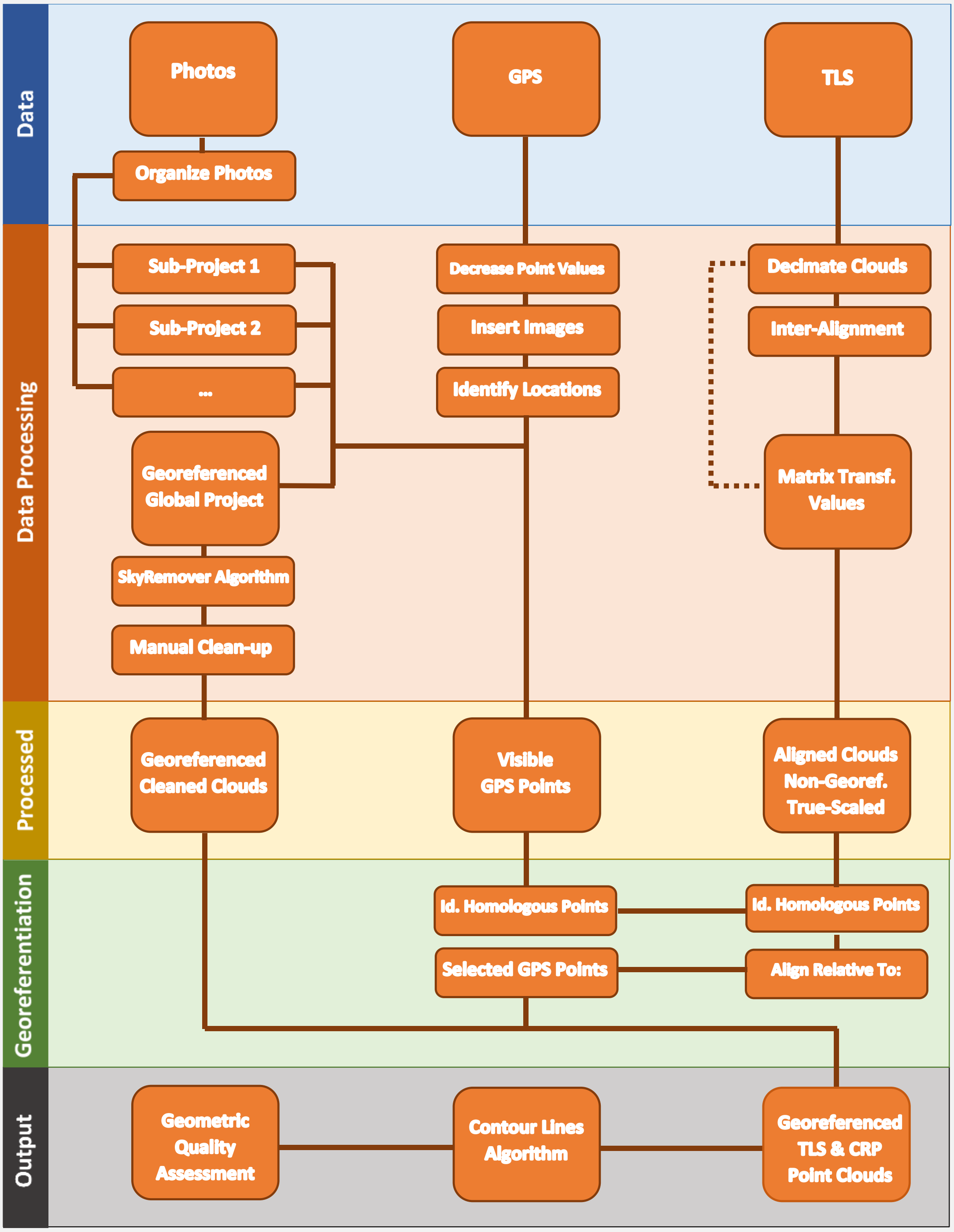


Figure 73: The workflow used in the second processing of the data.

5.4.5. Production of Outputs

Production of Outputs (c)

After the phase of data preparation, production of the drawings follows. As aforementioned, the administration of The Convent of Christ requested material at a drawing scale of 1:100, and simultaneously suggested if it is possible to produce drawings in which stereotomy is visible to accomplish deeper and comprehensive reading of the volumes. For this reason, it was decided to produce most of the material at a drawing scale of 1:100 and a few at 1:50 to demonstrate the potential that photogrammetry offers to create expressive material while taking into consideration the site under analysis is designated as a world heritage by UNESCO.

With the main objective of delivering drawings with the maximum level of interpretability, a few workflows have been researched in which image manipulation techniques are applied. There are 2 phases, each of which has 2 approaches to adopt. The first phase relates to the preparation of the data to produce drawings, and the second phase relates to the production of outputs.

Regarding the preparation of the data, the point cloud is decimated to 5mm of density and a few adjustments and corrections are performed before the point clouds are screenshotted in high resolution from CloudCompare software. The first step is related to the rotation of the point cloud to place the section cut parallel to one of the orthogonal views, preferably relative to the frontal view. Two approaches are possible to adopt.

In the first approach, a top view screenshot is saved from CloudCompare, opened in Autodesk AutoCAD, and then the angle of rotation is measured. Next, the rotation is calculated via insertion of the rotation value in CloudCompare. All the point clouds are rotated, and the operator segments the point clouds to remove points that are behind the section cut plane, and points behind surfaces of interest (non-visible). The problem of executing such an approach is the uncertainty of having the section cut plane truly parallel to the main surfaces of interest, particularly important for drawings at 1:50. In addition, as the point clouds are segmented, the new results must be saved for that specific section-cut, occupying much disk space. However, the advantage is the point clouds are already available for use if the drawings must be redone.

In the second approach, an algorithm developed for the current thesis is executed. Coordinates of two points of the surface are registered, plus another two points to indicate the direction in which the section cut looks at and the offset from the surface of interest. The second approach shares the same disadvantages as the first approach: the new outputs must be saved to avoid recalculating the section cut again.

After carefully setting-up the section-cuts by segmenting the point clouds in CloudCompare, the second phase corresponding to the production of drawings follows, and two approaches can be used.

Regarding the first approach - Method A- , in which the base of the drawings consists of point clouds, the exported screenshots present the operator with a few challenges. The points of the point clouds are represented as coloured squares and the edges, depending on the surfaces, are visible if analysed very closely. Furthermore, and as expected, the density of the point clouds is heterogeneous, sometimes presenting with vacant areas and points reprojected with wrong colours. The process is identical to restoring old photographs containing scratches. Specifically, Adobe Photoshop offers a tool named “Dust & Scratches” predominately utilized for that purpose, located under the menu Filter, Noise.

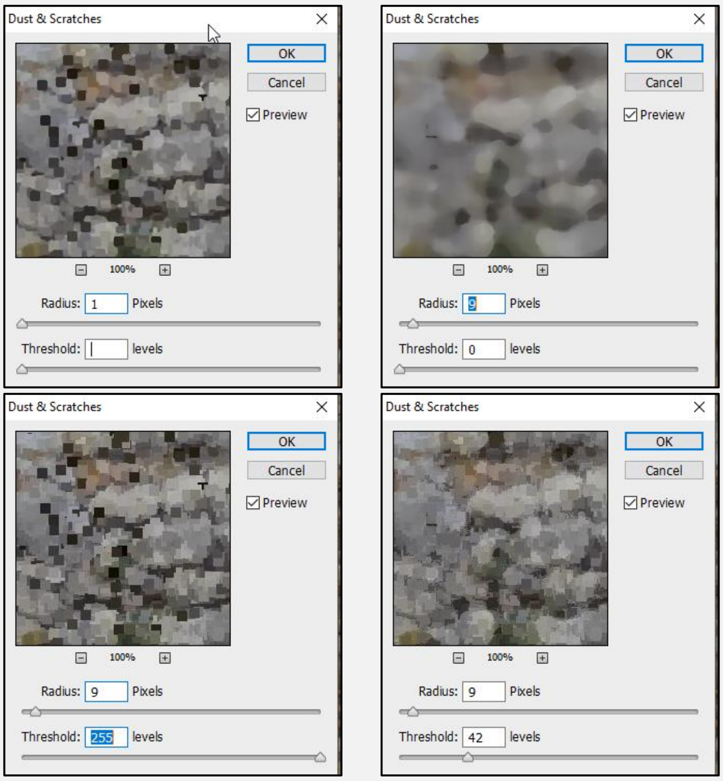


Figure 74: Manipulating the point cloud to increase interpretability. From the top left to the bottom right: Original point cloud; After applying the parameter Radius; Threshold adjustment; Final output with increased readability.

Dust & Scratches tool is executed in a specific procedure. The original layer is copied, and the tool is run on the copy. In the Dust & Scratches window, two sliding bars allow the operator to perform specific adjustments. See *Figure 74*. The "Radius" slider searches within the defined radius for colour values and softens the drawing (identical to the "Smudge" tool). That is, sharpness is lowered to fill in with information in the gaps, and to remove or replace spurious points. To ensure the level of interpretability is preserved as much as possible, the "Threshold" slider allows increasing sharpness, bringing back the square shapes of the points. In other words, Dust & Scratches is a practical tool to fill areas of the image with colours presented in the said image while preserving sharpness. See *Figure 75* to observe the results. On close inspection, even

Figure 75: Manipulation of the point cloud to increase interpretability. Top image: Original point cloud. Bottom image: Application of Dust & Scratches in Adobe Photoshop software.

if seemingly imperceptible, the highlights and shadows have been very slightly toned down, creating an image in which colours are “washed out”. Specifically, the maximum difference range from the whitest tones to the darkest tones is shorter, and the colours are less vivid as they are closer to the mid-tones in general. For perfect results, two layer-adjustments are introduced: “Brightness/Contrast Adjustment Layer” to increase contrast and therefore the highlights and shadows; and “Vibrance… Adjustment Layer” to increase the colour intensity. After all adjustments, the new layers are activated or deactivated allowing the operator to observe the original point cloud and estimate any necessary corrections.

Concerning Method B, the production of the base mesh must follow specific steps as well. The mesh is calculated by having the point cloud as a reference in CloudCompare. In the first step, normals are calculated for all points, via the execution of the tool “Compute Normals” under the

Figure 76: Comparison of the methods of manipulation of the point clouds to increase interpretability. Top image: Method A - point clouds; Bottom image: Method B - highly detailed mesh.

menu Edit, Normals. “Fast marching” mode is selected for fast computation but at the cost of accuracy. Such an option is preferred due to hardware limitations, and the point clouds still must be segmented into smaller parts to allow the tool to run efficiently. Several hours are required. Next, the mesh is calculated by running the tool under the menu Edit, Mesh. All mesh segments are merged, and artefacts removed, and the project is ready to export screenshots.

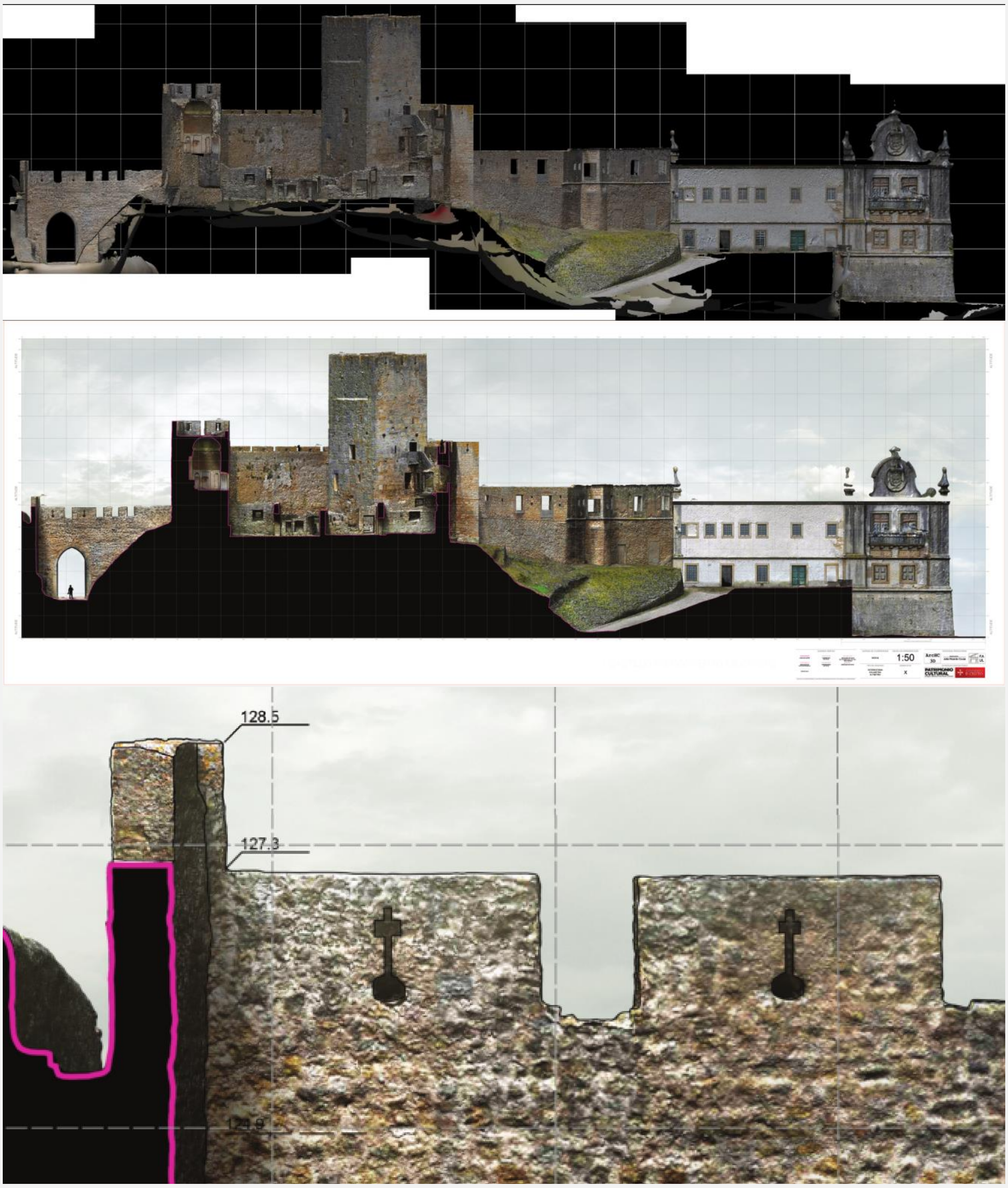


Figure 77: Example of all modifications to produce a drawing from a mesh at a drawing scale of 1:50. The true size of the drawing corresponds to 2 horizontal A0 sheets side by side.

As soon as the data are prepared via the use of Method A or Method B, two sets of images are acquired. The first set represents the data, and the second set represents the data with a background grid to allow rescaling of images in Autodesk AutoCAD to the correct proportions. The first set of images are placed over the second set of images with the background grid. Lines, hatches, and symbols are inserted, and for every layer, a PDF file is exported and opened in Adobe Photoshop as layers for final touches. Contrast, levels, vibration are adjusted. Additionally, a new layer is created with the blending mode “multiply”, and the brush is set to feathered selection with black colour at 25% opacity to cast shadow projections to increase depth perception. Additional symbols or imagery may be inserted, such as the sky, people, cars, etc.

Several perceptible differences provided by each method are recognisable. Method B produces outputs with the highest quality but at the cost of processing time for a Mesh must be computed. The image has high sharpness and soft colour transitions that promote the best interpretation of details. In Method A, even though masonry joints are visible, the texture of the stones are not as perceptible as in Method B. See *Figure 76* to analyse the output quality that each method provides with. To produce material at a drawing scale of 1:50 and 1:100, Method B and Method A are preferred, respectively.

The issues presented for the production of drawings of the Castle Tomar were similarly experienced by Kimpton et al. (Kimpton, Horne, & Heslop, 2010). Specifically, Kimpton et al. focused on analysing the best method to record and represent the 2D drawings of a masonry wall. That is, several approaches were experimented, such as tracing CAD polylines using a point cloud in the background, tracing CAD polylines on a surface model, tracing CAD polylines on a textured surface model, and tracing CAD polylines o a rendered point cloud. The authors conclude that the last method is the best one to deliver the intended outputs while considering the time required to trace all of the polylines by obviating the need to compute a mesh model.

SUMMARY OF THE PRODUCTION OF OUTPUTS:

i) Following the processing of the point cloud data, the production of outputs is structured in two phases: i) preparation of the data by transforming the point clouds to the frontal view; ii) production of outputs.

ii) The preparation of the data is executed manually, or semi-automatically via the application of an algorithm developed for such purpose.

iii) Production of outputs by using the point clouds, or by computing a mesh using the point clouds as a reference.

iv) Comparison of the two types of workflow outputs taking into consideration processing time and output quality.

v) Computation of meshes to produce material at a drawing scale of 1:50; and use of point clouds to produce material at a drawing scale of 1:100.

vi) Use of Adobe Photoshop Software to emphasize depth perception by inserting shadows, and adjustments to colours, highlights, and shadows to meliorate image quality.

5.5. Discussion and conclusions

Since the execution of the first recording campaign and respective office work that provided with outputs whose quality could be better, the identified setbacks and impediments are overcome during the execution of the second recording campaign due to the application of innovative methods and approaches researched in the *current chapter*. Narrow spaces, complex volumes, the transition of areas, bridges, volumes occluded by vegetation, and extremely dark indoor spaces not only are successfully recorded, but the highly distorted imagery also allows to compute outputs with a high level of detail despite the extremely lower GSD values.

Furthermore, the application of fisheye imagery to record world heritage constructions proves to be an efficient method to obviate the use of equipment whose inefficient or impossible application leads to poorer results or extended computing times. For example, to replace all fisheye images the surveyor requires at least 9 times more images to cover the same area covered by fisheye images - not to mention the need of acquiring overlapping images to allow positive image matching results.

Regarding the production of the final outputs, workflows were presented while bearing in mind the potential quality of the outputs to produce detailed information at a drawing scale of 1:50. Meshes proved to be the best approach to create detailed drawings, while information derived from point clouds was preferred to create outputs at a drawing scale of 1:100.

The most notorious aspect to retain from the main case study is the fact that three-quarters of the total images were acquired with a fisheye lens, which reveals the value and pressing need of acquiring fisheye images to overcome challenging problems or even seemingly impossible areas to record.

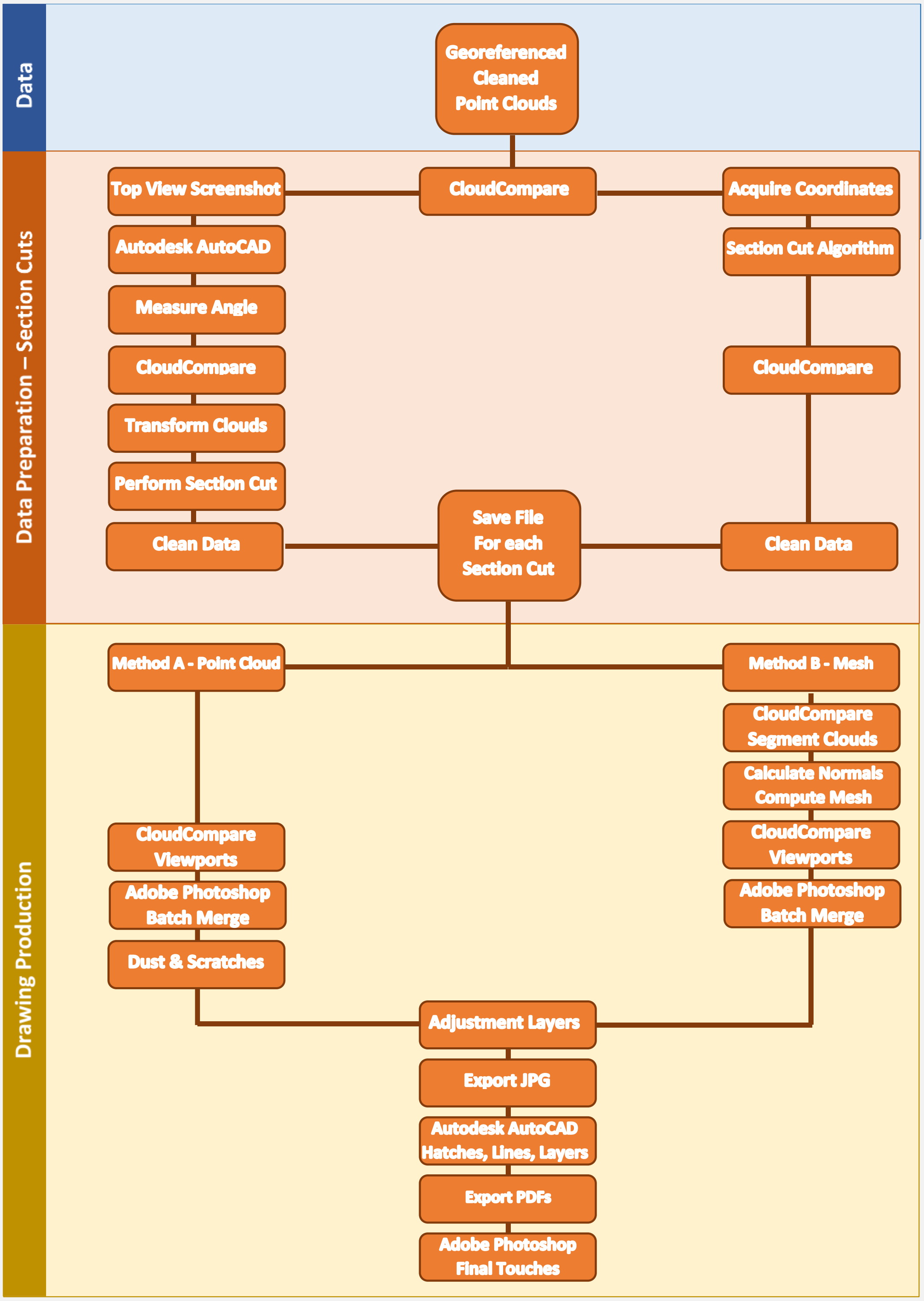


Figure 78: The workflows to produce material at a drawing scale of 1:50 and 1:100.

Figure 79: A planview of the photogrammetric point cloud. Very complete.

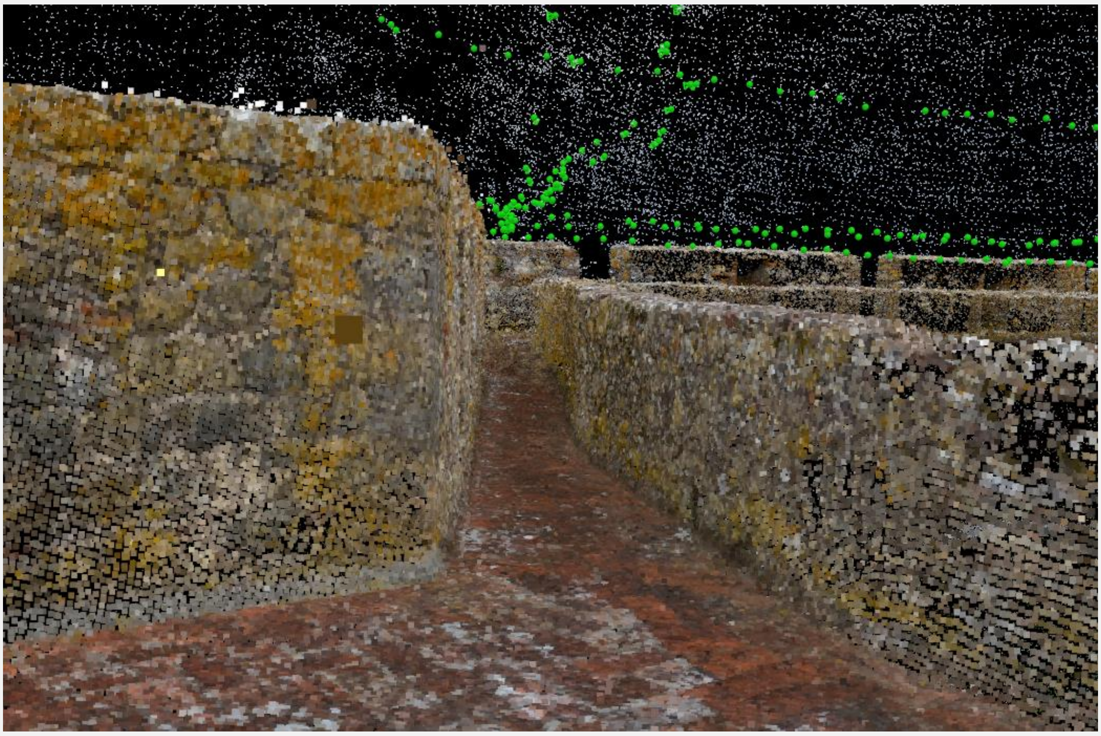


Figure 80: Top image: A perspective view of the photogrammetric point cloud from the second processing. Bottom image: A view from the chemins the ronde to illustrate the point cloud density and details.

6. CONCLUSION AND ILLATIONS

The present dissertation, with the title “Photogrammetry as a Surveying Technique Applied to Heritage Constructions Recording – Advantages and Limitations”, had the main objective to research the limits on the application of photogrammetry to record constructions and propose solutions to overcome such limitations.

For these purposes and intents, a few goals were established and studied such as:

i) To test the exclusive use of images, including fisheye images, to reconstruct 3D virtual models of the observed reality so to overcome the limitations of photogrammetry itself.

ii) Furthermore, as that would not be enough in the context of recording world heritage constructions, it has also been tested the geometric consistency of the resulting photogrammetric project.

iii) Yet, relative to documentation practices, it has been demonstrated that “2.5D” drawings offer a much richer interpretation of the object under analysis. That is, “2.5D” drawings executed from point clouds and meshes.

The case studies presented along *chapter 3* focused primarily on testing the limits of the application of photogrammetry in “extreme situations” requiring the use of “unconventional instruments” to achieve successful 3D reconstructions. By “extreme situations”, it is referred to as complex volumes, narrow spaces, indoor spaces, dim lit spaces, inaccessible locations, and other features that are predominantly experienced in heritage constructions such as medieval architecture. In addition, by “unconventional instruments”, it is conveyed the idea of using instruments not thought as the “ideal” or “normal” in the context of terrestrial photogrammetry, instruments such as fisheye lenses with extreme FOV resulting in remarkably high GSD values particularly at the margins of the image – when compared to “conventional” instruments.

Interestingly, ultra-wide-angle lenses and wide-angle lenses are frequently mounted on aerial platforms to perform agricultural, earthworks, real estate, mapping, forensics recordings, and other types of work. In other words, highly distorted imagery is acquired from the application of aerial platforms (UAV), and said images contain extremely high GSD values due to high distance between the subject and the aerial platform. Therefore, the research in the current thesis aims to propose the application of fisheye lenses in extreme-close-range situations (terrestrial).

Consequently, the hypothesized challenge brought forth efforts to research for solutions and execute thorough experiments that not only plausibly verify the application of fisheye images in recording heritage constructions, but also provide with geometrically accurate data when compared to TLS. For this reason, due to such "unconventional application" and in which outputs are acquired in a time-efficient method, it is proposed the branch term "Close-Range Fisheye Photogrammetry", included in the umbrella term "Photogrammetry".

In addition, from the bibliometric analysis and related work presented in chapter 3, it is verified that the application of fisheye lenses not only allows to overcome the traditional limits of photogrammetry but also predominantly increase the major characteristics of photogrammetry itself: flexibility, versatility, simple and low-cost application, and accessibility to seemingly impossible to record spaces.

In chapter 5, with the execution of the main case study it is proved that data provided via the use of close-range-fisheye photogrammetry is sufficiently trusting. If distortion parameters are accurately determined, the likelihood of acquiring positive results is high. However, as it occurs in the application of any surveying instrument, the recording must proceed with necessary precautions, and the ideal approach is to acquire additional information from the application of other surveying instruments and in a closed polygon instead of an open polygon to accurately verify the geometric quality of the outputs. Executing the formerly proposed approach ensures positive results with greater certainty. Specifically, Pix4D and other authors have concluded that the use of fisheye images offer the same accuracy and precision values if CPs are utilized.

Yet, it is vital to determine the reliability of the results provided solely from the application of fisheye imagery. The execution of the main case study utilized highly distorted imagery combined with conventional imagery to correct, whenever necessary, any distortions. Therefore, it is questioned if processing a project with the sole use of fisheye images generates a model that is consistent as a model generated with conventional imagery, despite the verification of correct reprojection of points in areas where only fisheye images were utilized.

The most valuable and meaningful achievement identified during the execution of the case studies relates to the accurate and precise reconstruction of the photogrammetric point clouds, especially with the use of highly distorted images. Such a success means an important milestone has been revealed to the scientific community, architects, historians, archaeologists, and engineers, as there are constructions in diverse regions of the world in which recording with conventional instruments proves to be difficult, and the application of close-range-fisheye photogrammetry is one of the solutions to overcome challenging problems.

Nevertheless, no matter how positive the results, more photogrammetric applications must be executed to corroborate the proposed solutions. In other words, even though more applications are needed to substantiate the plausibility of the use of fisheye images, case studies presented so far, although few for statistical confirmation, strongly suggest the possibility to perform accurate photogrammetric recordings with highly distorted imagery.

Other aspects regarding the office work phase are equally considered. For instance, in Chapter 4, the development of algorithms evidenced the importance of how programming languages allow the surveyor or user to manipulate data to obtain the best outputs within reasonable time limits while increasing data quality. In other words, not only is crucial to know how to produce data with the available tools and software, but it is also vital to know how data is computed to produce our own tools and to know the very limits on how data can be manipulated. A few algorithms were produced: “SkyRemover” to remove patches of spurious points along the edges of the model; “Section cuts” to allow placing the section cut plane parallel to the viewer and facilitate the production of traditional 2D drawings; “Contour Lines” to create contour lines and that is vital for topographic or architectural projects for instance.

In summa, the key points to retain is that close-range fisheye photogrammetry is a solution to record structures that present the surveyor with narrow spaces, transitions between spaces, and complex volumes. The following limitations and advantages are described for close-range fisheye photogrammetry:

Limitations:

- Fewer details due to increase GSD values;
- High distortion;
- Requires ad-hoc algorithms;
- Requires fisheye supporting software;
- Requires control information to reduce inaccurate reconstructions;
- Higher susceptibility for geometric errors.

Advantages:

- Increased FOV;
- Increased flexibility for it can be mounted on drones and poles;
- Increased user-friendliness;
- More recording possibilities;
- Uses more than 15x less images compared to “conventional” instruments;
- Higher coverage;
- Increased overlapping for image matching.

7. FUTURE WORK AND PROSPECTS

The recording projects presented so far revealed the need for utilizing fisheye imagery to accomplish complete reconstruction of models when conventional equipment or methods could not deliver the same results at all or in an efficient method.

In this context, seeing as the proposed recording strategies are not frequently applied to record heritage constructions, it is foreseen that in the future, the proposed recording strategies will be utilized in other constructions, including but not limited to castles, monasteries, tunnels, speleology, convents, or any other building presenting challenging physical configurations where the application of conventional photogrammetric instruments proves difficult. It is our intention to continue using such recording strategies in future works when necessary.

In addition, the application of the same strategies by other surveyors could propel the development or discovery of complementary strategies not yet thought of and that may be advantageous to other professionals to produce valuable work.

It is noted that as future work, it is possible the development of tools to operate point cloud data to produce unique outputs including, but not limited to, automatic detection of surfaces or solids, alignment of laser scanning data via the use of photographic data, etc. Relative to the SkyRemover algorithm, the parameters are fixed and one possible future work to ameliorate the code is to include a sampling of image areas to collect specific ranges of colours. That is, a semi-automatic approach. Perchance, there could be the integration of a surface detection algorithm with SkyRemover to avoid removing non-spurious data. The possibilities are numerous.

Other possible future work includes the development of strategies to improve the quality of the spectral information, particularly while transitioning from the interior to exterior spaces. Specifically, an automatic approach in which the software recognizes images were acquired from the same POV and blend colour information to produce an HDR image. Therefore, instead of utilizing 3 images from the same POV, the software uses 1 image that results in faster processing of a model with more accurate colour representation. In effect, one of the major challenges of photogrammetry is to acquire data with accurate colour information, which seems hard to obtain if the object is partially lit.

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