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Apple's iPad Pro sensors for Cultural Heritage Documentation

First tests and results

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Summary

The Documentation of Cultural Heritage (CH) is a complex process, since it requires a trained professional to manage expensive equipment such as Terrestrial Laser Scanner or drones, while CH itself is generally accessible by everyone, with a small ticket fee or for free. Therefore, the democratisation of this procedure could benefit the whole population, by enabling non-expert users to survey CH with a low-cost and mass-distributed solution to create 3D models of monuments or environments. Instead of using a high-cost laser scanner, the operator could exploit the LiDAR (Light Detection and Ranging) sensor equipped from 2020 by Apple in the camera module of iPhone and iPad Pro versions, to obtain models with a satisfying level of accuracy at a fraction of the cost and embedded in devices owned by a vast portion of the population. If the scenario of democratic documentation came true, the amount of people to access this feature would set up the basis for a wide network of remotely accessible documentation.

By exploiting the LiDAR sensor equipped on the 2020 11-inch iPad Pro, different apps available on Apple's App Store have been analysed to test their accuracy, as well as their settings customisation to adapt to different CH scenarios located inside or close by the Castello del Valentino in Turin, Italy.

From the broad selection of apps on the app store, ten have been subjected to a preliminary test on the small environment of the Cabinet of Golden Flowers located at the Noble floor of the Castle to assess the complexity and customisation

of the scanning process, and to declare based on price, sharing possibilities and general model accuracy, which apps can be further analysed on more complex CH scenarios.

The scenarios further analysed are the exterior Façade of the Castle on Viale Mattioli, the big and decorated environment of the Hall of Honour on the Noble Floor of the Castle and the Lion lying on the pedestal of the monument to Giuseppe Garibaldi located on Corso Cairoli. For each CH asset documented, the results have been compared with the ones obtained with the Faro Focus 3D X 330, a Terrestrial Laser Scanner used as reference dataset to understand the level of accuracy obtainable from the applications and different acquisition modalities under changing circumstances.

From each app, a point cloud model has been extracted and imported on the software Cyclone 3DR and PointCab, for analyses on the level of accuracy with respect to the reference dataset. By analysing the outcomes of this process and by confronting the levels of accuracy with the initial judgment on price, shareability and levels of customisation, it was possible to identify which app and which modality provides the best results and is therefore most suited for an accessible documentation of CH with satisfactory levels of accuracy.

Table of Contents

List of Figures VI

1 Introduction 1

1.1 Aims of the Work and Research questions 2

2 Theoretical Background 4

2.1 Cultural Heritage Documentation: generalities and historical background 4

2.2 Geomatics: generalities 11

2.3 Laser scanning: generalities 12

2.4 History of Laser scanning 14

2.5 Photogrammetry: generalities 16

2.6 History of Photography 17

2.7 History of Photogrammetry 23

2.8 Geometric principles of Photogrammetry 28

3 LiDAR solutions 33

3.1 Affordable LiDAR Solutions 33

3.2 Apple's LiDAR sensor 40

3.3 Reference Dataset: Faro Focus 3D x 330 44

4 LiDAR Applications available on App Store 46

4.1 List and description of LiDAR sensor-based applications considered in this research . . . 47

5 Case Studies Definition 60

5.1 Gabinetto dei Fiori Indorato . . . 61

5.2 Castello del Valentino's Façade . . . 62

5.3 Salone d'Onore . . . 65

5.4 Giuseppe Garibaldi's statue on Corso Cairoli . . . 69

6 Methods 71

6.1 Preliminary Testing: Gabinetto dei Fiori Indorati . . . 71

6.1.1 Data Collection . . . 72

6.1.2 Initial Scans Comparison . . . 81

6.1.3 Cyclone 3DR Scan Analysis . . . 83

6.1.4 Section Comparison . . . 89

6.2 Colour Perception Test . . . 95

7 Methodology Application on different CH Scenarios 97

7.1 Data collection . . . 97

7.1.1 Castello del Valentino's Façade . . . 97

7.1.2 Salone d'Onore in Castello del Valentino . . . 101

7.1.3 Lying lion on the pedestal of Giuseppe Garibaldi's monument in Corso Cairoli . . . 105

7.2 Information about the models' geometry . . . 109

7.3 Data processing . . . 110

7.3.1 Cyclone 3DR Scan Analysis . . . 110

8 Discussion 122

8.1 Definition of the best application according to the four initial factors of judgement: Price, Shareability, Customisation and Accuracy . . . 122

8.2 Apple's LiDAR for Cultural Heritage Documentation 131

9 Conclusions 135

Bibliography 138

List of Figures

2.1 Leonardo da Vinci's sketches on camera obscura, Source:[26] 18
2.2 Joseph Nicéphore Niépce, Point de vue du Gras, Source:[30] 19
2.3 Enrico Federico Jest, View of the Gran Madre, Source:[33] 20
2.4 Kodak N°1 Advertisement from 1888, Source:[34] 21
2.5 Aerial view of Boston, James Wallace Black, 1860, Source:[35] . . . 22
2.6 Julius Neubronner's pigeon camera patent, 1908, Source:[36] 22
2.7 Die Photogrammetrie, Albercht Meydenbauer, 1867, Source:[37] . . 24
2.8 Example on the use of different focal lengths, Source: [38] 28
2.9 Comparison between a satellite imagery and an image taken with a 360° camera of the same scene: Castel Sant'Angelo in Rome 29
2.10 The six parameters defining the exterior orientation, Source:[39] . . 31
2.11 The Collinearity Equations 31
2.12 Parallel and convergent camera acquisitions 32

3.1 The principle behind Wii's sensor bar 34
3.2 The principle behind Microsoft's Kinect, Source: [41] 35
3.3 Intel L515 and D415 cameras, Source: Intel RealSense [44] 36
3.4 Peanut Phone and Yellowstone tablet 37
3.5 Lenovo Phab 2 Pro sensors, Source: Lenovo [45] 38
3.6 Samsung S20 Ultra sensors 39

3.7 Apple's 2020 11-inch iPad Pro and iPhone 12 Pro 40
3.8 iPad Pro rear optical block and LiDAR module cross-section, Source: [51] 43
3.9 Faro Focus 3D X 330, Source: [59] 44

4.1 3DScanner App Main Interfaces 47
4.2 Canvas Main Features 48
4.3 Dot3DPro Android/Windows Solutions 49
4.4 Dot3DPro Android/Windows Solutions 51
4.5 Metascan Interfaces 51
4.6 Pix4DCatch Main Features 53
4.7 Polycam Interfaces 54
4.8 RTAB-Map Main Interface 55
4.9 Scaniverse Main Features 56
4.10 Sitescape Main Interfaces 57
4.11 Zappcha Main Features 58
4.12 Preliminary Table of Prices 59

5.1 Location of the Cabinet of the Golden Flowers 61
5.2 Gabinetto dei Fiori Indorato 62
5.3 Position of the portion of the Castle's Façade analysed 62
5.4 Original access to the Castle from the river side 63
5.5 Current access to the Castle from the city side 64
5.6 Salone d'Onore location in Castello del Valentino 65
5.7 Decorations on the Eastern Wall 66
5.8 Decorations on the Northern Wall 67
5.9 Decorations on the Western Wall 67
5.10 Decorations on the Southern Wall 68

5.11 Location of the monument to Giuseppe Garibaldi 69
5.12 Giuseppe Garibaldi's monument 70
5.13 Zoom on the lying lion on the back right corner of the pedestal . . . 70

6.1 3D scanner app LiDAR (A), Advanced (B) and Point Cloud (C) mode 73
6.2 Canvas Model 73
6.3 Dot3D Pro Model 74
6.4 Metascan: LiDAR (A) and Photo (B) mode 75
6.5 Pix4D Catch: Device Pose (A) and Image Overlap (B) modalities . 76
6.6 Polycam: LiDAR (A) and Photo (B) mode 77
6.7 RTAB-Map Model 78
6.8 Scaniverse Model 79
6.9 SiteScape: Max Area (A) and Max Detail (B) modalities 80
6.10 Zappcha Model 81
6.11 Comparison on the model's geometry on Gabinetto dei Fiori Indorati 82
6.12 Initial Table of Comparison for Price, Shareability, Customisation and Accuracy to define the four apps to further analyse 82
6.13 Initial Position and Rotation of the Different Point Clouds 84
6.14 Alignment of a Point Cloud to the Reference System 85
6.15 Summary Table of all the Clouds' Alignments on Gabinetto dei Fiori Indorato 86
6.16 Best and Worst C2C analyses on the Cabinet of Golden Flowers, Dot3D Pro (A) and 3DScanner app: Advanced mode (B) 87
6.17 Results of the C2C Analysis between Apple's acquisitions and TLS 88
6.18 Definition of Horizontal and Vertical sections on Gabinetto dei Fiori Indorati via Cyclone 3DR 89
6.19 Workflow on Horizontal Section of Gabinetto dei Fiori Indorati . . . 90
6.20 Workflow on Vertical section of Gabinetto dei Fiori Indorati 90

6.21 Overlap of the Horizontal sections on Gabinetto dei Fiori Indorati among the seven different modalities 91
6.22 Comparison of the Horizontal sections on Gabinetto dei Fiori Indorati on each modality 92
6.23 Overlap of the Vertical sections on Gabinetto dei Fiori Indorati among the seven different modalities 93
6.24 Comparison of the Vertical sections on Gabinetto dei Fiori Indorati on each modality 94
6.25 Colour Test 95
6.26 Colour perception results: 3D Scanner App (A), Dot3D Pro (B), Pix4DCatch (C) and Scaniverse (D) 96

7.1 Acquisition path on Castello del Valentino's Façade 98
7.2 3D Scanner App: LiDAR (A), Advanced (B) and Point Cloud (C) Mode Acquisition 98
7.3 Dot3D Pro Acquisition 99
7.4 Pix4D Catch: Device Pose (A) and Image Overlap (B) Mode Point Cloud Acquisition 100
7.5 Scaniverse Acquisition 100
7.6 Acquisition path in Salone d'Onore: plan view and Eastern elevation 101
7.7 3D Scanner App LiDAR (A), Advanced (B) and Point Cloud (C) Mode Acquisition 102
7.8 Dot3D Pro Acquisition 102
7.9 Pix4D Catch: Device Pose (A) and Image Overlap (B) Mode Point Cloud Acquisition 103
7.10 Scaniverse Acquisition 104
7.11 Acquisition path on Giuseppe Garibaldi's monument 105

7.12 3D Scanner App: LiDAR (A), Advanced (B) and Point Cloud (C) Mode Acquisition . . . 106
7.13 Dot3DPro Acquisition . . . 106
7.14 Pix4D Catch Device Pose: Point Cloud and Mesh Acquisition . . . 107
7.15 Pix4D Catch Image Overlap: Point Cloud and Mesh Acquisition . . 107
7.16 Scaniverse Acquisition . . . 108
7.17 Information about the dfferent models' geometry on Castello del Valentino's façade, Salone d'Onore and the Lying lion's statue . . . 109
7.18 Initial Location and Position of the acquisitions in the different scenarios . . . 110
7.19 Summary Tables of Alignment for the Castle's Façade and the Salone d'Onore . . . 111
7.20 Summary Tables of Alignment for the Lion's statue on the pedestal of the monument to Giuseppe Garibaldi . . . 112
7.21 Best and Worst C2C analyses on Castello del Valentino's Façade: Scaniverse (A) and Pix4D Catch: Image Overlap (B) . . . 113
7.22 Results of the C2C Analysis between Apple's acquisitions and TLS on Castello del Valentino's Façade . . . 113
7.23 Best and Worst C2C analyses on Salone d'Onore: Dot3D Pro (A) and Pix4D Catch: Device Pose (B) . . . 114
7.24 Results of the C2C Analysis between Apple's acquisitions and TLS on Salone d'Onore . . . 115
7.25 Best and Worst C2C analyses on the Lion's statue: 3D Scanner App: LiDAR (A) and Pix4D Catch: Device Pose (B) . . . 116
7.26 Results of the C2C Analysis between Apple's acquisitions and TLS on the Lion's statue . . . 116

7.27 Section definition on Cyclone 3DR on the portion of Castello del Valentino's façade 117
7.28 Overlap of the Horizontal sections on Castello del Valentino's façade among the seven different modalities 118
7.29 Comparison of the Horizontal sections on Castello del Valentino's façade 119
7.30 Section definition on Cyclone 3DR on the Salone d'Onore 120
7.31 Overlap of the Horizontal sections on Salone d'Onore among the seven different modalities 120
7.32 Comparison of the Horizontal sections on Salone d'Onore 121

8.1 Summary Table of the C2C analyses in the four different scenarios, in which the three best results for each scenario are highlighted . . 123
8.2 Horizontal and Vertical sections of the three most accurate scans for the Cabinet of the Golden Flowers 125
8.3 Vertical sections of the three most accurate scans for the Cabinet of the Golden Flowers 125
8.4 Sections of the three most accurate scans for the Castle's Façade . . 126
8.5 Sections of the four most accurate scans for the Hall of Honour . . . 127
8.6 Final Table of Accuracy scores in the four different scenarios 128
8.7 Final Table of the four factors of Price, Shareability, Customisation and Accuracy 129
8.8 Examples of NFT and AI generated art 134

Chapter 1

Introduction

This thesis revolves around the documentation process of Cultural Heritage (CH), and the feasibility in providing an accurate instrument which is at the same time affordable and exploitable by non-expert users, to achieve Cultural Heritage survey by scanning a monument or a small environment and by generating 3D models and other added value products. The use of industrial and professional laser scanners relies on a sub-millimeter accuracy, but it implies a high initial cost, as well as a trained operator.

Since 2020, Apple has been equipping the Pro versions of its iPhone and iPad with a LiDAR (Light Detection And Range) sensor to complete the camera module, thus enabling all owners of these devices of getting in touch with the technologies and the methodologies behind laser scanning, at a fairly moderate price considering that the sensor is embedded into one of the most sold smartphones in the world. As a consequence, the amount of people who can access this technology makes it possible to create a wide network not only in scanning objects and creating accessible models, but also in CH documentation.

This thesis will exploit the LiDAR sensor available on a 2020 11-inch iPad Pro along with the main camera sensor exploited for colour perception, and it will

analyse different apps available on Apple's App Store, to test their accuracy, as well as their settings customisation to adapt to different scenarios. After a preliminary phase, in which a wider spectrum of applications is tested on a small environment inside the Castello del Valentino, a selection of them will be used for surveying three other CH sites: a portion of Castello del Valentino's façade, a lion statue on the pedestal of the monument dedicated to Giuseppe Garibaldi, located along the river Po, and a larger environment, the Salone d'Onore inside of Castello del Valentino, which is widely decorated and which hosts conferences, graduations and other events.
The first test has been used to define the methodology, which is then carried out and validated throughout all the other scenarios, and the results have been compared with a Traditional Laser Scanner (Faro Focus X 330) reference dataset to understand the level of accuracy on the different applications and modalities of acquisition.

1.1 Aims of the Work and Research questions

The object of the thesis is to test the capabilities and the limits of both iPad Pro's LiDAR sensor and of a selection of the various applications available on Apple's App Store, by analysing the different working modalities on the chosen apps, which may take advantage of different parameters while scanning, in order to ultimately determine the one which best satisfies the four judgment factors of Price, Shareability, Customisation and Accuracy in the four scenarios of the Cabinet of the Golden Flowers; the portion of the Castle's Façade; the Hall of Honour and the Lying lion on the pedestal of the monument to Giuseppe Garibaldi on Corso Cairoli.

The main research questions to which an attempt has been made to answer are the following:

A. Which application available on the App Store is the one that better responds to the four judgement factors of Price, Shareability, Customisation and Accuracy in the four different scenarios: small environment, outdoor architecture, big environment and outdoor monument?

B. Can Apple's affordable sensors be used for Cultural Heritage documentation by non-expert users with satisfying results in terms of accuracy?

In the following chapters a general background on CH Documentation will be provided, as well as the theoretical aspects regarding the basics of Photography, Photogrammetry and of Laser scanning techniques, followed by a general view of the characteristics of affordable LiDAR solutions, of Apple's sensor and of the TLS with which the reference dataset have been collected. Then, a selection of apps available in the App Store will be tested on a small indoor environment, and from that a selection of the ones visually providing the best results will be used to carry on our analyses on color perception and on the survey of an outdoor architecture, a larger indoor environment and an outdoor monument compared with the Terrestrial Laser Scanner reference dataset. The data collected will be then analysed, compared and commented to finally declare which application and which modality best fits the four judgement factors of Price, Shareability, Customisation and Accuracy for the four different scenarios, and whether the use of Apple's LiDAR sensor provides acceptable results for Cultural Heritage documentation.

Chapter 2

Theoretical Background

2.1 Cultural Heritage Documentation: generalities and historical background

The expression *Cultural Heritage* (CH)is generally used to refer to those assets that make up the wealth of a territory and its inhabitants. This can be interpreted as a legacy for the population of a specific area, who identifies all those assets as an expression of their local beliefs, customs, practices, or traditions. By recognising the value of certain resources, it comes the need to protect and preserve them, and of following a predetermined set of rules in order to do so. In Italy, CH has been safeguarded by a series of laws, with the first one being the Legge n.411 from 1905 [1] for the safeguard of Ravenna's pine forest promoted by Minister Rava, followed by the Legge Croce n.788 from 1922 [2] for the protection of natural beauties and immovable goods with a particular historical interest.

In 1931 the First International Congress of Architects and Technicians of Historic Monument was held in Athens, followed by a manifesto on CH conservation called *Athens Charter for the Restoration of Historic Monuments* [3]. The seven principles were the following:

1. the establishment of International organizations for operational advice
2. the critical review of proposed restoration project to avoid mistakes
3. the establishment of National legislation for the preservation of historical sites
4. the reburying of excavated sites not under current restoration for public safety
5. the use of modern techniques and materials in restoration works
6. the custodial protection of historical sites
7. the protection of areas surrounding historical sites

Following Athens Charter, which acted at an international level, the *Carta Italiana del Restauro* [4] was established in 1932 by the Consiglio Superiore per le Antichità e le Belle Arti. The principles were similar to those expressed in the Athens document, but with a focus on the "philological scientific restoration" defined by the architect Gustavo Giovannoni as the idea of using modern techniques and materials to restore the monuments, and of ensuring that this operation is clearly recognisable by distinguishing the plain acts of intervention from the original parts. Then in 1939, Legge Bottai n.1089 [5] and n.1497 [6] were enacted for the protection of assets with an artistic and historical interest, and with the introduction of landscape territorial plans.

According to the laws from 1939, assets belonging to these categories had to be protected:

- Artistic and historical assets: all works and monuments, movable and immovable, which have a recognized artistic value or a particular historical significance;

- Architectural assets: all buildings, architectural ensembles and monuments which are recognized as being artistic or historically significant;
- Archaeological assets: movable or immovable evidence of the ancient past, brought to light through technical excavation or not yet found, but whose presence is ascertained in a given place;
- Historical centres: an urban and building complex that has never seen its residential viability and its urban function interrupted, nor has it ever undergone that process of enlargement outside the ancient walls that would have altered its view.
- Books and libraries: these goods can be state-owned or dependent on local authorities, non-profit organizations, monasteries or belonging to private individuals.
- Archival assets: documents and archives, intended for the conservation of public and private acts and documents that are of state competence.
- Museum assets: institutions, capable of hosting and exhibiting a series of movable assets, which are kept, cataloged and exhibited to the public.

All these regulations were made under the influence of King Vittorio Emanuele III and the dictatorship of Benito Mussolini, and after the Second World War they have been implemented into the Italian Constitution from 1947, which in the Ninth Article [7] states: *"The Republic promotes the development of culture and scientific and technical research. It protects the landscape and the historical and artistic heritage of the nation. It protects the environment, biodiversity and ecosystems, also in the interest of future generations. State law regulates the methods and forms of animal protection."*

The Second World War brought great destruction to CH and it became evident that such a situation should not happen again. To do so, the United Nations established UNESCO in 1945, whose acronym stands for United Nations Educational, Scientific and Cultural Organization, and it is aimed at promoting world peace and security through international cooperation in education, arts, science and culture. In 1954 the *Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict* [8] was held in The Hague, Netherlands in order to preserve CH from warfare. In 1964 the Second International Congress of Architects and Technicians of Historic Monuments was held in Venice, producing the *Venice Charter for the Conservation and Restoration of Monuments and Sites* [9], because the Athens' one from 1931 was outdated, since now there was not only the need to restore monuments, but whole cities. As a result to this congress, the International Council on Monuments and Sites (ICOMOS) will be formed in Warsaw in 1965, which works for the protection and conservation of CH sites all around the globe and which offers advices to UNESCO on World Heritage Sites.
The Carta Italiana del Restauro from 1932 was updated as well in 1972 [10] by the Ministry of Education, defining all those assets eligible to renovation and conservation procedures, such as monuments, painting and sculptures, historic buildings and portions of cities, furniture and book collections, parks and gardens, or ancient ruins. It was defined which restoration procedures were prohibited and which one were allowed, which modern techniques and materials could be used, and a new attention was given to athmosferic, thermal and hydrometric damages. Then in 1985 with Legge Galasso n.431 [11], territories with a specific environmental interest were protected, such as coasts and lakes up to 300 meters away from the water; river strips up to 150 meters; mountains from 1600 meters on the Alps and from 1200 meters on the Apennines and on the islands; glaciers, parks, forests, volcanoes, wetlands and areas of archaeological interest.

It was only in 1998 with the Decreto Legislativo n.112, art.148 [12] that a clear definition to Cultural Heritage was given: *"those assets that make up the historical, artistic, monumental, demo-ethno-anthropological, archaeological, archival heritage and the others that constitute testimony having the value of civilization thus identified on the basis of the law"*, and in the same year the Ministry for Cultural Heritage and Activites was founded with the Decreto Legislativo n.368, art.1 [13]. In the year 2000 the Charter of Krakow [14] was written, and a particular attention is given not only to monuments, but also to architectural, urban and landscape heritage, since the entire territory preserve important elements to understand human culture and history.

In 2004, with the Decreto Legislativo n.42, all the Italian laws regarding CH have been collected into the *Codice dei beni culturali e del paesaggio* [15], which has been updated troughout the years from 2006 to 2022. In the Codice are defined as Cultural Heritage all the movable and immovable assets both public and private which have artistic, hystorical, archaeological or ethno-anthropological interests, such as museum collections; archives and book collections; objects collections; assets regarding paleontology and primitive civilisation; assets of numismatic interest; manuscript, autographs and prints; geographical maps and musical scores; photographs, cinematographic films and audiovisual supports; gardens, parks and villas; squares, streets and other urban open spaces; mining sites; ships and floats; rural architecture.

On a worldwide level, from 1978 UNESCO protects World Heritage Sites (from here on WHS), a landmark or area designated for its cultural or historical significance and which is considered of outstanding value for humanity. As of 2022 there are 1154 sites selected among 167 countries. With 58 areas on the list, Italy is the country having the largest amount of sites, and Piedmont region on its own hosts five WHS:

- Ivrea, industrial city of the Twentieth century (2018) [16];
- Vineyard Landscape of Piedmont: Langhe-Roero and Monferrato (2014) [17];
- Prehistoric pile dwellings around the Alps (2011) [18];
- Sacri Monti of Piedmont and Lombardy (2003) [19];
- Residence of the Royal House of Savoy (1997) [20];

This last site also includes the Castello del Valentino, where the Faculty of Architecture is housed. In order to be declared WHS, a candidate site must be of "outstanding universal value" and must meet at least one of the following ten criteria [21].

1. represent a masterpiece of human creative genius;
2. exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design;
3. bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared;
4. be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates significant stage in human history;
5. be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change;
6. be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance;

7. contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance;

8. be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features;

9. be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals;

10. contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation;

Referring to Cultural Heritage, people often think about physical assets such as paintings and sculptures, monuments and buildings, but also the natural environment as well as intangible heritage like knowledge, oral history, and even traditional dance and music transmitted through generations. A common goal of all mankind is the protection of CH, that has to be preserved for everyone's sake. The recording and documenting of Cultural Heritage is one of the most fundamental parts of the protection process, which relies on many different techniques, many of which fall under the field of Geomatics, at least for tangible heritage.

2.2 Geomatics: generalities

The term Geomatics was first used by the French Ministry of Public Works in 1971 for the institution of a committe of geomatics, and later by Université Laval in Canada at the beginning of the 1980s, upon the recognition of electronic computing's growing potential concerning the sciences of surveying and representation which are the basis for modern computer-aided drawing (CAD). It is employed to define the multidisciplinary approach of collecting, analysing, storing, and processing geographical information in a digital format, and it is constituted by many different techniques and disciplines [22], such as:

- cartography: it provides a description of the shape and size of the Earth, and of its details, both natural and artificial, through a graphic or numerical representation of areas on the earth's surface.
- geodesy: the science which determines the shape and size of the Earth, of its reference surface: the geoid, and of its gravitational field.
- geographical information systems (GIS): a powerful set of tools capable of memorizing, transforming, representing and processing spatially related data.
- laser scanning systems: they are used for identifying objects and measuring their position and distance through the use of light radiation in the optical frequencies (0.3-15 μm), a range of the electromagnetic spectrum.
- photogrammetry: the science used to determine the position, size and shape of objects through measurements obtained from photographic images.
- remote sensing: remote acquisition of data concerning the territory or the environment as well as the set of methods and techniques for the their elaboration and interpretation.

- satellite positioning systems: they allow the three-dimensional positioning of moving objects in space and time across the globe, continuously and under any weather condition.
- topography: the set of direct survey procedures of the territory, to measure and represent in detail the surface areas of the earth in his aspects of planimetry, altimetry and surveying.

Geomatics sciences and techniques are exploited for many different application areas, such as Climate Change/Environmental Monitoring; Seismic Interpretation, Land management and reform; Air Navigation services and Aeromagnetic surveys; Natural resource monitoring and development; Urban and regional planning and Infrastructure management; Disaster risk reduction and response, and finally Archaeological and Architectural excavation and survey.

2.3 Laser scanning: generalities

Among the survey techniques, laser scanning is characterized by the ability to retrieve complex information with high precision, and with a certain level of automation. Thanks to an electromagnetic beam, which may be fixed or in motion, it is possible to detect an enormous amount of points surrounding the instrument up to a fixed range, and to accurately measure distances and recreate the three-dimensional image of the object or environment of interest.
Therefore, laser scanning techniques represent a big step forward from photogrammetry, since they directly supply three-dimensional models by reducing the involvement of experienced operators and by granting a certain automation of the process. This technique offers multiple applications in ground and aerial surveys, and its main disadvantage is represented by the complex filtering operations needed to select the enormous amount of data collected by the laser system to recreate the model.

Terrestrial Laser Scanning (TLS) offers an alternative to traditional survey techniques, because of the huge amount of automated data capture of complex surfaces and of inaccessible environments, becoming a valuable tool in the areas of survey or mine engineering, architecture and heritage documentation. With a TLS an object can be scanned from different view points, and then the single point clouds can be registered and merged into a unique point cloud with a common local coordinate system defined by the instrument and later modified by the operator.
Similarly to photogrammetry which takes advantage of Ground Control Points for the orientation of the frames, in order to complete the registration process of point clouds acquired from different points of view or, for instance in our research focus with different applications available on Apple's App Store, homologous points or objects are required. For this reason, automatic matching methods are available in specific software, thanks to which it is possible to manually register a small amount of tie points, and then let the program conclude the operation by automatically registering the remaining points via ICP (Iterative Closest Point), an algorithm used to minimize the difference between two point clouds to reconstruct 3D surfaces from different scans. In the ICP, the reference point cloud is kept fixed, while the source one is transformed to best match the first one. The algorithm iteratively revises the transformation made up of rotation and translation needed to minimize the distance from the source to the reference point cloud, which is usually estimated using a root mean square distance minimization technique to best align each source point to its match.
Based on the principles they rely on, laser scanners can be classified into three main categories: pulse-based scanners, phase-based and triangulation-based scanners [23]. The first two kinds of laser scanners are also known as "time of flight" (TOF), since they both determine distances by measuring periods of time. The pulse-based laser scanners (direct TOF) measure the time taken by a short laser pulse to go back

and forth from scanner to object. Since energy is concentrated in very short pulse widths, pulse-based laser scanners are adapted for long-range measurements, and a pulse is transmitted only when the echo of the previous one has been returned.
On the other hand, phase-based laser scanners (indirect TOF) send a continuous high intensity wave in the direction of the object and compare the phase difference between the transmitted and the received signal, therefore this technique is suitable for the measurement of short scanner–object ranges, since the high intensity continuous wave is less powerful than the one produced by a pulse-based laser scanner.
Finally, triangulation-based scanners measure distances by solving plane triangles, and it relies on the observation of a spot emitted by a laser diode with an optical receiver system. These laser scanners are designed for scanning objects at close range up to 30 cm range, and consequently relatively small objects. For this reason there are handheld scanners that operate on a principle which relies on triangulation, but it allows the user to turn around the object. Handheld scanners can be coupled with a mechanical arm which allows the acquisition with less than six degrees of freedom, while arm-free handheld scanners are stand-alone units that allow total freedom of movement.

2.4 History of Laser scanning

Our visual perception is the key factor for understanding the world around us, but technology has been always pushed to add precision to our sight, by creating systems to measure distances with the power of radio waves to create RADAR in 1904, which stands for and "radio detection and ranging", to detect objects at sea so that ships could avoid collisions.
Likewise happened in 1938 with the use of light beams to determine the height of clouds, but it was only in 1960 that laser was invented, and the first LiDAR system was introduced in 1961 by Malcolm Stitch for satellite tracking, with the name

"CoLiDAR", which stands for “Coherent light detecting and ranging”, from which many new systems are derived, including laser rangefinders and altimeters. The advantage of using laser light is that, thanks to its short wavelength, much smaller objects can be detected or measured, such as cloud particles and rain. Furthermore, since laser light is very narrow, it is also possible to capture small details with high resolution at relatively long distances.

The term LiDAR was firstly used as a stand-alone word in 1963 as a combination of the words “light” and “radar”. In the 1970s, LiDAR became publicly known for its accuracy and usefulness during the Apollo 15 mission, with astronauts using a laser altimeter to map the moon surface, and NASA began laser-based remote sensing to measure the properties of the ocean waters and atmosphere.

Since then, LiDAR has been used increasingly for scientific purposes and in the mid-1980s it was proved to be the best sensor to work with aerial photogrammetry, but it wasn’t until GPS (Global Positioning System) became available for public use that LIDAR became an incredibly accurate and crucial instrument for scientists. By the mid-1990s, LIDAR scanners were capable of producing 2,000 to 25,000 pulses per second and were mainly used for topographic mapping of the earth’s surface, helping governments and companies in planning, surveying and construction on uneven terrain.

More recently, with the use of LiDAR and many other remote sensing systems such as GNSS, 360° cameras and radar, mobile vehicles have been used to collect geospatial data in a process called Mobile Mapping.

Navigation and imaging sensors are mounted on a mobile platform to provide GIS data, digital maps, and georeferenced images or video. The idea of mobile mapping is as old as photogrammetry, but it is only at about fifteen years ago, with the advancement on satellite and inertial technology that it was possible to rely solely on the imagery platform.

The most known mobile mapping system is the one provided by Google for the Street View technology available on Google Maps and Google Earth, which from 2007 maps many streets in the world.

2.5 Photogrammetry: generalities

Along with the LiDAR sensor, the main camera is also exploited in the scanning process, since it uses the principles of photogrammetry to assign colours to each point. In fact, photogrammetry is the technique used to obtain physical information such as colour, shape or dimensions of an object or environment by extracting data from photographic images, and it can be used in several applications for different purposes: for instance, when a certain asset is out of human reach, it is still possible to acquire some desired information.

On top of that, by capturing the case study through images, any physical contact with fragile objects can easily be avoided. It is the branch of remote sensing which can be defined as the "science of measuring from photos", and this operation is possible thanks to the principle of *stereoscopic viewing*, which means to use two or more pictures of the same object taken from different positions in order to calculate the three-dimensional coordinates of any represented point.

By doing so, the photogrammetric process resemble the way our brain works when our eyes are used to observe things, by intersecting in space the line of sights connecting the image points to the corresponding object points and determining the three-dimensional position of the points.

The main goal of the photogrammetric process is therefore to generate the three-dimensional measurable model of an object by covering its surface with a sample of overlapping images, which represents a database accessible at any time.

Apart from geometric changes in the pictures, caused by the different positioning of the camera and the object, there may also be some radiometric changes, regarding the colour since the reflected electromagnetic radiation is affected by the transmission media, air or glass, and the light-sensitive recording medium, the film or electronic sensor.

Originally, photogrammetry was mostly used for territorial mapping purposes and cartography production, mainly in the war field, but throughout time it became more relevant in architecture, cultural heritage, engineering, and also in police investigation or cinematography.

2.6 History of Photography

In order to talk more in depth about photogrammetry, the first thing to deal with is the art of photography, which comes from the greek $\phi\omega\tau\omega\sigma$, *photos* (light) and $\gamma\rho\alpha\phi\iota\alpha$, *graphia* (writing), therefore meaning *"drawing with ligths"*.

The principle of *camera obscura*, for which light projects a image reversed through a pin hole onto an opposite surface, has been known since antiquity, with the first written record being the one of the Chinese philosopher Mozi(479 - 381 BC), but also Aristotle (384 - 322 BC) in his work *Problemata Physica* [24], where he deals with physical problems, and in the Book XV he notes that "when the light shines through an aperture with regular angles, the result is a round figure, namely a cone (two cones are formed, one between the sun and the aperture and the other between the aperture and the ground, and their apices meet)".

In more recent times, Leonardo da Vinci (1452 - 1519) studied optics and human vision, and he published the first clear description and sketch [Figure 2.1] of the camera obscura called *Oculus Artificialis*, Artificial Eye, by studying the reflection of light on spherical surfaces, which was later published in his work *Codex Atlanticus* [25].

Figure 2.1: Leonardo da Vinci's sketches on camera obscura, Source:[26]

However, to capture light, further studies on photosensitive materials had to be done, and it was only in 1727 that the German scientist Johann Heinrich Schulze found out silver nitrate reaction to light, for which he noticed that it turned dark red when hit by sunlight [27].
At the beginning of the nineteenth century, the English ceramist Thomas Wedgwood, experimented with the use of silver nitrate by soaking sheets of paper or leather exposed to light after having placed objects in it [28]. Where the paper was hit by the light, the substance blackened, while it remained clear in the areas covered by the objects. These images, however, did not stabilize and quickly lost contrast when kept in natural light, while stored in the dark they could be seen in the light of an oil lamp or candle.
The French Joseph Nicéphore Niépce studied to find a substance that could impress itself in the light in an exact way, while maintaining the result over time. The first attempt was with a sheet dipped in silver chloride and displayed inside a small darkroom, for which the resulting image appeared reversed, with white objects on a black background. He then discovered that bitumen of Judea was sensitive to light and in 1822 he used it by covering a pewter plate with this substance and overlaying an engraving of the Cardinal of Reims on it. Where the light managed to reach the pewter plate through the clear areas of the incision, it sensitized the

bitumen, and the surface that remained uncovered was excavated with the etching technique in order to use the final plate for printing, and he then used iodine vapors to blacken the areas washed by the bitumen [29].
This procedure was called heliography, which means "to draw with the sun", and it was used in the darkroom to produce positives on tin plates, with the first successful example of fixing a photograph permanently being *Point de vue du Gras* from 1826 [Figure 2.2]. Due to the very long exposure required of up to eight hours, outdoor shots were penalized by sunlight change in this period of time, while it became more successful for indoors shots with controlled lights.

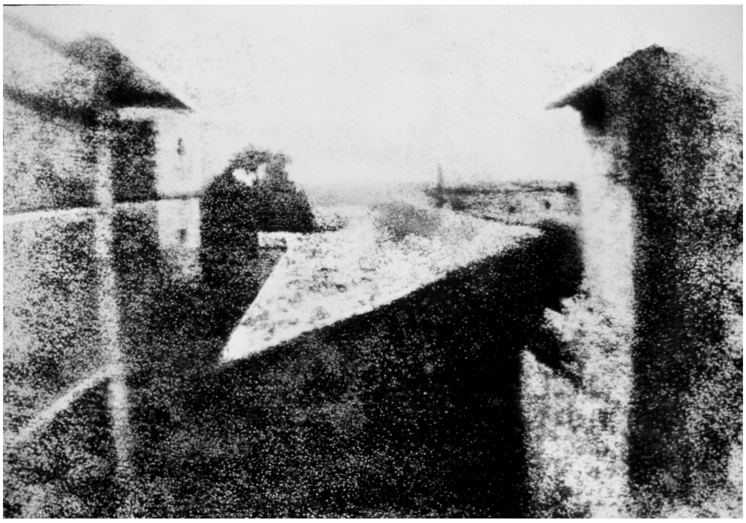

Figure 2.2: Joseph Nicéphore Niépce, Point de vue du Gras, Source:[30]

The technique was presented to the Royal Society in London, but it was not accepted because Niépce did not want to reveal the whole procedure. He then got in touch with Louis Jacques Mandé Daguerre, a Parisian painter who created a diorama theater, for which he used the camera obscura principle to provide a correct perspective, and with whom he concluded a contract to continue joint research. Following Niépce's death in 1833, Daguerre modified the contract and changed the name of the invention in *daguerreotype*.

This new procedure was very different from the original one prepared by Niépce, and by 1837 it was possible to capture a still nature scene with great results. Daguerre used a copper plate with a thin polished silver leaf placed on top of iodine vapors, which reacts to form silver iodide. By exposing this to the darkroom, the light turns the silver iodide back into silver, it is then exposed to mercury vapour to make the image visible, and finally it is fixed by soaking it in a strong solution of common salt [31]. The ability to capture a landscape in minutes and with a high amount of detail made photography the ideal tool for researchers and travelers, but it initially encountered problems in portraying human figures due to the long exposures required of at least eight minutes.
In Italy, the first images obtained with this method were made by Enrico Federico Jest and Antonio Rasetti in 1839, with a machine they built based on Daguerre's designs, which represent views of the Gran Madre [Figure 2.3], Piazza Castello and Palazzo Reale, all located in Turin [32]. In 1840 however, with the increased sensitivity of the daguerreotype plate through the use of bromine and chlorine vapours and with the introduction of an objective of brightness f/3.6, it was possible to obtain exposures of only thirty seconds, therefore allowing also portraits to be represented and not only landscapes.

Figure 2.3: Enrico Federico Jest, View of the Gran Madre, Source:[33]

After the development of the plate, all the images obtained up to this moment required the manual intervention of the photographer which had to work directly on the images to compensate the lack of colours, by using aniline pigments to blend and strengthen many portraits. It was only with the studies of the English physicist James Clerk Maxwell who in 1859 demonstrated, with a procedure called additive mixing, the possibility of recreating color by superimposing red light, green and blue. Then, in 1871 Richard Leach Maddox developed a new emulsion, prepared with cadmium bromide, silver nitrate and gelatin. The plates allowed for easier transport because they no longer required preparation before exposure, giving birth to a new category of photographic instruments, the portable devices. Finally, in 1888 the first portable camera called Kodak N.1 with 100 poses already preloaded was sold at the price of 25 dollars, with the slogan "You press the button, we will do the rest"2.4.

Figure 2.4: Kodak N°1 Advertisement from 1888, Source:[34]

At around the same period, aerial photography was practiced for the first time in 1858 by Gaspard-Félix Tournachon, also known as "Nadar", who flew with an air balloon over Paris, and again in 1859 to obtain reconaissance photographies in preparation of the Battle of Solferino, by order of the Emperor Napoleon. However, the pictures taken by the French photographer have not reached us, therefore the most ancient aerial images are the ones from James Wallace Black, who captured the city of Boston from above in 1860 [Figure 2.5]. Then, during the American Civil War, the U.S. Balloon Corps were established to create large-scale maps of battlefields to determine troop movements. There was also an attempt with the use of carrier pigeons by the German pharmacist Julius Neubronner, who in 1903 experienced with the delivery of light-weight medicines. He experimented by releasing pigeons in a distance of about 60 km from home, and realised that they have an innate ability to fly along geodesics, the shortest way between the starting point and the arrival point, and to return from where they had left, and by 1908 he obtained the patent for aerial photography with pigeons, who were equipped with a photographic camera for military use [Figure 2.6]. In the 20th century, aerial photography improved dramatically, with airships used in the World War I, but that were replaced in the Second World War by airplanes. The greatest development of aerial photography took place during the Cold War, with high-performance spy planes which by 1950 could reach the stratosphere, but then it became clear that it was safer to use satellites in orbit to spy on the opponent.

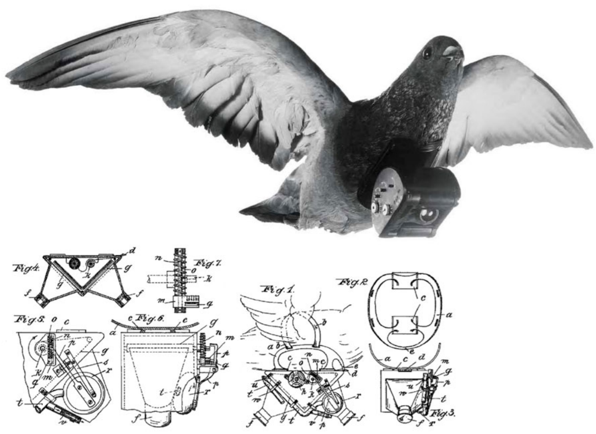

Figure 2.5: Aerial view of Boston, James Wallace Black, 1860, Source:[35]

Figure 2.6: Julius Neubronner's pigeon camera patent, 1908, Source:[36]

2.7 History of Photogrammetry

As stated before, the development of photogrammetry is influenced by the one of photography and aviation, but the first steps can be traced back to Leonardo da Vinci, who in 1480 wrote about perspective and who in 1492 began working on central projections with the Lanterna Magica, a further development of the camera obscura principle.

Other scientists followed da Vinci's works on perspective and projections, such as Albrecht Dürer who in 1525 invented an instrument used to create a true perspective drawing, and Johann Heinrich Lambert who in 1759 wrote the treaty called "Perspectiva Liber", free perspective, in which he developed the mathematical principles of a perspective image. Then, thanks to Niépce and Daguerre's discoveries in photography, at around 1840, the French geodesist Dominique François Jean Arago began to use photogrammetry, using the daguerreotype, in front of the French Arts and Science Academy.

In 1849, Aimé Laussedat was the first person to use terrestrial photographs for topographic map compilation. He experimented with aerial photography supported by a string of kites and then with balloon photography. In 1865, the Italian inventor Ignazio Porro designed the photogoniometer, an instrument for the survey of the territory activities to create geographic maps, which later acquired great importance when it came to building the stereoscopic recovering devices for aerial photogrammetry, with the first aerial photograph captured for mapping purposes from a plane by Italian captain Cesare Tardivo in 1908.

The term *"photogrammetry"* was used for the first time in 1867 in an unsigned article called "Die Photogrammetrie" [Figure 2.7], later attributed to the German engineer Albrecht Meydenbauer, who had used photography for the survey of terrain and architectural objects, in which photogrammetry was adressed as a remarkable science for civil engineers with a promising future.

Jahrgang I.

Zusendungen
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Expedition, Oranienstr. 75.
(Buchhdlg. v. C. Beelitz).
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Erscheint jeden Freitag.	Berlin, den 6. Dezember 1867.	Preis vierteljährlich 18¾ Sgr.

Die Photogrammetrie.

Die Photogrammetrie*) scheint sich allmälig zu einer so beachtenswerthen Hülfswissenschaft des Bau- und Ingenieurfachs auszubilden, dass ein Rückblick auf den bisherigen Entwickelungsgang derselben gerechtfertigt sein dürfte.

rain-Abschnittes von etwa 400 Ruthen Länge und 350 Ruthen Breite, den ganzen von der Unstrut durchströmten Thalkessel umfassend, in welchem das Städtchen Freiburg mit seiner mittelalterlichen Ringmauer und seinen engen steilen Strassen liegt,

Figure 2.7: Die Photogrammetrie, Albercht Meydenbauer, 1867, Source:[37]

The development of photogrammetry can be divided into four main periods: the first one spans from 1850 to 1900 and is called *Plane Table Photogrammetry*, in which the exposed photos were oriented on a plane table and the directions to the different objects were transferred onto the map sheets.
As already seen, with the advent of photography and the ability to make exposures from the air, this procedure was initially used for military purposes by Tournachon (1859, Battle of Solferino), but then thanks to the photogoniometer designed by Porro in 1865 which removed lens distortion, it became more significant also for other applications.
Finally, Meydenbauer's method of mapping the terrain by intersection, where conventional surveying was used to locate the position of the cameras and of a few control points in the scene being photographed. Meydenbauer's methods reached high accuracy levels because of the large format size used and because of the selection of ratio between photo scale and mapscale.

The second period spans roughly from 1900 to 1950 and is called *Analog Photogrammetry*, in which operations like measuring and mapping had to be carried out manually by experienced operators with the use of analogic metric cameras which had to be calibrated in laboratories in order to guarantee great levels of accuracy.

Therefore, even though photogrammetry was being used for mapping purposes, it was mainly in situations where plane table mapping was too difficult to use. Furthermore, images had to overlap of at least 50% of the area of interest, thus creating stereopairs, and on top of that, a network of ground control points had to be created to better reconstruct the original scene or object. Aerial cameras had to use a large film format, usually a size of 230 by 230 mm, in order to receive a good ground resolution in the photos, and the lens system was constructed as a whole with the camera body, meaning that no zoom or lens change was allowed, with a fixed focal length and a central shutter.

As already seen, the first aerial photography captured from a plane for mapping purposes was done by Captain Cesare Tardivo for a 1:4,000 mosaic of Bengasi. In 1921 German professor Reinhard Hugershoff created the first analog plotter, a very complex mechanical plotter with two incorporated photogoniometers to map both planimetric features and contours. It could be used for terrestrial, vertical aerial, oblique, and convergent photography. He also developed an aerial camera with glass plates to obtain oblique photography by hand or by attaching the camera on the side of the aircraft.

The historical developments discussed up until now are focused on terrestrial and aerial photogrammetric techniques, but there had already been research around underwater survey by Dimitri Rebikoff, who is credited with a number of work on underwater photography such as the electronic flash, underwater film cameras and photogrammetric correction lenses for underwater surveys.

The third phase of photogrammetry, *Analytical Photogrammetry*, began in the early 1950s, when Everett Merritt developed a series of analytical solutions for camera calibration, interior and exterior orientation, relative and absolute orientation of stereo pairs, and when Dr. Hellmut Schmid developed the principles of modern multi-station analytical photogrammetry using matrix notation.

In 1955 Duane Brown developed new approaches to camera calibration, as well as the mathematical formulation of the bundle adjustment, granting a simultaneous solution of the exterior and interior orientation parameters of the camera and systematic radial lens distortion. He then continued to refine the bundle adjustment to include self-calibration, in order to improve the accuracy and reliability of the photogrammetric adjustment.

His final goal was to transform photogrammetry from a tool requiring highly-trained technicians to perform the measurement into a turn-key system that could be used directly by the client. To do so, he introduced retro-reflecting targets which offered significant improvement over conventional ones, and he helped in the mathematical development to move bundle adjustment software from large main-frame computers to personal computers.

However, conventional aerotriangulation still required a good metric camera and its calibration parameters, and this precluded the use of non-metric cameras for precise surveys. Thanks to the work of Sam Karara, a way to perform a direct linear transformation that did not require camera calibration data and initial approximations of unknowns was found in 1971.

With the introduction of digital equipment in the 1990s, the limits of surveying were once more diminished thanks to the use of automatic measuring algorithms and of software to manipulate images.

Finally, with the advent of digital cameras at the end of the 20th century, began the last phase of photogrammetry, *Digital Photogrammetry*, which is when the imagery processing steps, even including stereo-plotting, can be managed by a computer, with software to handle the geometric characteristics of a camera, but also to define them from images acquired on a calibration surface, or on any surface thanks to the approach of Computer Vision on self-calibration, and with calculations done using internal camera parameters which are known or estimated using Exif (Exchangeable Image File Format) data.
With the use of Computer Vision, images are analysed to discover common (homologous) points and then the geometry of the acquisition gets reconstructed. Therefore, unlike metric cameras, there is no more need for pre-calibration, and since not all digital cameras can obtain the same image quality, a choice has to be made beforehand based on the level of detail to be achieved.
The traditional photographic process develops in subsequent steps, and processing and printing operations are expensive, complex and time consuming, while with digital acquisition image availability and monitoring are real time with immediate feedback on the acquisition's quality and the operator has total and immediate control of the operative phases.
On top of that, in digital photography, the image is not formed from light sensitive films containing silver halide crystals and chromatic layers sensitive to yellow, magenta and cyan colours, but it is formed from an analogical electric signal transformed into a pixel to which three different Digital Number values are assigned, corresponding to red, green and blue percentages, and the processor's screen uses RGB values to reproduce the colour of each pixel.

2.8 Geometric principles of Photogrammetry

To understand how the photogrammetric process works, the principles governing the operation of the camera have to be defined. The first parameter to take into account is the focal length [Figure 2.8], which is the internal distance between the central plane of the lens and its focus point. It is measured in millimeters and the more curved is the lens, the smaller is the focal length.

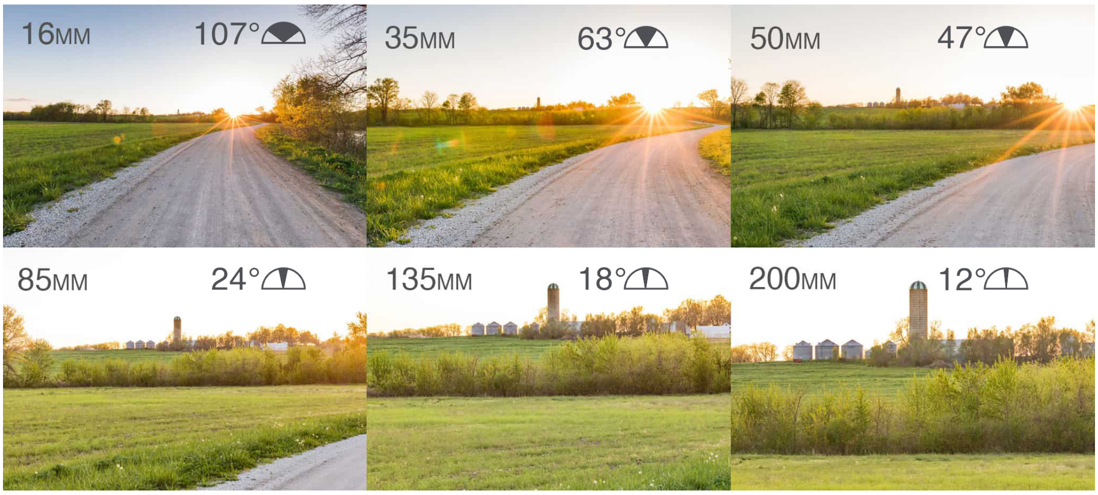


Figure 2.8: Example on the use of different focal lengths, Source: [38]

Based on the distance between the camera and the object, different lens to capture the image can be chosen, but not with the same results: By choosing a wide angle lens relatively close to the object to capture, the displacements of the central perspective will be greater than if it was chosen a smaller angle lens set at a bigger distance from the object. Assuming it was possible to go at an infinite distance and still see the object with a super telephoto lens, the displacements of the central perspective would be zero, and it would be a parallel projection.
This is an obviously an extreme scenario, but it is similar to what happens for aerial imagery, with pictures taken by satellites orbiting at hundreds of kilometers from the object to be captured, the earth. On the other extreme [Figure 2.9] are

images acquired with fisheye lens and 360° cameras, which mount two of these lenses on the opposite sides in order to capture everything that is around it, but with the maximum of displacement from the parallel projection.

Figure 2.9: Comparison between a satellite imagery and an image taken with a 360° camera of the same scene: Castel Sant'Angelo in Rome

When dealing with the photogrammetric approach, the first procedure to take into consideration is the interior orientation, which means to define the inner geometry of the camera and to correlate the internal coordinate system with the pixel coordinate system.

For metric cameras, the first coordinate system is given by the *fiducial marks* on the image and their coordinates, which can be found in the camera calibration certificate, and which consists of 4 marks at the middle of the image borders on older cameras, while in newer ones there are 8, with one more for each corner. Once the fiducial marks nominal coordinates and the focal length of the camera are known, the camera definition is complete, and it is valid for all pictures taken with the same camera and with the same lens. The next step is then the transformation of the fiducial marks from the camera into pixel coordinates, which is done automatically

if the marks have a high contrast with the background.
For non-metric digital cameras, which are often not calibrated, the process of determining the internal orientation parameters is more complex because they are unstable, but nonetheless a non-metric camera can be turned into a precision instrument by determining them regularly, before and after a survey. A camera is considered calibrated when its internal orientation parameters such as the principal distance or focal length of the lens, principal point and lens distortion parameters are known. Camera calibration is usually carried out together with the calculation of object coordinates within a self-calibrating bundle adjustment and with the use of a calibration grid pattern, and commercial programs are available to solve the calibration task for photogrammetry.

The next step within the orientation process is the exterior orientation, which is the relation between image and object coordinates, and to do this, ground control points (GCP) have to be measured. GCPs are object points represented in the image and from which the three-dimensional object coordinates are known. For solving exterior orientation at least 3 GCPs are needed, but in order to get a stable over-determination the more, the better. Furthermore, they have to be well-distributed, which means that a minimum of 3 points should form a triangle, not a line. GCPs can be distinguished in two main categories: targeted and natural points.
The first ones are signalised on the ground by high-contrast crosses with the point itself marked in the center. The second kind of points are real object points which can be clearly identify in the image as well as in a topographic map, such as rectangle corners from buildings or from other objects that are unlikely to move over time, like the corner of a sewage manhole.
The exterior orientation parameters [Figure 2.10] are the ones to define fully position and orientation of the camera coordinate system with respect to the global one.

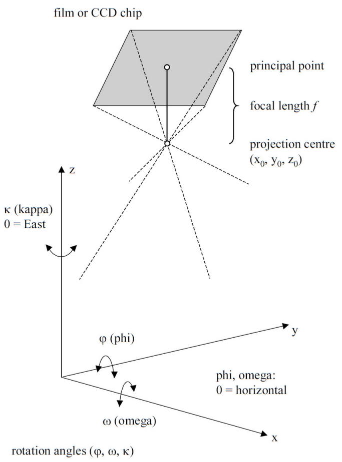


Figure 2.10: The six parameters defining the exterior orientation, Source:[39]

In fact, once the coordinates of the projection center are known (X_0, Y_0, Z_0) and the three rotation angles (ϕ, ω, κ), it is possible to define from where the picture has been acquired. For aerial photogrammetry, in order to obtain a parallel projection, also known as *nadir photo*, the angles ϕ and ω have to be equal to zero, but in reality these will have values close to zero, because of wind drift and small movement of the aircraft on which the camera is mounted, while the third orientation angle, κ, has set values at "E=0", and then counting anti-clockwise in grads, with "N=100", "W=200" and "S=300". These six parameters are used to define the *collinearity equations* [Figure 2.11], which are used to relate the image coordinates to the object coordinates, and which are at the basis for the equations used in bundle adjustment. The expression *collinearity* indicates that the image point, the object point and the projection center of the camera were aligned when the picture was captured.

$$x'_p = x'_0 + z' \cdot \frac{r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0)}{r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)} + \Delta x'$$
$$y'_p = y'_0 + z' \cdot \frac{r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0)}{r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)} + \Delta y'$$

Figure 2.11: The Collinearity Equations

As already seen, in order to obtain information about three-dimensional coordinates of object points, a model with a minimum of two pictures of said object captured from different positions (stereoscopic model) has to be created. Stereo vision is the way we are used to look at the world with two eyes in order to acquire depth perception, with two slightly different images captured at a pupillary distance of about 63 millimeters, which are then combined in our brain to obtain spatial information. An object point P will be then calculated as the intersection of the rays coming from the projected points of the two images P' and P". Since wide-angle cameras have a bigger overlap area, they are preferred for stereoscopic image acquisition, with pictures also acquired in convergent positions 2.12 to get more information about the z direction, but causing some perspective distortions in the images. However, in close-range photogrammetry multi-image configurations are the most common scenarios, for all those situations where a great number of different viewing locations is necessary due to the object structure or to maintain specified accuracy requirements. The object is acquired by an unlimited number of images and intersecting rays in the object space, for which object coordinates are determined by multi-image triangulation.

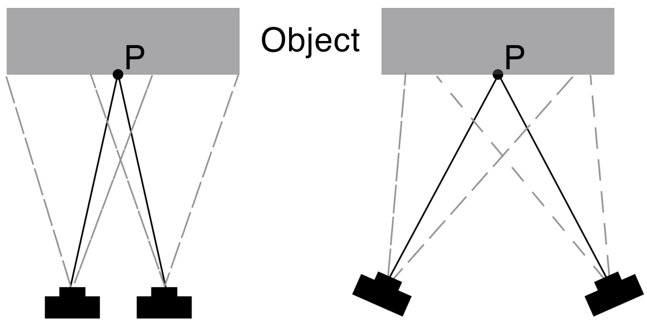


Figure 2.12: Parallel and convergent camera acquisitions

Chapter 3

LiDAR solutions

3.1 Affordable LiDAR Solutions

The main disadvantage of the LiDAR technology is its expensiveness, with prices for terrestrial laser scanning starting from just under 20’000 € and going up to over 100’000€ [40] based on their range, features and speed, making it not much appealing to the vast majority of the public. Through the last two decades though, there have been different affordable approaches to laser scanning and time-of-flight cameras, mainly focused of AR applications, but which can also be exploited for different scopes, such as robotics, geomatics, and 3D documentation.

Nintendo Wii

In the video game industry the first attempt in using sensors to study an environment is the Nintendo Wii, launched in 2006 and controlled by a remote and a sensor bar with ten infrared LEDs, divided into two groups of five LEDs on each end of the bar [Figure 3.1]. The light emitted from the sensor bar is focused on the remote's image sensor which sees it as two light dots separated by a distance d. The distance of the LEDs in the sensor bar is fixed D, therefore using triangulation the Wii CPU can calculate the distance between the remote and the sensor bar, and it can also figure out the rotation with respect to the ground, which can be calculated from the relative angle of the two dots in the image sensor. Since the whole process is done by the console through the infrared camera inside of the remote, the sensor bar itself is replaceable by any two sources of LEDs, with the most common one being candles.

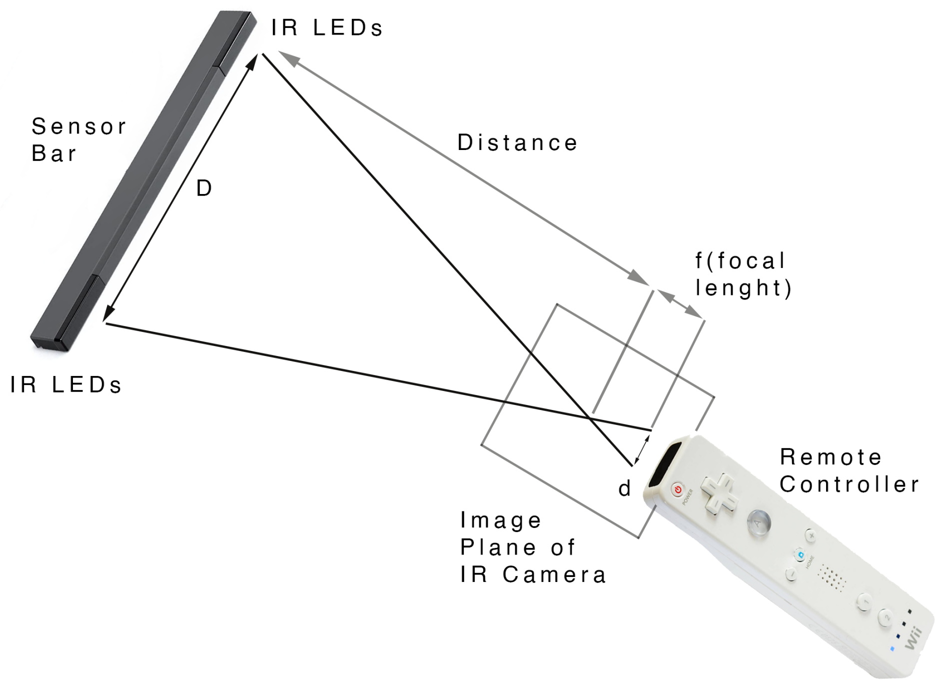


Figure 3.1: The principle behind Wii's sensor bar

Microsoft Kinect

Following the success of Nintendo's gaming console, Microsoft released in 2010 the Kinect [Figure 3.2] for the Xbox 360 gaming console. This motion sensor add-on is composed of a RGB camera that detects the three main colour components as well as facial and body features. Then, a depth sensor can be found, used along with the infrared projector to create the three-dimensional model of the environment by measuring the distances of each point on the player's body calculating the time of flight of the transmitted near-infrared light which has been reflected off the different objects in the field of view of the sensors. Thanks to the system of Light Coding, it is possible to interact with computer generated scenarios using the player's body as a remote to detect its motions and to track 48 points on it with a frequency of 30 times per second. The technology behind the Kinect was later on used to develop Microsoft's HoloLens, an augmented reality headset which can also be exploited for the acquisition of 3D models.

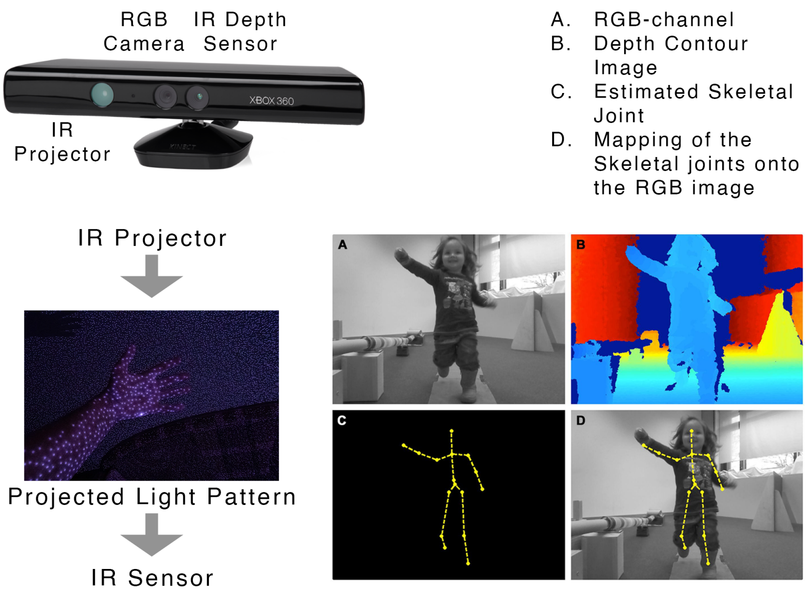


Figure 3.2: The principle behind Microsoft's Kinect, Source: [41]

Intel

Even Intel has experimented in the field with two Families of products: the Stereo Depth and the LiDAR. In the first one there are products like the D415 camera [42], with a standard field of view which results in higher depth resolution for smaller objects or when more precise measurements are required. The camera uses rolling shutter sensors and smaller lenses, which allow for a highly capable depth camera at a lower cost. Then there is the LiDAR Family, with the first product being the model L515 [43], designed for indoor applications and which uses an advanced MEMS (Micro Electro-Mechanical Systems) mirror scanning technology to capture depth data at high resolution and high accuracy. Coming at a cost of 650€, this is the most affordable laser scanner, and with a power consumption of 3.5 W it is also the most power-efficient one.

Figure 3.3: Intel L515 and D415 cameras, Source: Intel RealSense [44]

Google Tango

Later on, there has been a few attempts at implementing depth and motion sensors on hand-held devices with Google's project Tango, an augmented reality computing platform which used computer vision to enable mobile devices to detect their position in the environment without the use of GPS signal. The team leader of Tango's project is Johnny Lee, a computer engineer already famous for his inventions related to the Wii Remote and Microsoft's Kinect. To demonstrate this technology, two devices have been produced based on Tango, the Peanut phone and the Yellowstone tablet [Figure 3.4], which were sold mainly to researchers and software developers. It was only in 2016 that Google announced a partnership with Lenovo to release a consumer smartphone to feature Tango technology, the Phab 2 Pro with a depth sensor and a motion sensor on the back, in addition to the main camera [Figure 3.5]. These sensors combined with Tango's software could accurately measure three-dimensional objects, and also offer simulations of object in the real environment and augmented reality video games.

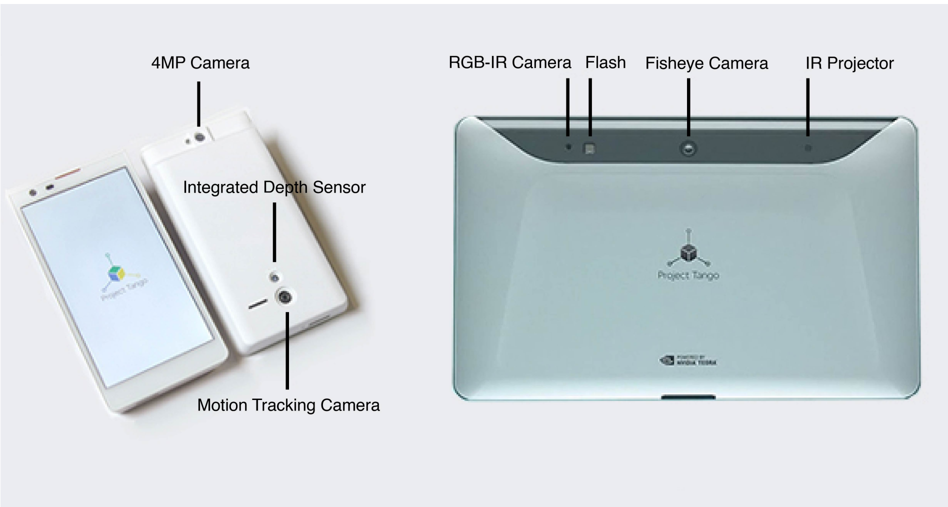


Figure 3.4: Peanut Phone and Yellowstone tablet

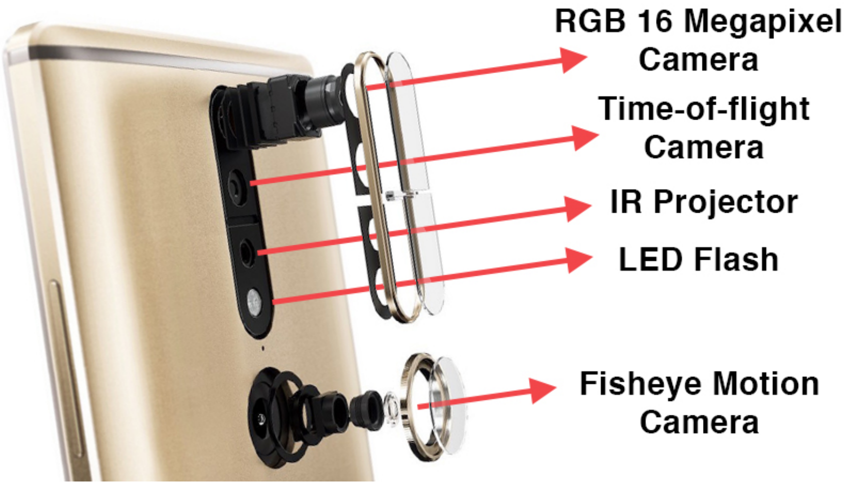


Figure 3.5: Lenovo Phab 2 Pro sensors, Source: Lenovo [45]

Samsung S20

Later on, also Samsung tried to include a Time of Flight camera called DepthVision [46] on their Galaxy S10, S20+, S20 Ultra and Note 10+ to enhance pictures thanks to the perception of depth and distances [Figure 3.6]. Just like previous examples, it uses the known speed of light to figure out distances, by measuring the time it needs for a reflected beam of light to return to the sensor.

Unfortunately, Samsung has abandoned the use of this sensor in more recent models, maybe because of the lack of interest by software developers to publish apps that could fully highlight the sensor utility, given that only a few models in the whole vastness of the Android world supported this technology. In fact, the main apps advertised by Samsung to exploit the DepthVision camera were the Camera app itself, Quick Measure and 3D Scanner. With the first one you could use the Live focus video mode to blur out the background in real time, or to switch up the focus between foreground and background with a tap, while with Quick Measure you could get some references on width, length, area and volume of objects in frame, and 3D Scanner allows you to take a 360 degree snapshot of an object and to turn

it into a GIF to send to friends or to add it into photos and videos.
Finally, at the end of 2020 it was time for Samsung's main competitor in the mobile phone industry. Apple decided to upgrade the Pro versions of the 12th generation of iPhones, as well as the 2020 Pro models of iPad by gearing them up with a LiDAR sensor, becoming until now are the only mobile devices on the market to really take advantage of this technology.

Figure 3.6: Samsung S20 Ultra sensors

3.2 Apple's LiDAR sensor

Figure 3.7: Apple's 2020 11-inch iPad Pro and iPhone 12 Pro

Apple firstly introduced the LiDAR sensor on its devices [Figure 3.7] in 2020, in the 4th generation of the iPad Pro [47], both for the 11 and the 12.9 inches versions, as well as the 12th generation of the iPhone Pro and Pro Max [48], with the main intent to take Augmented Reality to a new level. In fact, by capturing a tremendous amount of high-resolution data in the entire field of view, and by doing it in nanoseconds, it is possible to constantly map an environment, and to instantly understand the surfaces in the space, in order to use AR apps to analyse the different scenes and create custom experiences: through the detailed representation of a room, AR apps can be exploied to place 3D generated content everywhere, and thanks to depth maps occlusions can also be understanded, so that if an object is in front of others, the AR model will accurately be displayed behind the first one and in front of the latter. On top of that, the LiDAR sensor can also be used to enhance the Pro camera system, to reach six-times faster autofocus in low light, or to capture Night mode portraits even on the Wide camera, thanks to the detail of LiDAR depth maps which is helpful to have a subject in focus with a dark or blurred background.

The device tested in this thesis is the iPad Pro released in March 2020 [49], with the following characteristics:

- Dimensions and Weight: 178.5 x 247.6 x 5.9 mm (w x h x d) and 471 g;
- Display: 11-inch diagonal Liquid Retina IPS LCD at 120 Hz;
- Resolution: 2388-by-1668-pixel at 264 pixels per inch (ppi);
- Cameras: Wide at 12 MP f/1.8 aperture; Ultra Wide at 10 MP f/2.4 aperture and 125° field of view; Front Facing TrueDepth Camera at 7MP f/2.2 aperture;
- Other sensors: Face ID, LiDAR Scanner, Ambient light sensor;
- Chip: A12Z Bionic at 7nm+ with 64-bit architecture, octa-core GPU, octa-core CPU at 2.5 Ghz;
- Memories: 256 GB internal storage, 6GB RAM;
- Connectivity: 802.11ax Wi-Fi 6 dual band (2.4GHz and 5GHz), HT80 with MIMO Bluetooth 5.0 technology;
- Software version: launched with iPadOS 13.4, currently with iPasOS 15.6;

The advantage of using an iPad Pro over an iPhone 12 Pro is that the bigger screen allows the operator to better understand what is being acquired and what is yet to capture. On the other hand, the iPhone 12 Pro is lighter and easier to handle in tight spaces and it can easily access higher surfaces with the use of a selfie stick, and with the A14 Bionic chip it can perform better than the A12Z mounted on the iPad Pro.

For what concerns the price, the iPad Pro in the configuration used for our thesis is sold at around 1000 €, but it can go up to 2280 € for the maximum storage of 2TB in the Wi-Fi + Cellular 11-inch version, and up to 2600 € for the same configuration in the 12.9-inch version.

What makes this LiDAR scanner significant is the specific technology used to sense and measure depth. Among the several technology options available for 3D sensing, such as stereo vision, structured light, and time of flight (ToF), Apple's uses structured light for Face ID, with an IR emitter sending out 30,000 dots arranged in a regular pattern for depth estimation which are visible only to IR camera, and direct time-of-flight (dTOF) for the LiDAR sensor.
The structured light method provides high depth accuracy, but with the downside of having complex post-processing in order to calculate the depth from the pattern matching. On the other hand, dTOF is able to provide simple post processing, but it requires photodetectors with high-sensitivity, such as single-photon avalanche diodes (SPAD).
System Plus Consulting, which is part of the Yole Group [50], disassembled Apple's camera module [Figure 3.8] to show that Apple sensor is made up of an emitter: a vertical cavity surface emitting laser (VCSEL) from Lumentum, and a receptor: a near infrared complementary metal-oxide semiconductor (CMOS) image sensor to measure direct time of flight, developed by Sony.

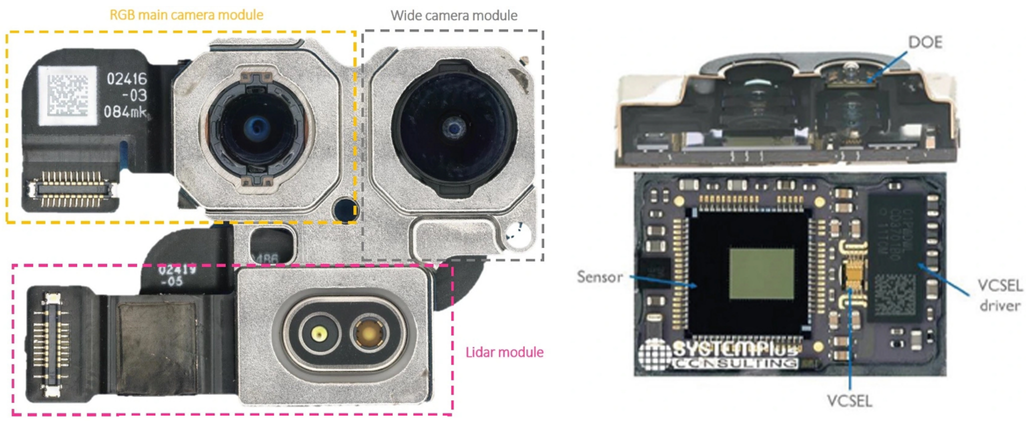


Figure 3.8: iPad Pro rear optical block and LiDAR module cross-section, Source: [51]

VCSELs are different from the edge-emitting lasers (EEL) used for other applications such as the automotive and industrial LiDAR systems. In fact, VCSELs are optimized for low-power and short-range applications, and a VCSEL array consists of up to 10,000 individual emitters, therefore it grants a higher reliability, since the impact of a single emitter failure is lower compared to EELs with one to four emitters. The VCSEL equipped on Apple's devices and manufactured by Lumentum is designed with multiple electrodes connected separately to the emitter array. To generate the pulse and to drive the VCSEL power and beam shape, the emitter uses a driver integrated circuit (IC) from Texas Instruments, which uses wafer-level chip-scale packaging (WLCSP). Finally, a diffractive optical element (DOE) from Himax is located above the VCSEL to generate the dot pattern.
The cross-section of Sony's CMOS image sensor revealed to experts that what looked similar to an old indirect Time-of-Flight (iToF) design with 10 micron pixels was actually the first ever consumer CMOS Image Sensor (CIS) product with in-pixel connection in a SPAD array. Sony has therefore entered the dToF segment by developing a new generation SPAD array NIR CMOS image sensor, which features 10 µm size pixels and a resolution of 30 kilopixel.

The LiDAR sensor on Apple's devices has been studied in the last few years on different applications, such as industrial 3D scanning on small objects like LEGO bricks [52], for forest inventory [53], for monitoring snow depth changes in small areas through time [54], for the 3D survey of rocks and cliffs for geological purposes [55], for human body measurements[56].
Finally, it has also been tested for heritage documentation purposes on three different scenarios (Small–medium objects, building exterior façades and indoor mapping) [57], and for 3D modelling in two indoor and outdoor scenarios [58]. For all these applications, the results obtained with Apple's LiDAR sensor have been compared with a TLS or photogrammetry reference dataset.

3.3 Reference Dataset: Faro Focus 3D x 330

Figure 3.9: Faro Focus 3D X 330, Source: [59]

To collect the reference dataset for our app analysis, the 2014 Faro Focus 3D X 330 [Figure 3.9] has been used, with the following characteristics:

- Dimensions and Weight: 240 x 200 x 100 mm (w x h x d) and 5200 g;
- Sensors: GPS, compass, height sensor, dual axis compensator;
- Field of View: 300°/360° (vertical/hotizontal);
- Range: 0.6m - 330m indoor or outdoor;
- Ranging Error: ±2mm;
- Measuring Speed: up to 976 thousand points/second;

This high-speed 3D scanner with extra-long range can scan objects such as large building or vast terrains up to 330 meters away with fewer scans, and even in direct sunlight. In fact, it comes with an integrated GPS receiver, which is used to correlate individual scans in post-processing.
Thanks to its range and scan quality, with very low noise level, it considerably reduces the effort involved in measuring and post-processing, because the data can easily be imported into commonly used software solutions for different applications such as architecture, forensics, industrial manufacturing and land surveying, thanks to which information about distances, areas and volumes, analysis and documentation can be carried out in a more accurate, reliable and swift way.
The main disadvantages compared to Apple's solution are the weight of more than five kilograms, the cost of around forty thousands euros, the data dimensions of captured scenes which is much higher, because of the greater levels of accuracy and the fact that, in order to acquire data from a fixed position, a tripod is required. Some discontinuity could be caused by obstructions: this problem can be overlooked by combining multiple scans, but it can also be avoided by using Apple's devices to walk around the scenes and capture hidden details.

Chapter 4

LiDAR Applications available on App Store

The evolution and availability of apps on Apple's App Store faced a rapid growth from the release of LiDAR, with a vast amount of different applications taking advantage of the sensor for many scopes. Trough a selection of ten out of the countless apps available, each ones' features and modalities are going to be analysed to detect the best ones in order to proceed with the study of the iPad sensor and its properties.

4.1 List and description of LiDAR sensor-based applications considered in this research

3D Scanner App

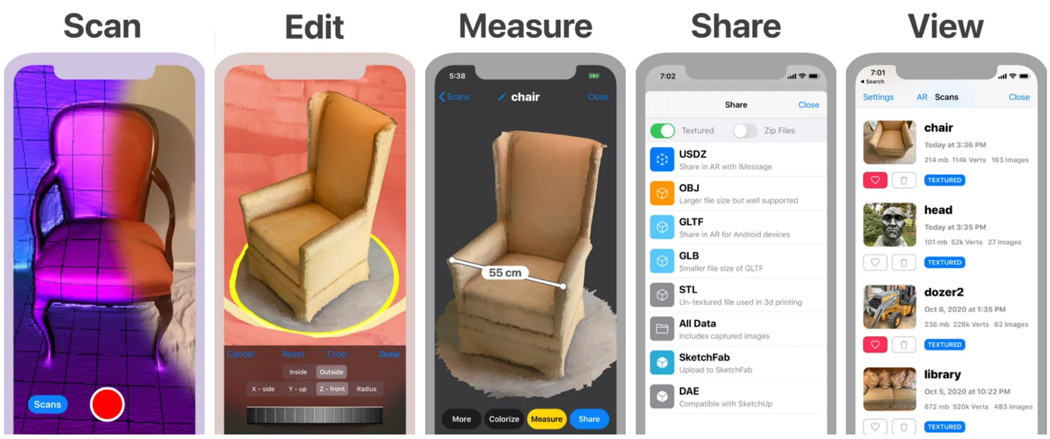


Figure 4.1: 3DScanner App Main Interfaces

This first app is *3D Scanner App* [Figure 4.1] by Laan Labs [60], which offers different scan modalities to choose from, with each of them having some scanning tips accessible by touching the question mark icon on the top right corner. The basic one is LiDAR, which does not include any kind of customisation or tweaking, and is ideal for quick scans, but it does not capture small details. The scanning tips on this one suggest to move slowly and keep a steady motion to reduce blurry images, and to plan the route by scanning each area once and by avoiding re-doing the same area. It is also pointed out that this mode works best with bigger things, like a room, while small or thin objects might not get picked up. Then, LiDAR Advanced offers the same quality of the previous mode but with the possibility to adjust different parameters: the maximum depth which is the distance from the sensor to be captured, in a range from 0.3 m to 5.0 m; the resolution from 5 mm to 50 mm, where the lower values give a more detailed scan, but it is suitable for smaller objects, and higher values are recommended for capturing larger areas like a house, and can be refined after the scan; the confidence from Low to High, which means to threshold the data coming in from the sensors, and by choosing high only the best quality data are kept, but reducing the amount of data available; finally, the absence or presence of masking can be chosen, whether it is on a object, or on a person. The third mode is Point Cloud, which records raw point cloud data rather than constructing a mesh, and which does not give any option to choose from before scanning. The last one is TrueDepth, which uses the front-facing sensor, therefore making it more difficult to scan an object, and it is not suitable to obtain scans at an architectural level.

Canvas

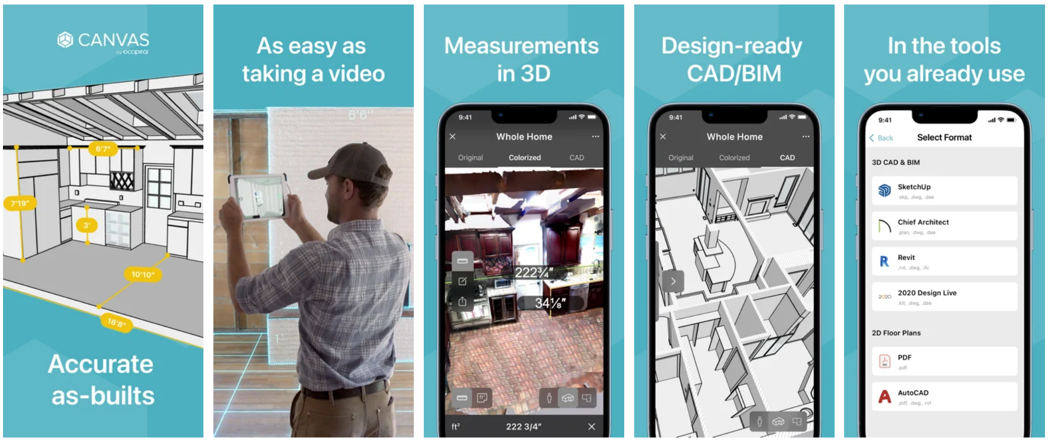


Figure 4.2: Canvas Main Features

With this second app by Occipital,Inc. [61] you can easily obtain measurements and generate as-built 2D drawings and 3D CAD/BIM models at an architectural level [Figure 4.2]. The app itself does not offer any adjustment while scanning, but through a question mark icon on the top right corner of the display it guides the user throughout the entire procedure, with a video or through a short guide containing tips such as to prepare the environment by turning on lights, opening all doors, closets and windows to pick up any corner, and by avoiding the presence of people, animals or object from the planned path. It suggests to start from a corner rather than a blank wall, and to scan like you have to paint a fence: to start from the floor, sweep up the wall, move to the side, and then back down, going on by repeating this patterned motion. It also indicates to stay between 1 and 3 meters from the walls and to move in a single continuous loop. While scanning it reminds you to move in a patterned motion, and it also signals when it is going too fast to pick up any information. Once the scanning process is completed, it is only possible to view the model from the outside, from a top view or from the inside, and to place a horizontal section plan, measure distances, and take notes on the model. There is no way to obtain a point cloud in any format, because the only exportation supports are 2D or 3D CAD/BIM drawings, for which the user has to pay up to \$1.50/m^2.

Dot 3DPro Beta

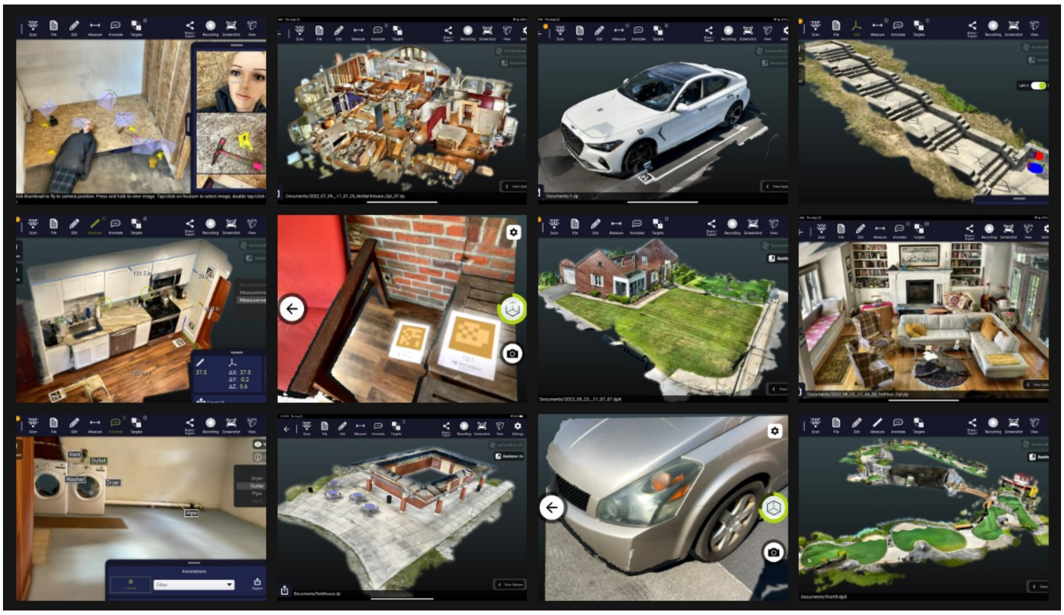


Figure 4.3: Dot3DPro Android/Windows Solutions

Dot3D Pro is the only application in this list that is not available in Apple's App Store. In fact, it is developed by DotProduct [62] and in order to download it the user has to sign up to the beta program that will grant him access to a license key. Then, through the app Testflight, which is available in the App Store, it is possible to download Dot 3DPro Beta, and to validate the license. Once the Beta Program has been finished, the app will be released to public on the App Store While scanning, the only settings available are the one regarding the maximum depth, which can be set in the range from 1.0 m to 5.0 m, then there are two boxes that are ticked by default, which can activate strong depth filtering and the detection of AprilTags, a visual fiducial system useful for a variety of tasks such as augmented reality, robotic and camera calibration. On top of that there is a cube icon which alerts if you're too close to an object and the app is not picking up any information, and a counter on the top which indicates in real time the number of pictures used to create the final model. Once the scan is completed it can be optimized to then enable other features such as to define a coordinate system, to measure and annotate on the model itself, to enable or disable backfaces and to change point size from 1 to 12. This app is also available for Android and Windows devices, but to use it, it is mandatory to purchase DotProduct's scanning kits such as DPI-10, DPI-10SR or Intel RealSense D455 [Figure 4.4].

Figure 4.4: Dot3DPro Android/Windows Solutions

Metascan

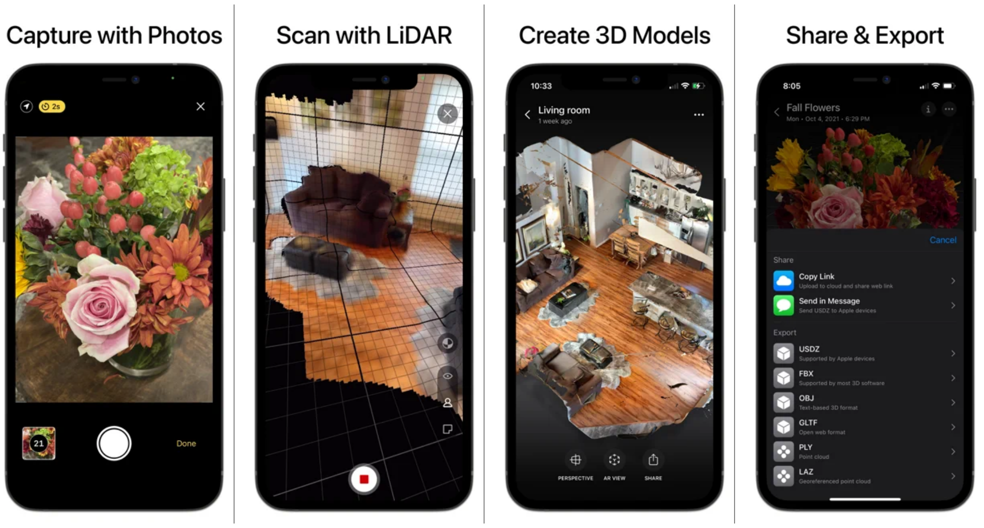


Figure 4.5: Metascan Interfaces

With this app by Abound Labs Inc. [63] the user can choose between two different modes, Photo or LiDAR [Figure 4.5]. The first one is most useful for objects which are non-trasparent, non-reflective and with a varied surface, and it lets you take up to 200 pictures of the object, therefore it resembles more the process of photogrammetry. The scanning tips in this mode suggest that adjacent shots should have 70% overlap or more for alignment, that the object should be captured from all sides, in a stable environment and under good lighting. You can choose to enable location to have a better alignment of the shots, and whether to take them manually or automatically every 2, 3 or 4 seconds. LiDAR mode lets you scan the environment in a similar way to the previous app, but you can switch between color or grid view, and you can choose between a camera, person or top view to have a simultaneous look of the whole acquisition and to check wether some spots have been missed. Once you are satisfied with your scan, you can choose in which quality you want it to be processed: Fast, with a medium resolution and a grid of 30 mm; Standard, with a High resolution and a grid of 20 mm or Pro, at full resolution and a grid of 15 mm. Unfortunately, the free version of this app is quite limited, since it lets you capture only 5 photo scans, and you can not process scans in Pro level of detail, with a resolution of 15 mm. Upgrading to the Pro version lets you have unlimited exports, the highest detail scans and 150 photo scans/month, but at a a cost of 6.99€/month or 50.99€/year.

Pix4DCatch

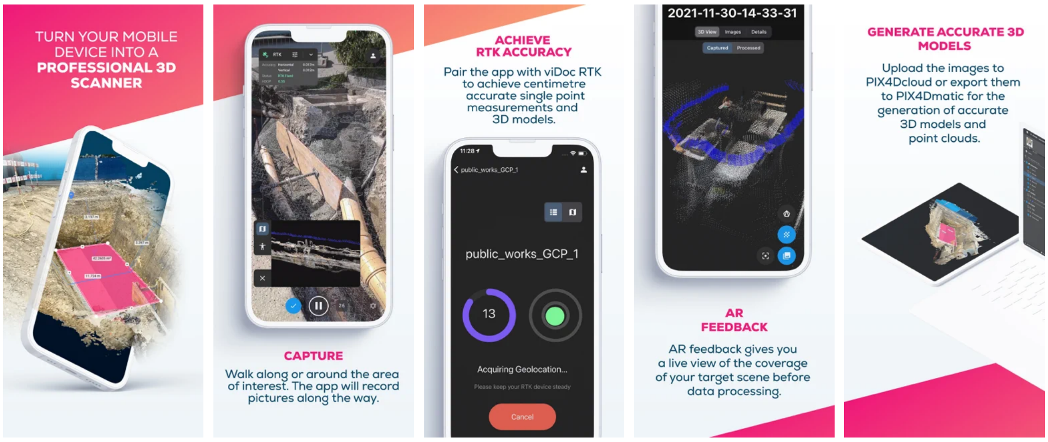


Figure 4.6: Pix4DCatch Main Features

On Pix4DCatch [Figure 4.6] by Pix4D [64] you can choose between two image trigger methods: Device Pose or Image Overlap. With the first, images are triggered by the movement and rotation of the device, and you can set a trigger distance from 1 cm to 100 cm and an angle from 1° to 45°. The second method triggers when the overlap goes below a selected value, ranging from 75% to 99%. Then, in Advanced Settings you can choose to view texture, overlap, cameras, movement path, feature points, and whether to display the mesh as solid or as wireframe. You can also adjust the mesh color by tweaking RGB and opacity values between 0 and 1. On top of that, you can decide to set an auto focus, to skip low quality images and to automatically save a video of the capture session. This application uses both the LiDAR sensor and the Main Camera for an approach more close to photogrammetry, and it also supports RTK Modules (Real-Time Kinematic) for direct positioning and for acquisitions' georeferencing. Finally, it is also paired with a Cloud service in which you can process, store and share your project, but the subscription comes at a price of 170€/month or 1700€/year for the basic version, and 260€/month or 2600€/year for the advanced version.

Polycam

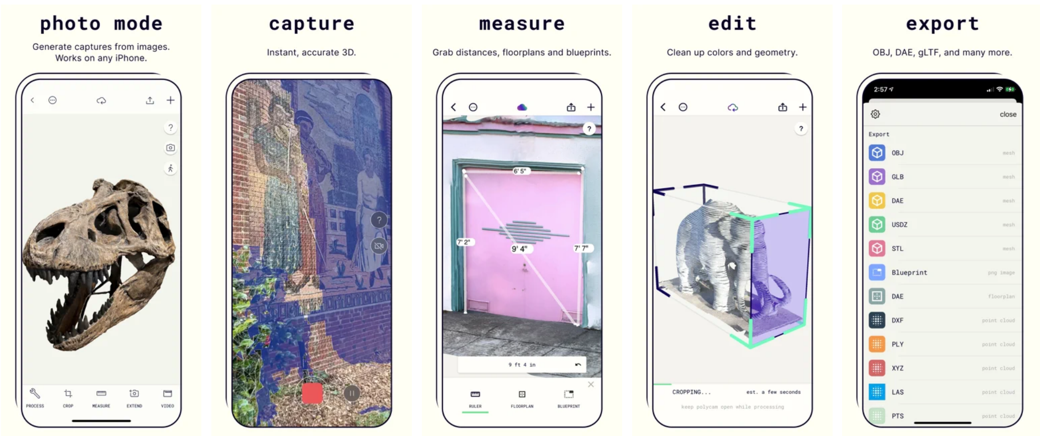


Figure 4.7: Polycam Interfaces

Similarly to Metascan, in this app by Polycam Inc. [65] you can choose between LiDAR or Photo Mode, with the first being the best for capturing spaces and the latter being the best for capturing objects [Figure 4.7]. It is suggested to plan the route in advance, by avoiding capturing the same area twice across large gaps of time. There is no option during the scanning process, except disabling real-time view of the environment and only displaying as polygons what has been already scanned and by showing with a blue color what has yet to be captured. With LiDAR mode, you can process your scans in four different ways: three presets which are fast, space and object, or custom, where you can adjust the depth range from 0.1 m to 6.0 m, you can change the voxel size from 8 mm to 84 mm, you can apply a simplification ranging from 0% to 99%, and you can automatically crop the scan. With Photo Mode, you can choose to manually or automatically capture each image, with 20 being the minimum number of pictures needed to obtain the scan and 250 being the maximum. Just like Metascan, also with Polycam you can upgrade to the Pro version, which costs 7.99€/month or 59.99€/year.

RTAB-Map

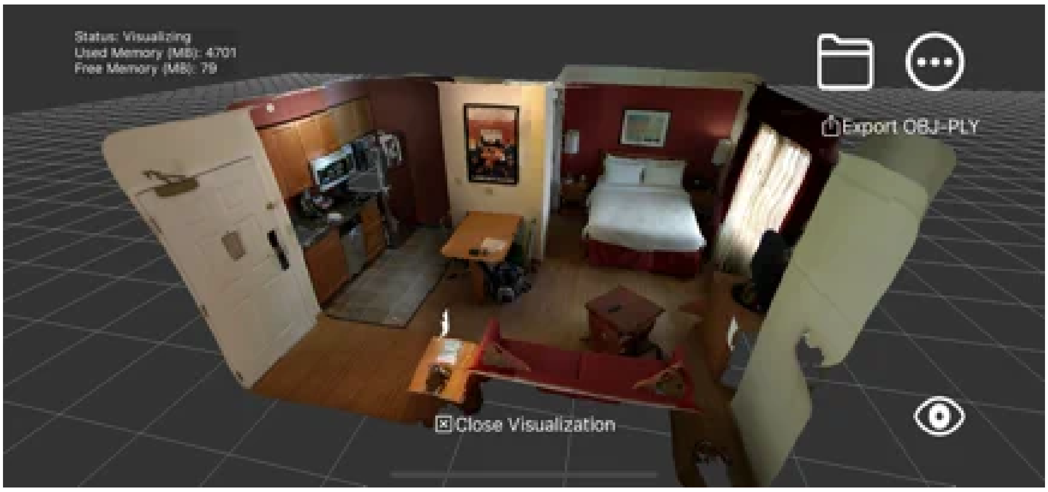


Figure 4.8: RTAB-Map Main Interface

With RTAB-Map [Figure 4.8] made by Matthieu Labbe [66] there is no initial setting or modality while capturing your scans, but once you have finished you can optimize it, by choosing standard or advanced optimization, and get access to different options, such as Global Graph Optimization, Detect More Loop Closures, Adjust Colors (Fast or Full), Mesh Smoothing, Bundle Adjustment and Noise Filtering. Then, in the Assemble menu, you can adjust point cloud density between current or maximum, at 0.01 m, and colored or textured mesh, with up to 900'000 polygons, or with no limit. Then, in the settings menu, you can adjust the density of the Point Cloud between very low, low, high or maximum level, you can set a Maximum Depth from 1 m to 5 m, or no limit, and a Minimum Depth from 0 m to 3 m, and the Depth Confidence between Low, Medium or High. On top of that, you can also adjust the Mesh Angle Tolerance from 5° to 60°, the Mesh Triangle Size from 2 pix to 6 pix, the Mesh Decimation Factor from Disabled to 99%, and the Texture Resolution, between Very low, Low, High or Maximum. This is by far the app with the highest amount of settings in order to satisfy every need.

Scaniverse

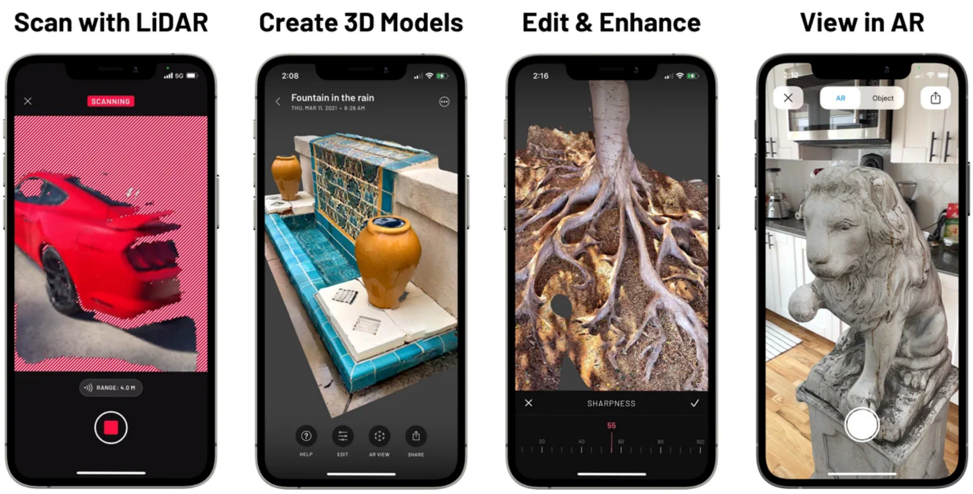


Figure 4.9: Scaniverse Main Features

Within this app [Figure 4.9] by Toolbox AI [67] you can select which asset you are going to scan between a small object, for instance a toy or a pet, a medium object such as a person or a vehicle, or a larger object like a room or a outdoor space While scanning you can only adjust the range in which to scan from 0.2 m to 5.0 m, and whether to turn on or off the location. Once you have finished capturing, you can choose between three different processing mode: Speed, Area and Detail. The first two use the LiDAR sensor with a resolution of 12 mm and 8 mm, while the last one reconstruct the scene using photogrammetry. Just like previous apps, the first one is the quickest, the second one is the best for rooms and the last one is the most suitable for small objects with detailed textures. After the scan has been processed, you can edit your model by cropping it, by measuring it, by applying filters on it or by adjusting its exposure, sharpness and contrast.

Sitescape

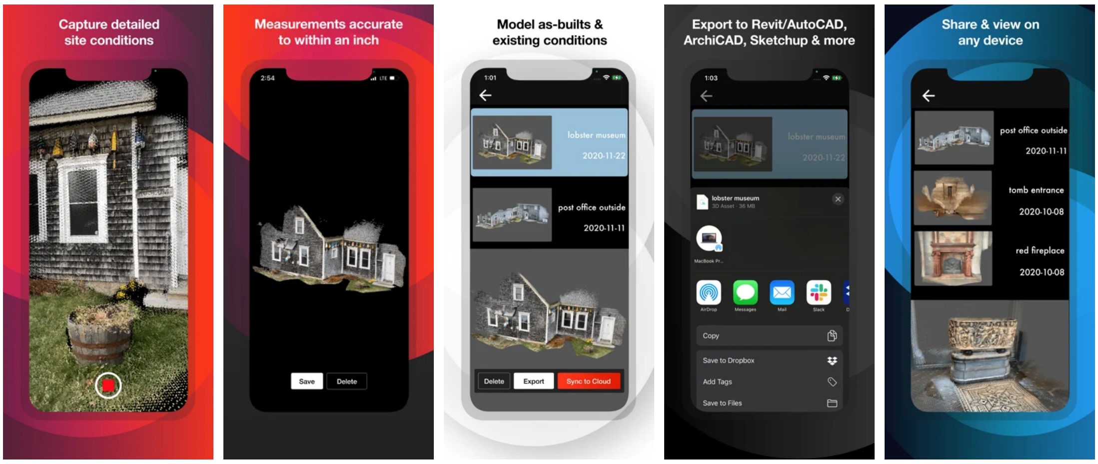


Figure 4.10: Sitescape Main Interfaces

With the app [Figure 4.10] by SiteScape Inc. [68] you can only adjust two parameters, Point Density and Point Size by choosing Low, Medium or High. While scanning, you can drag your finger vertically to adjust the Camera Passthrough, showing less of the device's camera feed during the acquisition when the slider is at the bottom, and more of it when the slider is at the top. There is no processing option at the end of the scan, and the models can be exported as point cloud or synced to the cloud. It is by far the most prohibitive app, since with the free version you do not have much customisation, and you can only upload a file at a time, while the pro version gets you unlimited syncing and measurements, but at a cost of 53.99€/month or 499.99€/year.

Zappcha

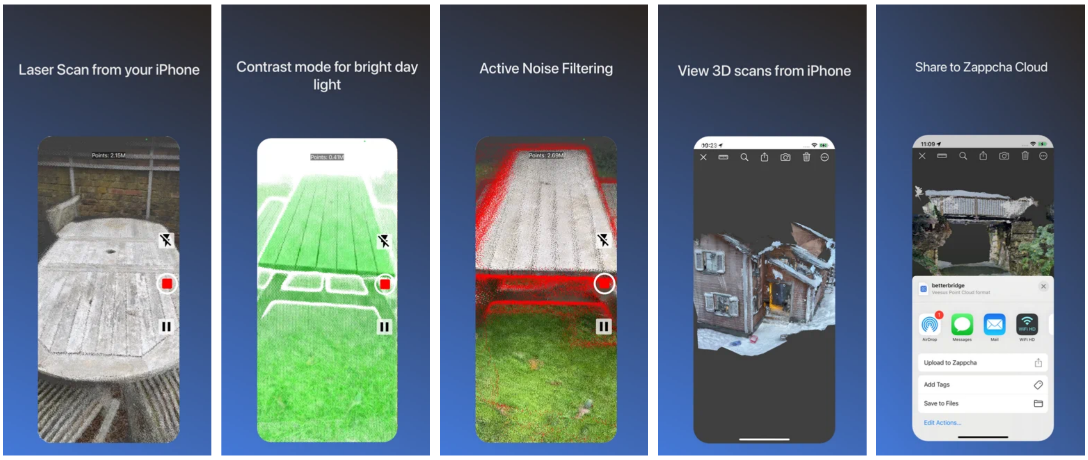


Figure 4.11: Zappcha Main Features

Opening this last app [Figure 4.11] by Veesus Ltd. [69], you can greeted with settings, in which you can enable Georeference, you can choose among three capture methods: Scan, which will capture data continuously, Burst, which captures only when the button is pressed or Timed, which captures automatically every 2 seconds, and you can also enable different features, such as noise filtering, switch between normal or contrast display for outdoor or bright light settings, enable auto view, set fixed or automatic exposure. During the scanning procedure, you can enable the flash, in order to scan rooms also in a scarcely lit environment. After the acquisition, you can switch between three view mode: Intensity, Colour and Contrast, which represent Gray-scale, True Colors and High Contrast based on the depth of different surfaces. On top of that you can set the reference system with the Up arrow being the Y or Z axis, and you can adjust the point cloud size and dynamic size from 1 to 4.

From the characteristics of each application on Apple's App Store, a preliminary rating can be drawn up [Figure 4.12], based on the price for which basic features such as the processing or the exportation of the model in different formats are available.

App	Version	Pro Version Price			Rating
		Month	Year	Other	
3D Scanner App	2.0	-	-	-	5
Canvas	3.5	-	-	1.50/m²	3
Dot3DPro	0.16.21	-	-	Beta	5
Metascan	2.6.0	6.99	50.99	-	2
Pix4DCatch	1.12.0	(170 - 260)	(1700 - 2600)	Optional Cloud (Basic - Advanced)	4
Polycam	2.2.9	7.99	59.99	-	2
RTAB-Map	0.20.19	-	-	-	5
Scaniverse	1.8.5	-	-	-	5
SiteScape	1.5	53.99	499.99	-	1
Zappcha	4.2	-	-	-	5

Figure 4.12: Preliminary Table of Prices

Chapter 5

Case Studies Definition

The selected apps will be tested on a small environment located in the Castello del Valentino called "Gabinetto dei Fiori Indorato" to define and verify the methodological setup which will then be used in different context of three-dimensional metric survey of Cultural Heritage. A selection of the applications providing the best results in the Cabinet of the Golden Flowers will be done to assess a further test on colour perception and to retrieve the documentation on three different Cultural Heritage assets located in Turin. The first one is a portion of Castello del Valentino's façade on the internal courtyard, followed by a large ambient located at the Noble Floor of the Castle, while the last one is the statue of a lying lion on the pedestal of the monument dedicated to Giuseppe Garibaldi sited on Corso Cairoli, along the river Po. Therefore, a total of four scenarios will be analysed, two of which are outdoor (Castle's Façade and Lion's statue) and two are indoor (Cabinet of the Golden Flowers and Hall of Honour), and for both kinds one is a small-scale scenario (Lion's statue and Cabinet) and one is a big-scale scenario (Façade and Hall of Honour). For each app, all the suitable modalities will be tested, with the best available processing options, and accessible information about the model's geometry will be provided.

5.1 Gabinetto dei Fiori Indorato

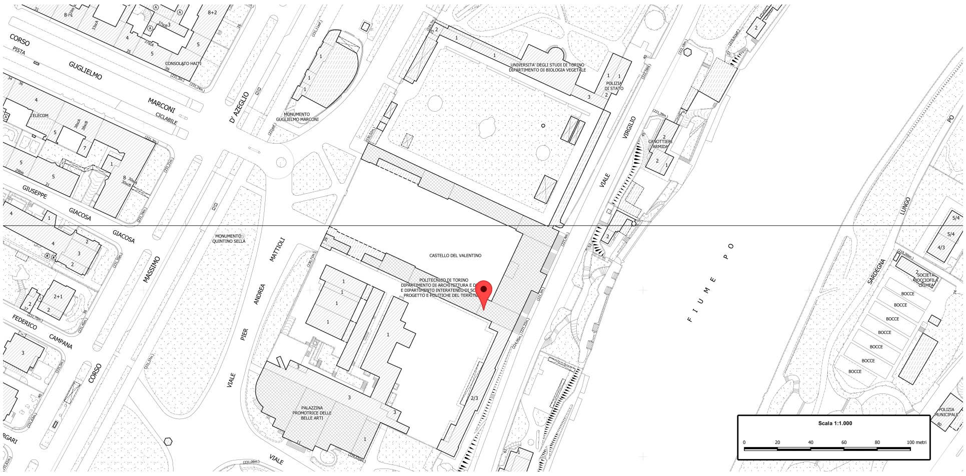


Figure 5.1: Location of the Cabinet of the Golden Flowers

The first test to understand which apps are able to provide the best results on an architectural level was done in the "Gabinetto dei Fiori Indorato", which means "Cabinet of the Golden Flowers", inside the Castello del Valentino [Figure 5.2].
The room is located on the southern wing of the noble floor and it is entirely decorated with golden plaster to resemble flowers and cherubs holding the royal crown, while on the lower part of the eastern and western walls there is a perspective effect to simulate the terracotta flooring of the entire noble floor. Each wall houses two decorated mirrors, which will most likely affect the LiDAR acquisition, causing some distortions in the whole laser scanning process.

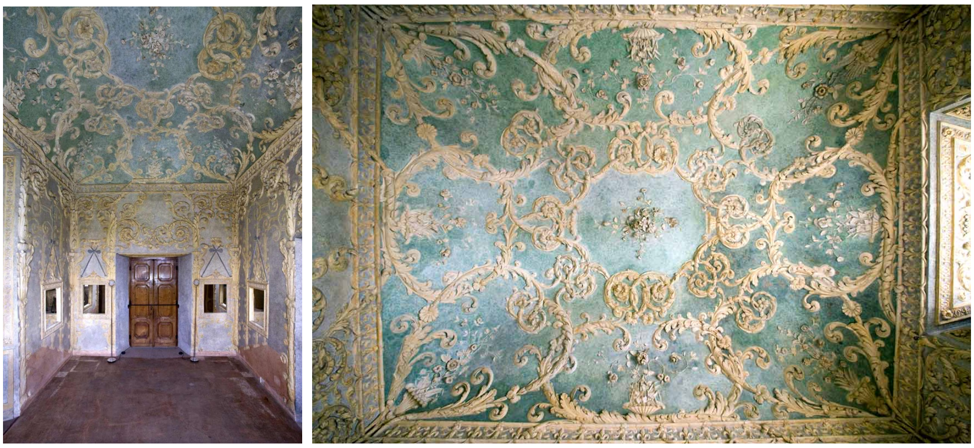


Figure 5.2: Gabinetto dei Fiori Indorato

Once the results from the first test have been acquired, a selection from the initial apps will be further exploited in different Cultural Heritage documentation scenarios: outdoor architecture, large indoor environment and outdoor monument.

5.2 Castello del Valentino's Façade

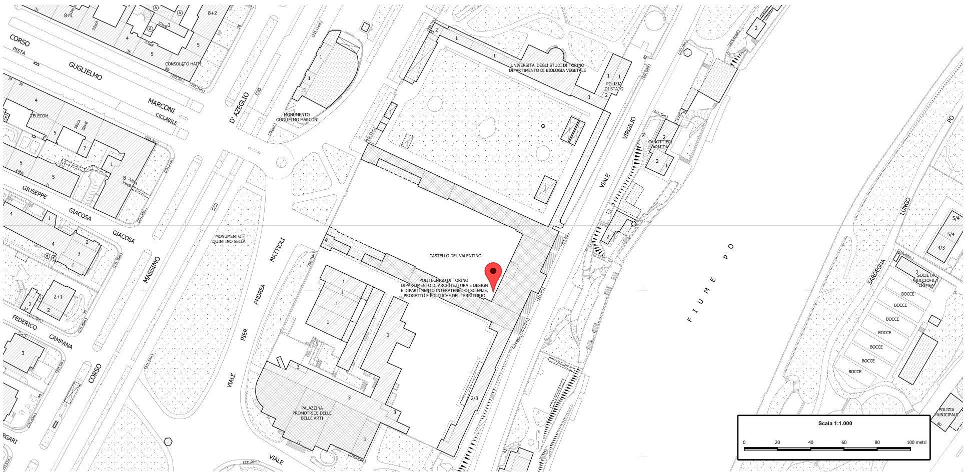


Figure 5.3: Position of the portion of the Castle's Façade analysed

The first scenario in which the selection of apps are going to be further analysed is a portion of the façade of Castello del Valentino, facing Corso Mattioli.
The Castle owes his name to the nature of the land, named “Vallantinum” after the presence of a natural valley with a watercourse still flowing underground. When Emmanuel Philibert bought it in 1564, with the transfer of the Savoy capital to Turin, and in that period the building was mainly involved in embellishment works to modify its interior. In the XVII century the Madama Reale Christine of France promoted the conversion into maison de plaisance under the work of the architects Carlo and Amedeo di Castellamonte, who doubled the existing architectural structure, which consisted in a simple wing parallel to the Po with four floors delimited by a stairwell to the south and a prominent section to the north, by enclosing it with two tall lateral towers connected with terraced porticoes to two new pavilion roofs and linked by a semicircular exedra.
The portion extending towards the river Po [Figure 5.4] can be identified as the main entrance and symmetrical focus of the whole building, and the creation of a double staircase facing the city and leading into the Salone d’Onore at the noble floor also gave greater importance to the central section.

Figure 5.4: Original access to the Castle from the river side

At the beginning of the XIX century the building housed the Veterinary Medicine School and it was later employed by the army until 1850, when it was given by the Crown to the State. Then in 1858, with the creation of a large city park on the left bank of the river for the Sixth National Exposition of Industrial Products, the Castle was restored, the terraces linking the two towers were replaced by two big galleries and the main façade was changed from the Po side towards Turin [Figure 5.5]. Finally, with the Casati Law from 1859, which marked the rearrangement of educational programs at different level, the Castle started housing the Royal School of Application for Engineers.

Figure 5.5: Current access to the Castle from the city side

5.3 Salone d'Onore

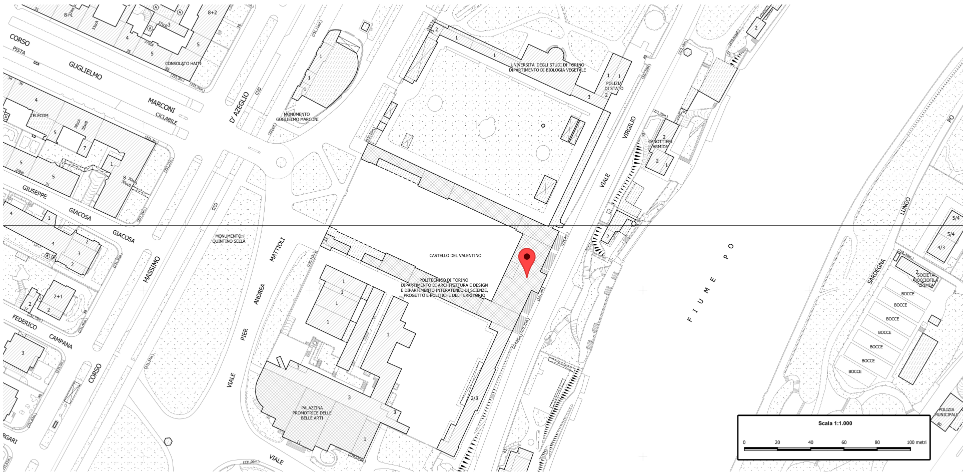


Figure 5.6: Salone d'Onore location in Castello del Valentino

Salone d'Onore is the Italian expression for Hall of Honour, and it is the core of the Castello del Valentino, with a privileged view on the river and on the hills to truly express the magnificence of the salon, along with the size of the environment and the quality of its decorations. The hall is decorated by Isidoro Bianchi and his sons Pompeo and Francesco in the early 1640s, who created a continuity of scenes on the walls, stressed by the presence of spiral columns in support of a balcony with statues. The subject of the paintings, along with the words on the plaques, were probably chosen by Count Emanuele Tesauro, author of several publications on the royal family. [70] The main theme of the decor is the exaltation of the origins of the Savoys, but is also an expression of the political situation in the 1640s, and the relationship with the King of France.

The scenes start in the eastern wall [Figure 5.7], where on the left it can be seen Aimone the Peaceful, one of the founders of the Savoy dinasty, who helped the King of France Filippo VI against the English King Edward III in the siege of Tournay of 1340. At the center, over the entrance door, one can see Filippo II Senza Terra, who helped Carlo VIII enter Italy. Then, on the right side of the wall is represented Filippo II's illegitimate son Renato, who died in the Battle of Pavia with Francesco I of France in 1525.

Figure 5.7: Decorations on the Eastern Wall

On the northern wall [Figure 5.8], starting from the left, is pictured the young Carlo II Savoy, welcoming Carlo VIII and giving him an horse which he will use in the battle of Fornovo. Then, at the center of the wall, there is Amedeo V, amongst the King of France Filippo IV and Count Roberto of Fiandra. Finally, on the right, the Green Count Amedeo VI entering Costantinople after the expedition of 1365 with the King of France Giovanni II.

Figure 5.8: Decorations on the Northern Wall

Continuing on the western wall [Figure 5.9], the one facing the river Po, the paintings are damaged and there is no descriptive plaque, so it is difficult to interpret them with certainty, but the colours and members of the Savoy and the French family can be recognised to confirm their alliances.

Figure 5.9: Decorations on the Western Wall

Ultimately, on the southern wall [Figure 5.10], in the leftmost part it is depicted the Battle of Cressy of 1347, with the Green Count Amedeo VI and Filippo VI of Valois against the English reigned by King Edward III. In the central portion of the wall is represented Amedeo II, who was allied with Ludovico VII of France in Damaskas and who perished in Nicosia. On the right is pictured Edoardo the Liberal, who collaborated with Filippo of Valois in the battle of Cassel in 1328.

Figure 5.10: Decorations on the Southern Wall

At the center of the ceiling there is a fresco, surrounded by scenes in oval pictures regarding mythology and Ovidio's Metamorphosis: Venus healing Aeneas wounded by Turno in a duel; the Banquet and the rat of Ippodamia; the Fight of the Centaurs; Bacco's return from the Indies and the giants struck by Jove's lightning while climbing Mount Olympus. A great amount of restoration works has also been done between 1924 and 1926 for the conservation of the architectural framework, and plaques to commemorate those fallen in the Great War have been placed on the southern and northern walls.

5.4 Giuseppe Garibaldi's statue on Corso Cairoli

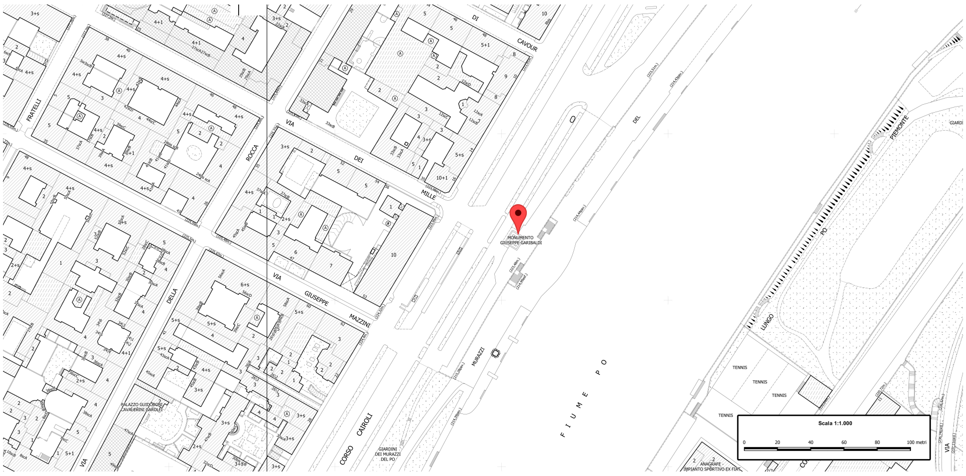


Figure 5.11: Location of the monument to Giuseppe Garibaldi

The statue of Giuseppe Garibaldi made by Odoardo Tabacchi [71] in 1887 is placed on Corso Cairoli, at the intersection with via San Lazzaro, where the "Hero of the Two Worlds" lived for a period of his life, and which after his death in 1882 was renamed Via dei Mille, the patriots following him [Figure 5.11].
The whole monument [Figure 5.12] is 10 meters tall and is composed by a bronze statue of Giuseppe Garibaldi standing on top of a tall pedestal, with rocks reminiscent of the Isle of Caprera, where he spent the last years of his life. He is represented with a thick beard and long hair, details which made him famous, wearing his typical cloak, skullcap and necktie, and with the hands holding a sword placed horizontally on his knees.

Figure 5.12: Giuseppe Garibaldi's monument

Figure 5.13: Zoom on the lying lion on the back right corner of the pedestal

On the front of the pedestal there is an inscription: *"A GARIBALDI TORINO MDCCCLXXXVII"*, while a shield with the writing: *"I MILLE"* is placed on the left side and the coat of arms of Turin, a rampant bull, on the right side. On the frontal left corner there is the marble sculpture of a female figure, which is an allegory to Italy. The woman wears a classical draped dress and a laurel crown, and sits with the national flag in her left hand and a symbol of freedom in her right hand. On the opposite corner, a lying roaring lion [Figure 5.13], which represents the strength of italian popular identity. The lion on the back right corner of the statue's pedestal will be our main focus in the object level analysis.

Chapter 6

Methods

6.1 Preliminary Testing: Gabinetto dei Fiori Indorati

In order to decide which apps out of the initial list of ten will be selected for further testing, a first acquisition on a small environment was completed. Once the ten apps will have acquired the three-dimensional model of the Gabinetto dei Fiori Indorati, data were exported in .las file format and further analysed in the software Cyclone 3DR by Leica. This analysis represented the second terms of reference for app rating and selection, togheter with the overall accuracy of the model. Finally, a further test on colour perception and acquisition will be done on this selection of apps.

6.1.1 Data Collection

3D Scanner App

By opening 3D Scanner App, different modalities can be accessed: LiDAR, Advanced LiDAR, Point Cloud, Photos and TrueDepth, with each of them having different scanning tips accessible by touching the question mark on the top right corner of the screen. For the different modalities tested, the acquisitions have been carried out by scanning on a patterned clockwise motion starting from the southern wall, with a particular attention to elements such as the doorway decorations in order to acquire better details.
In LiDAR mode [Figure 6.1/A], the only setting to adjust was the processing quality, which was set at High definition with a 26 millimeters resolution. The scanning tips suggest to move slowly and keep a steady motion to reduce blurry images, and to plan the route by scanning each area once and by avoiding re-doing the same area. It is also pointed out that this mode works best with bigger things, like a room, while small or thin objects might not get picked up. The model acquired with this mode is built up of 277 thousands vertices and 472 thousands faces, obtained from 178 images and 1062 depth maps.
In LiDAR Advanced mode [Figure 6.1/B], the Maximum Depth has been initially set to 3 m, but then the upper part of the ceiling was not properly captured, so it was changed to 5 m, with the Resolution of 10 mm and the Confidence set to High. No Masking has been applied. The final model is made up of 425 thousands vertices and 780 thousands faces obtained from 151 images.
Finally, in Point Cloud mode [Figure 6.1/C] no setting could be adjusted before the acquisition, while True Depth mode was not used since it relies on the front facing camera, therefore it is best for objects and not really suitable for environments. The model acquired in Point Cloud mode is obtained through 155 images and 964 Depth Maps.

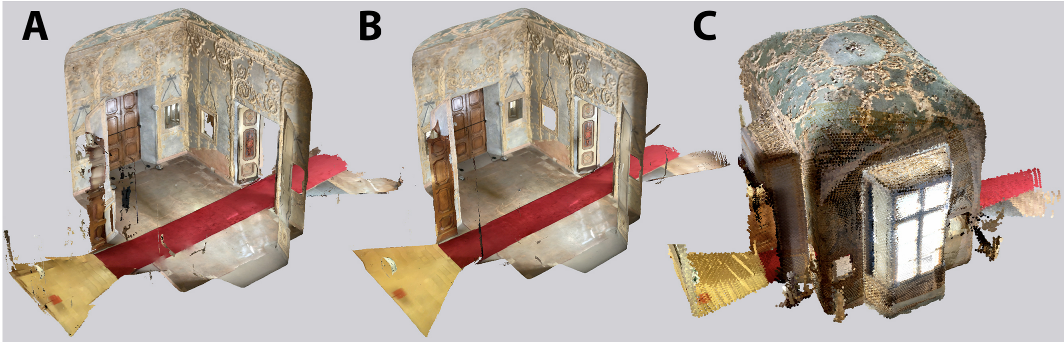


Figure 6.1: 3D scanner app LiDAR (A), Advanced (B) and Point Cloud (C) mode

Canvas

This app suggested to scan in a patterned motion, just like if we were to paint a room, going up and down while moving on the side. Within this app there is no fine tuning of the process, but after the capture a CAD 2D/3D model can be obtained at a cost of up to \$1.50/m^2. It is not possible to download the 3D model [Figure 6.2], since it can only be shared as a link to view it online, and there are no information about the number of vertices and faces that make up the model.

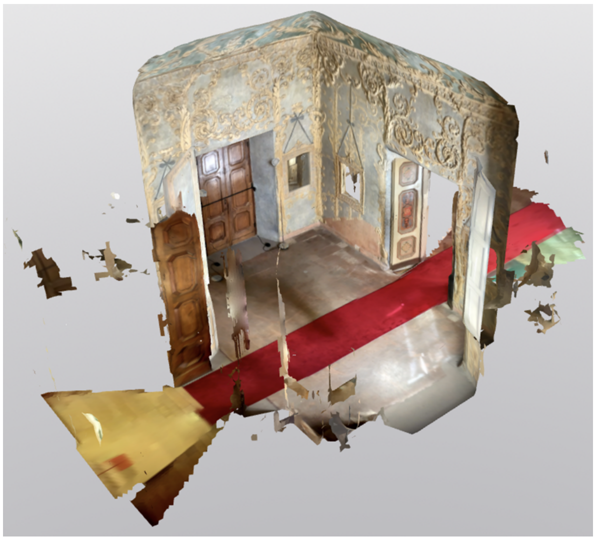


Figure 6.2: Canvas Model

Dot3D Pro Beta

In Dot3D Pro the Maximum Depth has been set at 5.0 m just like in 3D Scanner App, in order to properly capture every surface in the Cabinet, and Strong Depth Filtering and AprilTags Detection were enabled. Once the capture has been obtained, it has been optimized to better display the point cloud. The scan can be exported as DP file, or as other files such as .pts, .ptx, .ply and .ptg.
The model acquired with Dot3DPro [Figure 6.3] is obtained from 106 frames and it is made up of 31.25 million points.

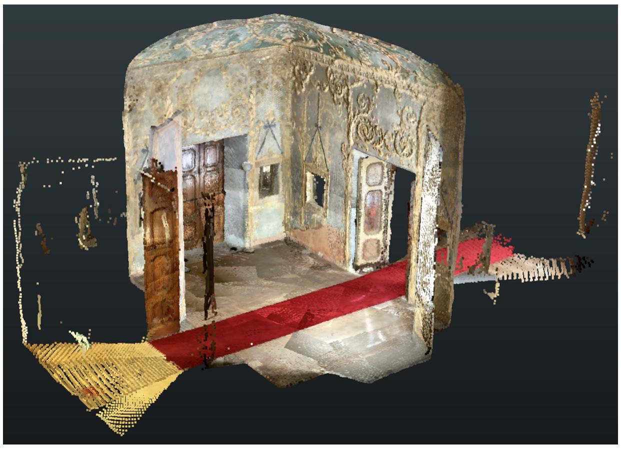


Figure 6.3: Dot3D Pro Model

Metascan

With LiDAR mode [Figure 6.4/A], the capture has been acquired in a circular motion for the walls going clockwise from the western wall, setting the processing to the Standard quality, with a High resolution grid of 25 mm, since the best quality can only be unlocked upgrading to the Pro version, and a self-timer of 2 seconds. This mode has a maximum amount of 5 scans in the Free version, and it requires stable internet connection to process them. The model obtained from the LiDAR mode is made up of 49 thousands triangles.

In Photo mode [Figure 6.4/B], the capture has been obtained scanning on a circular clockwise motion from the bottom going upwards, with a more precise attention to the decorations of the mirrors. The pictures have been set to be taken manually in order to have a better control over the capture, but they could also be automatically obtained every 2, 3 or 4 seconds.

The maximum amount of pictures which can be acquired is 200, with the same Standard quality as in the LiDAR mode, and enabling Object Masking and Location in order to better align the pictures. For the Gabinetto dei Fiori Indorati, 75 photos were acquired, creating a model made up of 55 thousand triangles. The scans obtained with Metascan can be uploaded online and a share its link, or the mesh can be exported in a .USDZ file. There are more common extensions such as .obj, .ply or .laz, but they are only available in the Pro version.

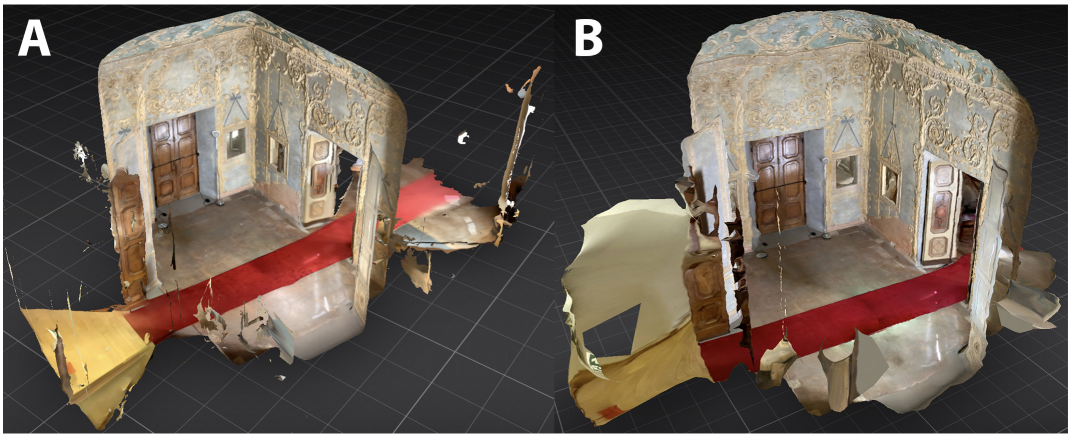


Figure 6.4: Metascan: LiDAR (A) and Photo (B) mode

Pix4D Catch

For the test on Gabinetto dei Fiori Indorati, no Ground Control Point has been set before the scanning procedure. In the first modality available on Pix4D Catch, Device Pose [Figure 6.5/A], the trigger has been set to a distance of 0.5 m and at an angle of 20°. The capture has been obtained on a circular clockwise motion generating 132 pictures with a global Horizontal Accuracy of 35 meters, and a Vertical Accuracy of 24.01 meters. In Image Overlap mode [Figure 6.5/B], the trigger has been set to an overlap of 95%, and also this capture has been done following a circular motion, with 679 images to scan the whole Cabinet, with a Horizontal Accuracy of 35 meters and a Vertical one of 16.35 meters. The scan can be uploaded into Pix4D Cloud, or it can be exported as .ply, .obj or as a .zip file that contains all data including every single picture taken to obtain the 3D model.

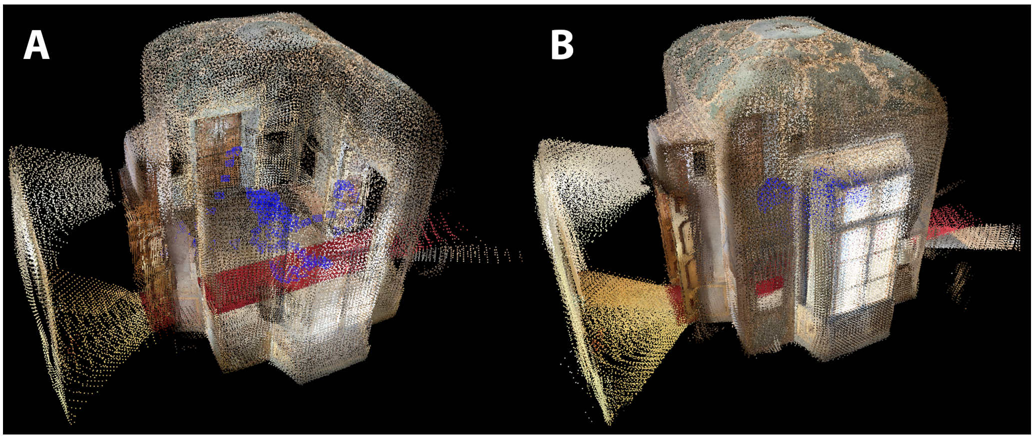


Figure 6.5: Pix4D Catch: Device Pose (A) and Image Overlap (B) modalities

Polycam

In LiDAR Mode [Figure 6.6/A], the scanning has been done following a circular clockwise pattern, starting from the bottom and going upwards. Initially the app crashed a few times while scanning, but then there were no more problems with it. Just like Metascan, the only adjustment available is the one regarding the

processing quality, which here was set in the Space setting. The model is built up of 41.2 thousands vertices.
In Photo mode [Figure 6.6/B] the scan was captured following a patterned motion, with more attention given to the frame of the mirrors, but the maximum amount of pictures set to 250 was a bit limiting.
On top of that, only 5 scans can be taken with Photo mode in the free version of Polycam, even though more can be obtained by signing up to a polycam account or by doing different operations such as uploading 3D models to the cloud. The model is built up of 125.1 thousands vertices. The scans can be uploaded and shared via link, or they can be exported as mesh in .gltf format. Many other exporting formats can be unlocked by upgrading to Pro, such as .obj, .dae, .dxf, .ply or .las.

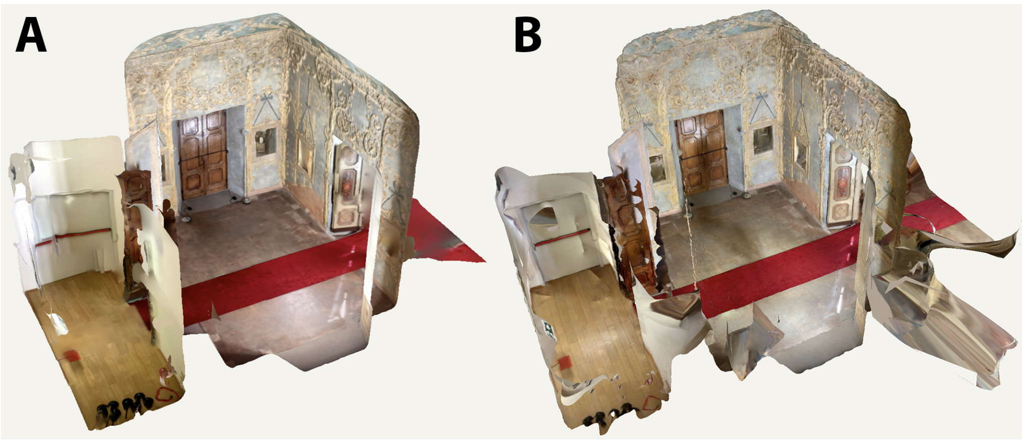


Figure 6.6: Polycam: LiDAR (A) and Photo (B) mode

RTAB-Map

The scans with RTAB-Map were obtained following a circular motion: by opening it, there is no initial tweaking available, and once you finish scanning you just have the optimization process. Only then you can change the Rendering settings such as the point cloud density, maximum and minimum depth. The scans obtained with this app [Figure 6.7] had some problem with the ceiling acquisition, and they were very noisy overall. Once you have optimized you scan, you can assemble the point cloud or the mesh, and only then you can export the model in a .ply format. There are no information regarding the geometry of the model such as the number of points acquired, or images taken to build up the model, nor on how many vertices and triangles it is composed by.

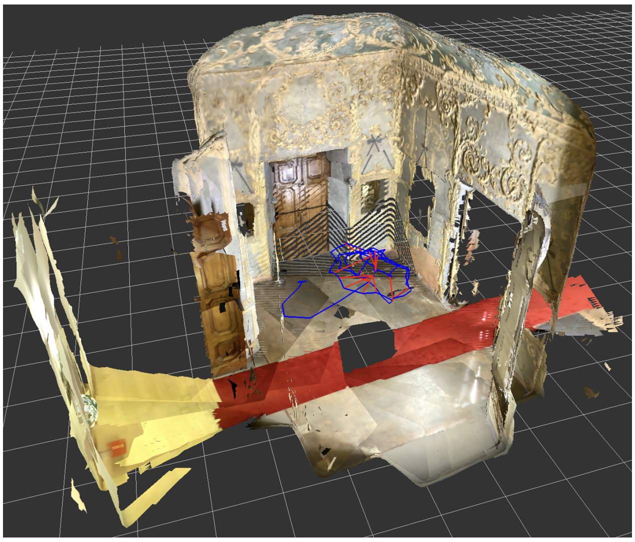


Figure 6.7: RTAB-Map Model

Scaniverse

In the first phase of the acquisition with Scaniverse, the only customisation available is the lidar range, from 0.15 m to 5.0 m, and the possibility to switch on or off the location. The scan has been acquired in a circular motion from the bottom to the top, with a range set to 5.0 m, and the capture was processed in Area mode, which is the best one for rooms and spaces, with a definition of 8 mm. The model obtained in Scaniverse [Figure 6.8] is composed by 236 thousand vertices and 409 triangles. You can then edit the model by cropping it, measuring it and adjusting exposure, contrast and sharpness. You can share it by posting it on Scaniverse cloud, or you can export the model in different formats such as .obj, .ply and .las.

Figure 6.8: Scaniverse Model

SiteScape

This application lets you choose between two different modalities: Max Area or Max Detail. On Max Area the Point Density is set to high, and Point Size to medium, whereas on Max Detail they are respectively set to medium and low.
Max Area [Figure 6.9/A] was captured in a patterned motion going clockwise top to bottom, and then being more precise with detailed portion of the decorations.
Max Detail mode [Figure 6.9/B] on the other hand was not able to capture the whole room in one take, unless this was done quickly and therefore with much less accuracy. A solution to this problem is to capture overlapping scans that could later be merged into one, once they have been properly aligned, but this procedure could cause a greater error than the one of the whole scene captured in a single session.
The models can then be synced into the cloud, but in the free version this can be done only one at a time, or they can be exported as a .ply or a .e57 file just as point clouds. No other information regarding the geometry of the models obtained with SiteScape is available directly via the app itself. The Pro version of this app

is far too expensive to be considered, giving that it only unlocks unlimited cloud support and no other exporting format.

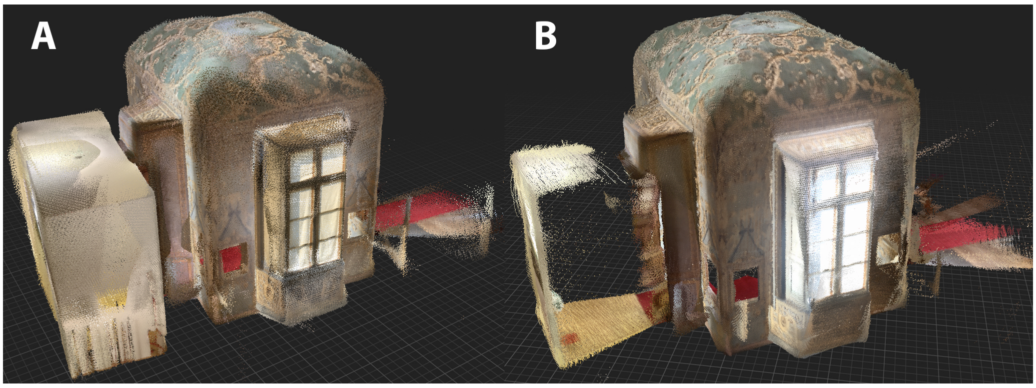


Figure 6.9: SiteScape: Max Area (A) and Max Detail (B) modalities

Zappcha

By opening the last app there are quite a few options to choose from: for our scans the Georeference was set to on, with the Scan capture mode which acquires data continuously. The noise filtering and the auto view were turned On, the Display mode was set to Normal and the exposure to Automatic. The capture was obtained in a patterned motion, and once you complete it you can measure it and choose between different display modes: intensity, colour and contrast, which represent a gray-scale model, the original model and a high-contrast model. The model is made up of 24.81 million points, whose size and density can be adjusted. For what concerns the sharing of the model, this app uses a proprietary format which is the Veesus Point Cloud format .vpc.

Figure 6.10: Zappcha Model

6.1.2 Initial Scans Comparison

Starting from the ten original applications and using the Gabinetto dei Fiori Indorati as an example [Figure 6.11], a selection of those to be more deeply analysed and tested has been done, based on three main factors: Price, Shareability, Customisation and Accuracy [Figure 6.12]. For each category, a vote from 1 to 5 will be assigned, with 1 being respectively Prohibitive, No Customisation, No Sharing options and Inaccurate, and 5 being respectively Free, High Customisation, Multiple exporting formats and Accurate. For this preliminary judgment, Accuracy refers to the global model, and whether it is composed by coherent and continuous surfaces, since a more detailed analysis on the quality of the point clouds and on differences from the reference dataset will be carried out using Cyclone 3DR and PointCab software.

App	Mode	Number of					Scan Size (MB)
		Pictures	Depth Maps	Points	Vertices	Faces	
3D Scanner App	LiDAR	178	1062	-	277k	472k	218
	Advanced	151	0	-	425k	780k	305
	Point Cloud	155	964	-	-	-	221
Canvas	-	-	-	-	-	-	-
Dot3DPro	-	106	-	31.25m	-	-	45.3
Metascan	LiDAR	-	-	-	-	49k	120
	Photo	75	-	-	-	55k	116
Pix4DCatch	Device Pose	132	-	-	-	-	7
	Image Overlap	679	-	-	-	-	36
Polycam	LiDAR	-	-	-	41.2k	-	16
	Photo	-	-	-	125k	-	58
RTAB-Map	-	-	-	-	-	-	34
Scaniverse	-	-	-	-	236k	409k	24
SiteScape	Max Area	-	-	-	-	-	117
	Max Detail	-	-	-	-	-	160
Zappcha	-	-	-	-	-	-	273

Figure 6.11: Comparison on the model's geometry on Gabinetto dei Fiori Indorati

App Name	Version	Developer	Mesh/Point Cloud	In-App Purchase	Main Exporting Formats in the Free Version	PERSONAL RATING				TOTAL RATING
						Price	Shareability	Customisation	Accuracy	
3D Scanner App	2.0	Laan Labs	M/PC	-	PLY, LAS, E57, OBJ, DAE, USDZ, STL, FBX	5	5	3	5	4.5
Canvas	3.5	Occipital Inc.	M	3D CAD & BIM 1.50/m²	-	3	1	1	3	**2.0**
Dot3DPro	0.16.21	DotProduct	PC	-	PLY, PTS, PTG, PTX, DPX	5	4	2	4	3.8
Metascan	2.6.0	Abound Labs Inc.	M	Pro: 6.99€/M or 50.99€/Y	USDZ	3	2	4	4	**3.3**
Pix4DCatch	1.12.0	Pix4D	M/PC	Optional Cloud: 170€/M or 1700€/Y	PLY, OBJ	4	3	4	4	3.8
Polycam	2.2.9	Polycam Inc.	M	Pro: 7.99€/M or 59.99€/Y	GLTF	3	2	2	4	**2.8**
RTAB-Map	0.20.19	Mathieu Labbe	M/PC	-	PLY, OBJ, DB	5	3	5	1	**3.5**
Scaniverse	1.8.5	Toolbox AI	M	-	PLY, LAS, OBJ, STL, GLB, FBX, USDZ	5	5	3	4	4.3
SiteScape	1.5	SiteScape Inc.	PC	Pro: 53.99€/M or 499.99€/Y	PLY, E57	1	3	3	5	**3.0**
Zappcha	4.2	Veesus Ltd	PC	-	VPC	5	1	4	4	**3.5**

Figure 6.12: Initial Table of Comparison for Price, Shareability, Customisation and Accuracy to define the four apps to further analyse

From the ten initial apps, only four were chosen to continue the surveying process: 3D Scanner App, Dot3D Beta, Pix4D Catch and Scaniverse. The other six were not considered in this research for different reasons: Metascan and Polycam offered a fairly accurate scan, but the only exporting format available in the free version are respectively USDZ and GLTF, which can be converted into .ply trough the use of online converters or apposite software. Zappcha only supports a proprietary format, which is the Veesus point cloud .vpc, while Canvas offers no exporting format at all in the free version, and only supports CAD/BIM softwares at a high cost (at 1.50€/m^2, it would mean that even a small environment like the "Gabinetto Dei Fiori Indorati" would cost more than 30€). Sitescape achieves a good accuracy level, but it offers only two exporting formats, and the Pro version is way too expensive at a cost of 53.99€/month. Finally, RTAB-Map has had some noise problem on our test and was not able to achieve an acceptable accuracy level.

6.1.3 Cyclone 3DR Scan Analysis

Import

The seven different models acquired from the four selected apps (3D Scanner App, Dot3D Pro, Pix4D Catch and Scaniverse) were compared among each other and most importantly with a reference cloud, obtained using a TLS (Faro Focus 3D X 330). The models are exported as point clouds in the format .las, available for all the chosen apps except from Pix4D Catch, where it is exported in the .ply format and then converted into .las through the use of the software CloudCompare [72] which, as the name states, can also be used to compare the different clouds. For this analysis, however, a different software, Cyclone 3DR by Leica Geosystems [73] is going to be used, which does not support natively the .ply format, but whose interface is much more user-friendly than the one of CloudCompare. The .las point clouds acquired by the different apps and by the TLS reference system are imported in Cyclone 3DR, and the first thing to notice is that they are all positioned and rotated differently in the workspace [Figure 6.13]. This is related to the fact that each application adopts its own local reference system during the acquisition.

Figure 6.13: Initial Position and Rotation of the Different Point Clouds

Translation

In Cyclone 3DR there are new information about the clouds' geometry that were not originally available via the different apps, such as the number of points forming the clouds and the size of the model expressed in meters by simply hovering on the clouds name.

All the clouds except the one from Scaniverse are automatically positioned roughly in the same spot, whereas this last one is in a completely different area, located about 50'000 meters away from the other ones and therefore it has to be translated closer to them to proceed with the alignment of the clouds.

To do this translation, the cloud to be moved has to be selected, then the command *Translation* in the *Coordinate System* tab has to be used, and by clicking on the blue arrow, one can access different translation modalities such as moving in the X, Y, Z direction, or following the local normal or the direction of a component, but the easiest one to use is the one called *Click two points*. To define the direction with this modality, the first thing to do is to click on the point cloud to move, and then on the one to move it to. Finally, the length of the translation has to be defined, with a real time vector displayed to easily understand how much it has to be moved.

N Point and Best Fit Registrations

The next operation is to register all the different clouds with respect to the reference one, by selecting the ones to move and by using the command *N Points Registration* in the *Coordinate System* tab, and by clicking on the corresponding points in the cloud to move and in the reference one, with at least 3 points selected on different planes for an accurate registration [Figure 6.14].

Figure 6.14: Alignment of a Point Cloud to the Reference System

To increase the accuracy in the alignment procedure a second command called *Best Fit Registration* can also be applied, while selecting the reference point cloud and then the one to align. This procedure employs ICP (Iterative Closest Point), the algorithm used to minimise the differences between two point clouds by iteratively revising the transformation needed to reduce the distances between the coordinates of the matched pairs from the source to the reference point cloud .
By selecting the reference point cloud first, this becomes the fixed object to which the second one has to be aligned, and finally rotations and translations can be computed. This operation provides a report [Figure 6.15] composed by the three angles of rotation (roll, pitch and yaw), the three translations of the Gravity Center (DX, DY and DZ), the mean error and the Standard Deviation, which is the amount of dispersion of the set of values from the mean value.

App	Mode	Rotations [°]			Gravity Center Translation [cm]			Mean error [cm]	Standard Deviation [cm]
		Roll (X)	Pitch (Y)	Yaw (Z)	DX	DY	DZ		
3D Scanner App	LiDAR	0.010	-0.004	-0.002	0.047	0.318	0.022	1.972	2.427
	Advanced	0.064	-0.014	0.002	0.026	0.325	-0.118	2.922	3.508
	Point Cloud	-0.010	0.059	0.000	-0.205	0.104	0.016	2.686	3.372
Dot3DPro	-	-0.052	-0.006	0.024	-0.001	0.048	-0.272	1.282	1.757
Pix4DCatch	Device Pose	-0.070	0.011	0.010	0.008	0.141	-0.010	1.799	2.252
	Image Overlap	-0.097	-0.261	-0.008	0.120	-0.117	1.425	1.898	2.479
Scaniverse	-	0.101	0.229	-0.166	-0.035	-0.367	-0.734	1.152	1.501

Figure 6.15: Summary Table of all the Clouds' Alignments on Gabinetto dei Fiori Indorato

Cloud to Cloud Analysis (C2C)

Once the point clouds acquired from the selected apps have been aligned with the reference one, the next step is to compare them by using the command *Cloud to Cloud* accessible in the *Analysis* tab. In order for this step to work properly, the two clouds to be compared have to be selected in a specific order: firstly the reference one and then the one obtained from the apps.
The maximum distance between the two clouds has to be set, which here was set

to 0.1 meters, representing the maximum search distance beyond which the points will not be considered in the analysis, therefore excluding outliers. The distance of ten centimeters is a value compatible with the representation scales of interest for our CH Documentation.

Once everything is set, the two models are compared by creating a new one with high-contrast colours. By default this representation is made with a continuous gradient from blue (with 0 being the minimum distance) to red (with 0.1 being the maximum distance), but it can be edited to easily classify and compare each apps' acquisition. Therefore, this range is divided into 5 equal thresholds of 0.02 meters each, represented with the following colours: blue, cyan, green, yellow and red [Figure 6.16].

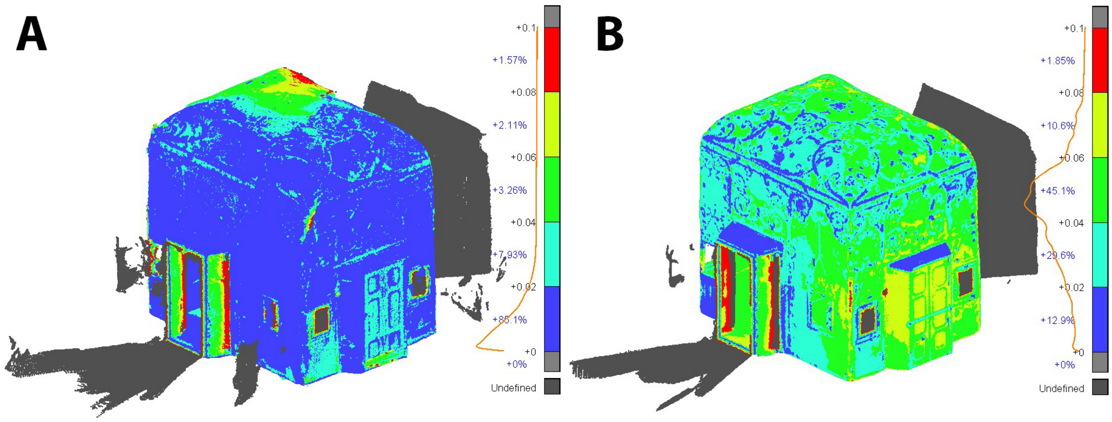
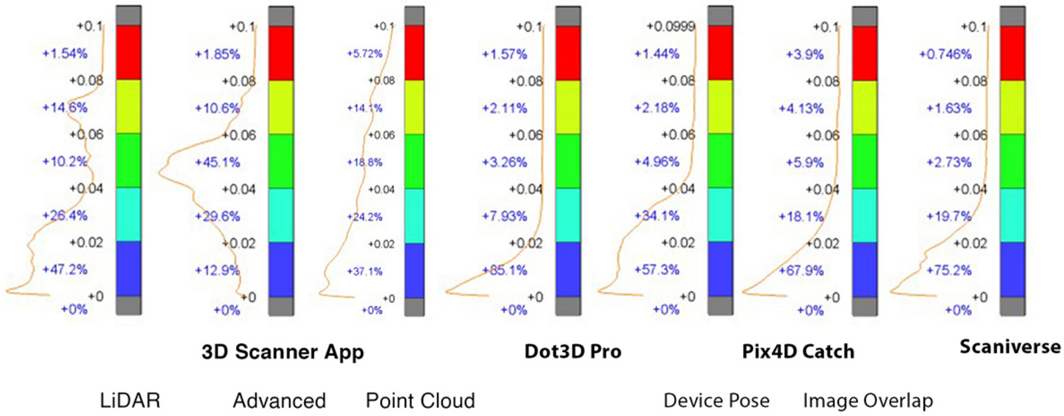


Figure 6.16: Best and Worst C2C analyses on the Cabinet of Golden Flowers, Dot3D Pro (A) and 3DScanner app: Advanced mode (B)



App	Mode	Percentage of points of comparison in distance ranges [m]				
		0-0.02	0.02-0.04	0.04-0.06	0.06-0.08	0.08-0.1
3D Scanner App	LiDAR	47.2%	26.4%	10.2%	14.6%	1.5%
	Advanced	12.9%	29.6%	45.1%	10.6%	1.9%
	Point Cloud	37.1%	24.2%	18.8%	14.1%	5.7%
Dot3DPro	-	85.1%	7.9%	3.3%	2.1%	1.6%
Pix4DCatch	Device Pose	57.3%	34.1%	5.0%	2.2%	1.4%
	Image Overlap	67.9%	18.1%	5.9%	4.1%	3.9%
Scaniverse	-	75.2%	19.7%	2.7%	1.6%	0.8%

Figure 6.17: Results of the C2C Analysis between Apple's acquisitions and TLS

The percentages of overlap among the different apps and the reference system have been put side by side and is summarised in a table [Figure 6.17], in which it can be seen that the ones giving the best results for this first scenario are Dot3D Pro, with the 85.1% of points being aligned to the corresponding ones from the TLS with a difference comprehended in the range from zero to two centimeters, followed by the results of Scaniverse with a 75.2%, and by Pix4D Catch's Image Overlap mode with a 67.9%. Therefore, from this first test, we can state that the result are quite good overall, and it seems that the best ones on small environments are obtained from the Beta version of Dot3D Pro.

6.1.4 Section Comparison

Once all the acquisitions have been aligned with Cyclone 3DR, a section line can be defined and extracted from the point clouds [Figure 6.18] to better understand in which portions bigger drifts can be identified. This procedure can be obtained directly from Cyclone 3DR by selecting a point cloud and using the command *Section* in the *Extract* tab, where different parameters can be tweaked, such as the direction of the section, the distance among sections, the range, the slice thickness and the chaining distance, which is the distance at which the software will set the connection of open polylines, and finally noise reduction can also be enabled.

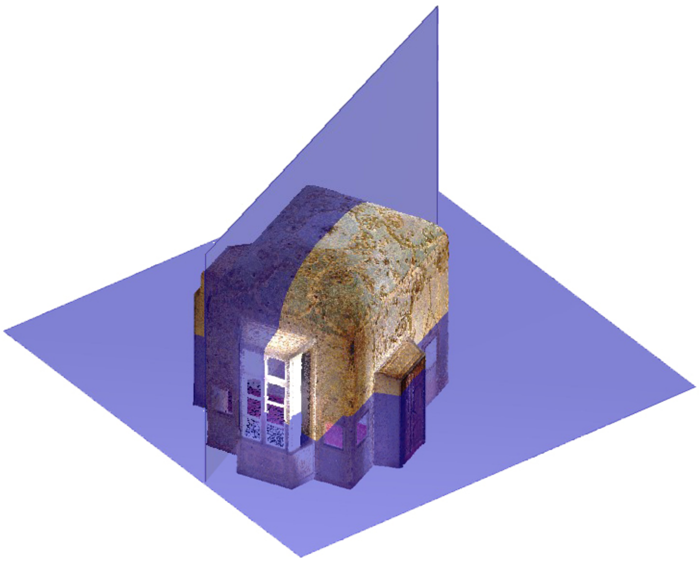


Figure 6.18: Definition of Horizontal and Vertical sections on Gabinetto dei Fiori Indorati via Cyclone 3DR

The results however were not much satisfying, given the general noise overall creates a chaotic polyline which does not really help with understanding the real direction of the surfaces.
Therefore, the aligned point clouds were exported from Cyclone 3DR into the software PointCab Origins 4.0 [74] in the .las format. From there, we can access

the command *Section and Layout* in the *Ortophoto* tab, and different parameters can be managed regarding on which point clouds the section has to be extracted, as well as its position, depth and direction, but also on the resolution, reflectance and colour percentages, and on the exportation formats. For our purposes, the DWG format was chosen, which creates a raster image that can be opened in AutoCAD and that can be traced to obtain results which are more precise than the ones automatically obtained from Cyclone 3DR. This procedure on PointCab can be pursued for every point cloud obtained from the four selected apps with the first scope of visually understanding which section is the best fit to the reference one, while the best ones will be discussed at the end of the whole thesis.

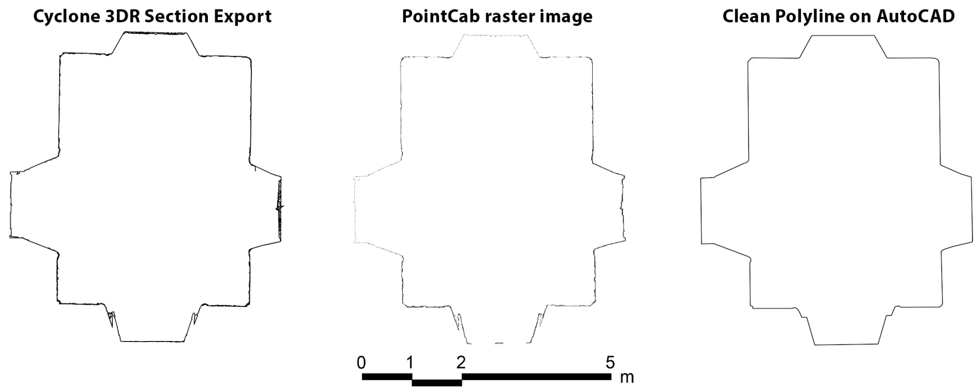


Figure 6.19: Workflow on Horizontal Section of Gabinetto dei Fiori Indorati

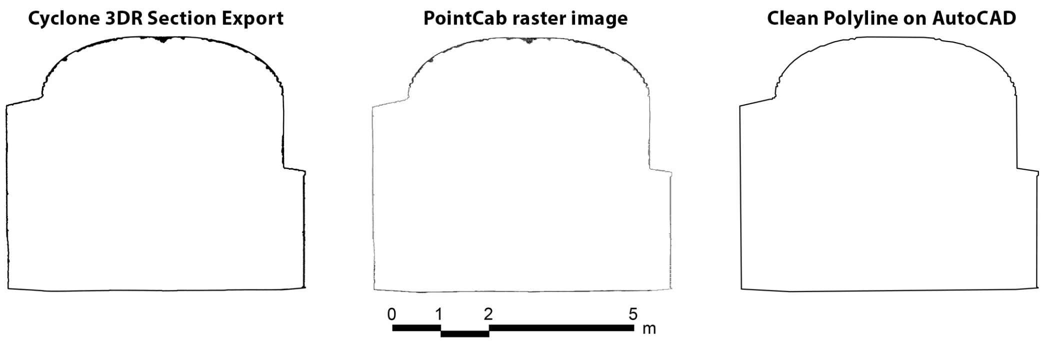


Figure 6.20: Workflow on Vertical section of Gabinetto dei Fiori Indorati

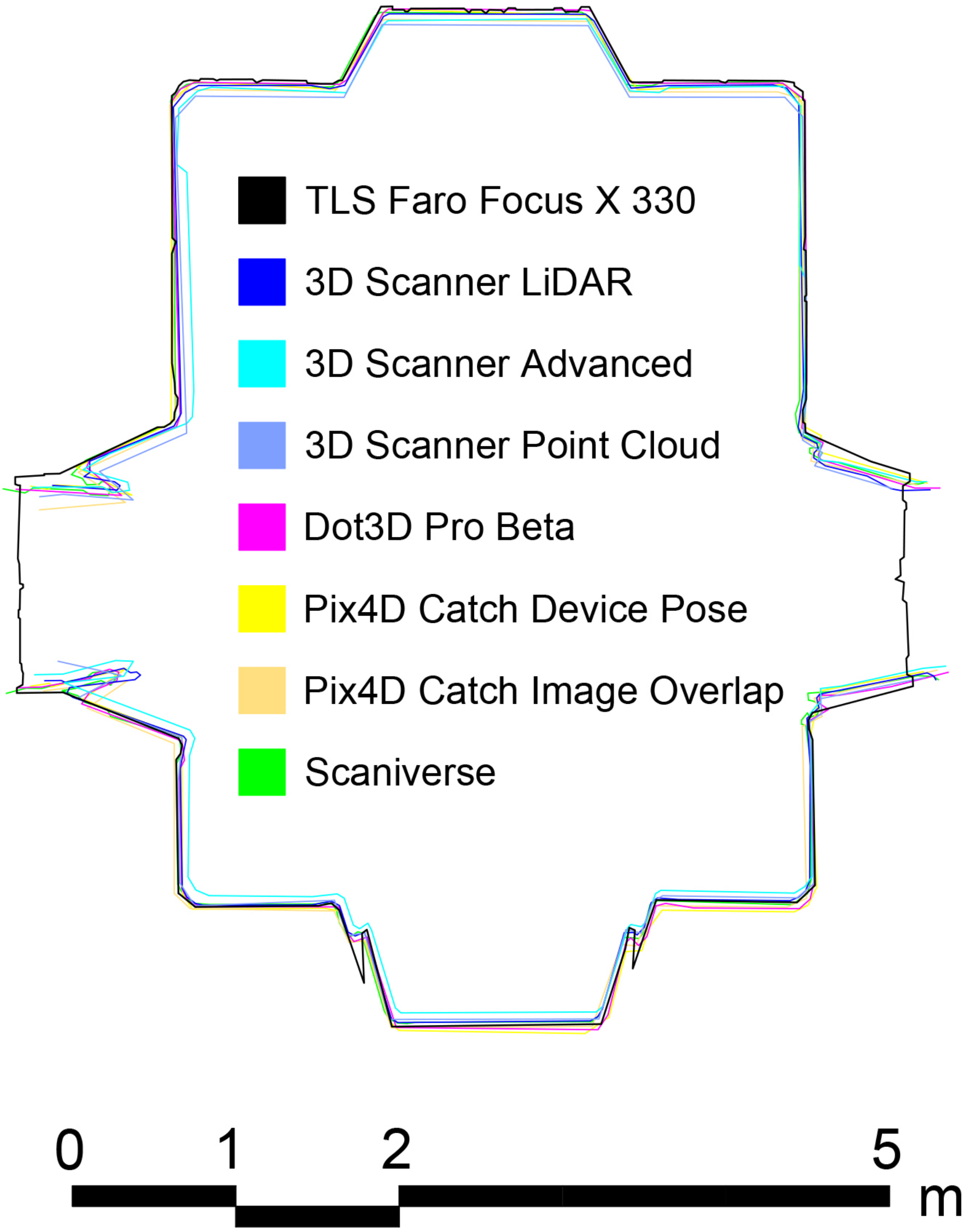


Figure 6.21: Overlap of the Horizontal sections on Gabinetto dei Fiori Indorati among the seven different modalities

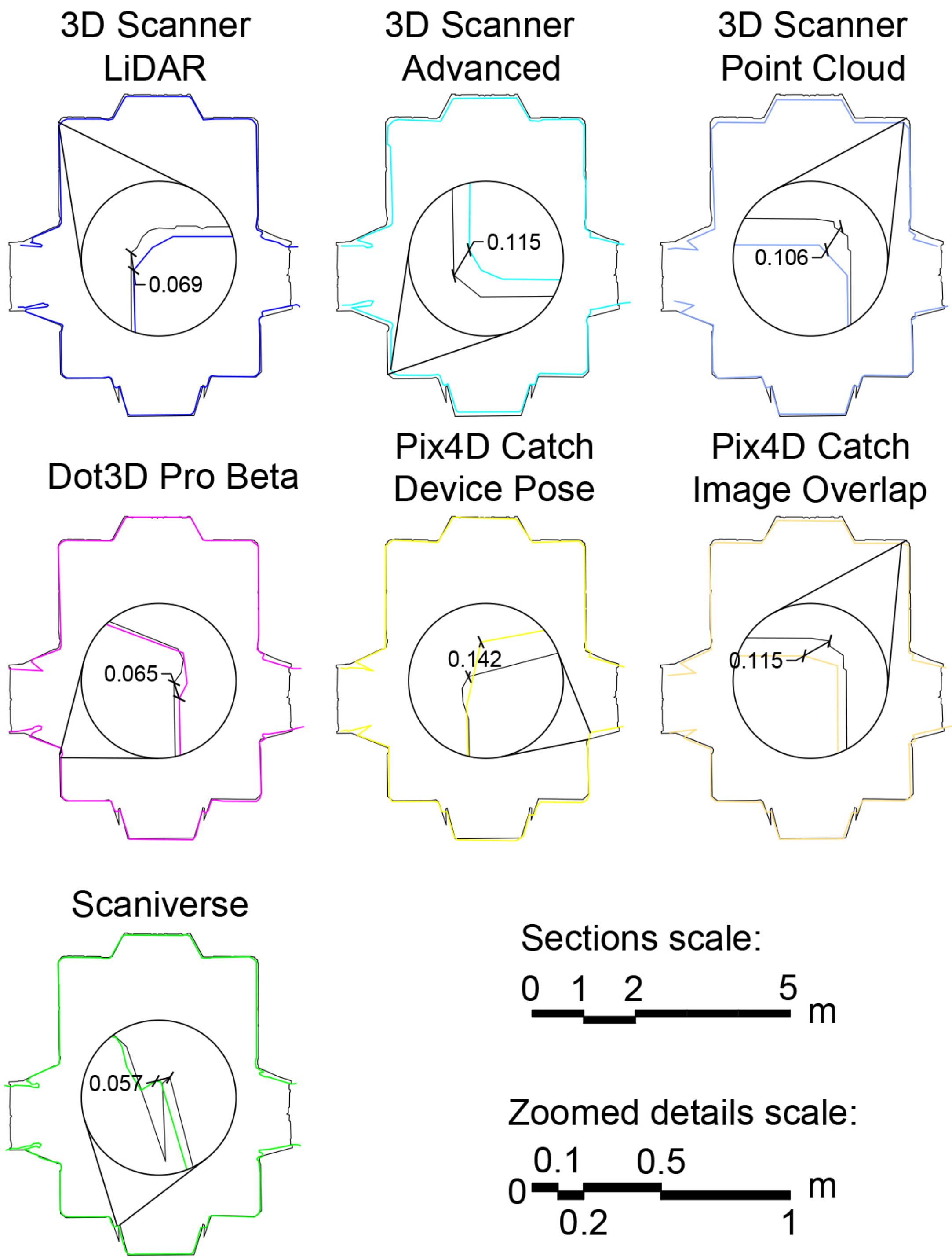


Figure 6.22: Comparison of the Horizontal sections on Gabinetto dei Fiori Indorati on each modality

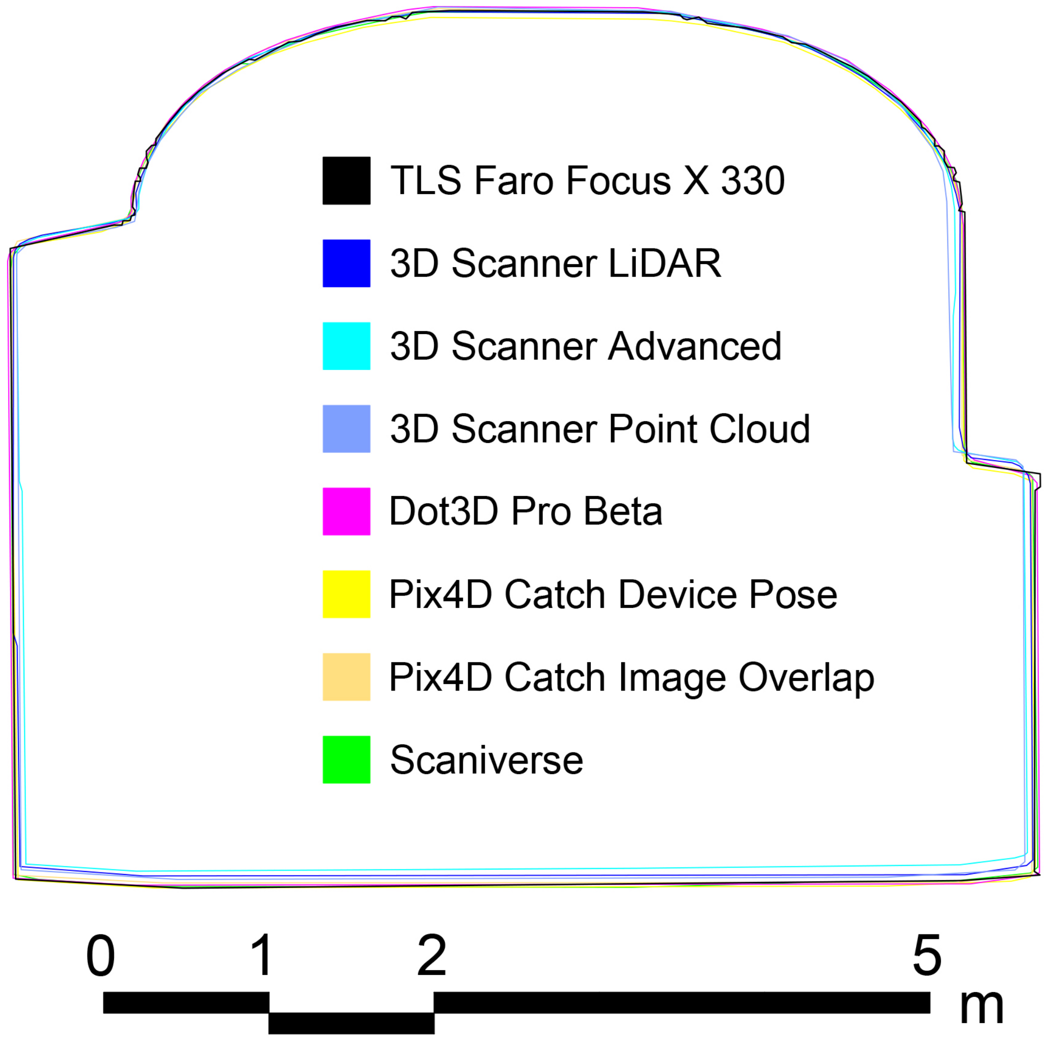


Figure 6.23: Overlap of the Vertical sections on Gabinetto dei Fiori Indorati among the seven different modalities

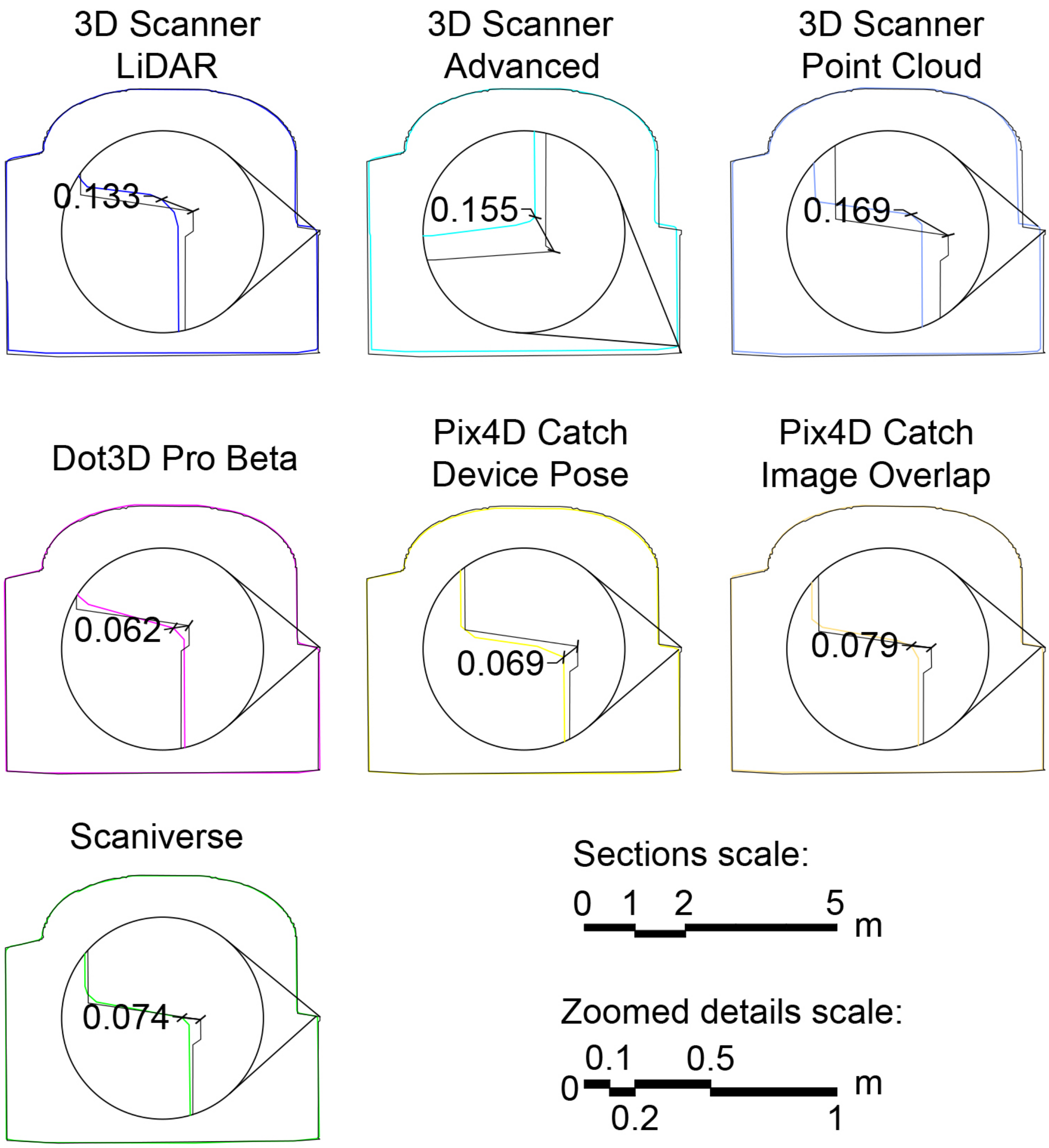


Figure 6.24: Comparison of the Vertical sections on Gabinetto dei Fiori Indorati on each modality

6.2 Colour Perception Test

By testing the different apps in the Gabinetto Dei Fiori Indorato, there were problems with certain surfaces such as windows and mirrors, on which the sensor could not determine the distance. In order to understand if this situation is also affected by the colour of a surface, the iPad camera was tested by creating and printing a colour sheet and by comparing its features with the ones captured by the sensor using the four apps previously chosen: 3D Scanner App, Dot3D Pro, Pix4D Catch and Scaniverse. The sheet is made up by twelve columns and nine rows, with different shades of the primary and secondary colours, and a gray-scale [Figure 6.25].

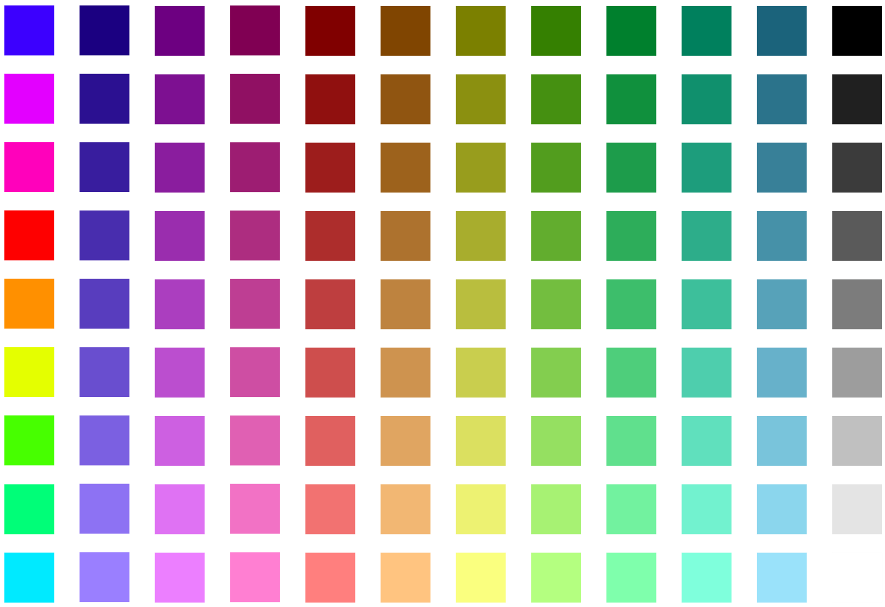


Figure 6.25: Colour Test

Since the sheet is a two-dimensional object, the apps had some trouble with its geometry and most of them are trying to overlap the images by creating a three-dimensional surface, especially in the outermost part [Figure 6.26]. This could be due to the scanning process and the environment in which the pictures were acquired. However, there seems to be no problem with the colour perception, since all the shades of the different colours were properly represented.

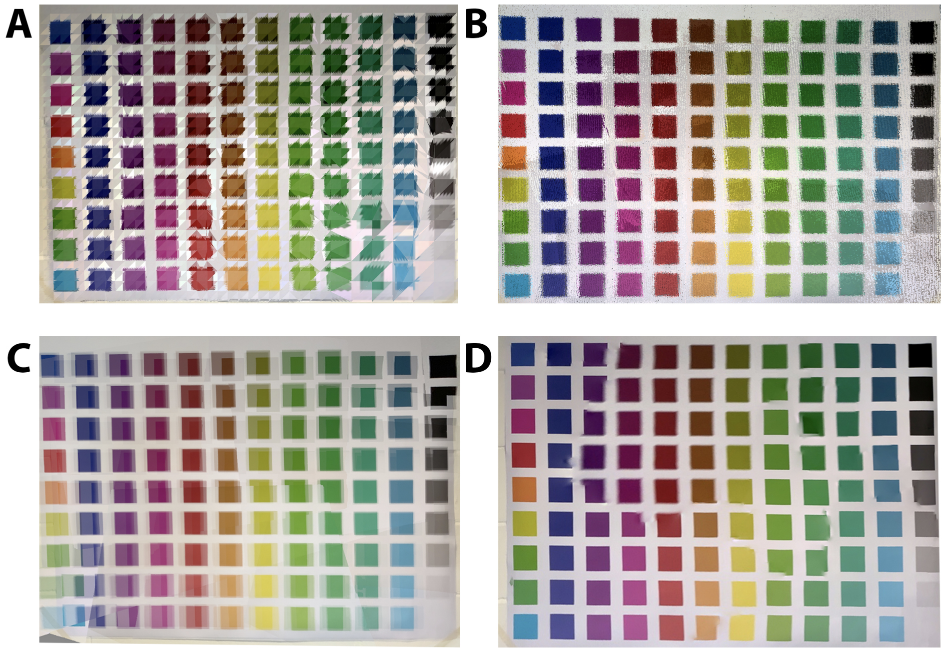


Figure 6.26: Colour perception results: 3D Scanner App (A), Dot3D Pro (B), Pix4DCatch (C) and Scaniverse (D)

Chapter 7

Methodology Application on different CH Scenarios

7.1 Data collection

7.1.1 Castello del Valentino's Façade

All the data have been acquired following the same operational practises, by scanning in a patterned motion going clockwise from the central double stairway [Figure 7.1]:

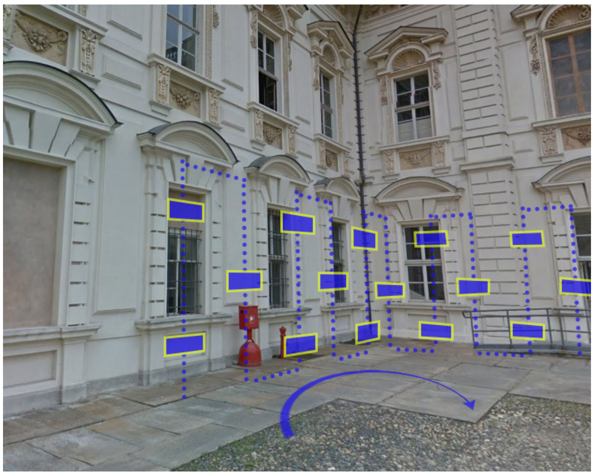


Figure 7.1: Acquisition path on Castello del Valentino's Façade

3D Scanner App

On 3DScanner App's LiDAR Mode [Figure 7.2/A] there is no initial tweaking available, and the only customisation regard the processing quality, which was set to HD, with a 22 mm resolution. On Advanced Mode [Figure 7.2/B] the maximum depth was set to 5 meters, with a resolution of 15 mm, a High Confidence and No masking applied. The processing quality was set to HD, but with no information about the resolution applied. The last Mode, Point Cloud [Figure 7.2/C] does not have any setting to be adjusted neither at the beginning nor regarding the processing quality.

Figure 7.2: 3D Scanner App: LiDAR (A), Advanced (B) and Point Cloud (C) Mode Acquisition

Dot3D Pro

Dot3DPro's acquisition [Figure 7.3] is built up from 152 frames and is composed of 43.5 million points, but the only initial settings available are the one regarding the maximum depth, which was set to 5 meters, and the one about the strong depth filtering, which was turned on. Once the acquisition is completed, it is time to optimise it, but with no further customisation available.

Figure 7.3: Dot3D Pro Acquisition

Pix4D Catch

On Pix4D's Device Pose Mode [Figure 7.4/A] the distance and angle were set to 0.5 meters and 20° before the acquisition process. Advanced settings were left the default ones: Enable Mesh: ON; Save Mesh: ON; Show Cameras: ON; Show Movement Path: ON; Show Feature Points: ON; Warning Sounds: ON; Auto Focus: ON; Skip Low Quality Images: ON. The mesh colours values were set as 0.8 for Red, Green and Blue, and 0.6 for Opacity.

On Pix4D's second mode, Image Overlap [Figure 7.4/B], it is only possible to set the percentage of Overlap between each image, and here it was set to 95%. Advanced settings were left as default just like in the first modality of this app.

Figure 7.4: Pix4D Catch: Device Pose (A) and Image Overlap (B) Mode Point Cloud Acquisition

Scaniverse

While starting Scaniverse's acquisition [Figure 7.5], one can choose between Small Objects, Medium Objects or Large Objects/Area, which will affect the Maximum depth, respectively set at 0.8, 2.5 and 5.0 meters. To scan the façade of the Castle, the last option was selected, and location was enabled. Once the acquisition process is over, the processing mode can be selected between Speed, Area or Detail. For our purposes, the best one is Area, with a resolution of 12 mm.

Figure 7.5: Scaniverse Acquisition

7.1.2 Salone d'Onore in Castello del Valentino

All the data have been acquired following the same operational practises [Figure 7.6]: starting from the main door on the Eastern Wall, then proceeding clockwise and in a patterned motion to cover all the wall surfaces as well as all the seating rows and the central pathway, finishing with a circular motion around the chandelier. Due to the maximum range of 5 meters of the LiDAR sensor, it is impossible to reach the ceiling without an external support to elevate the iPad.

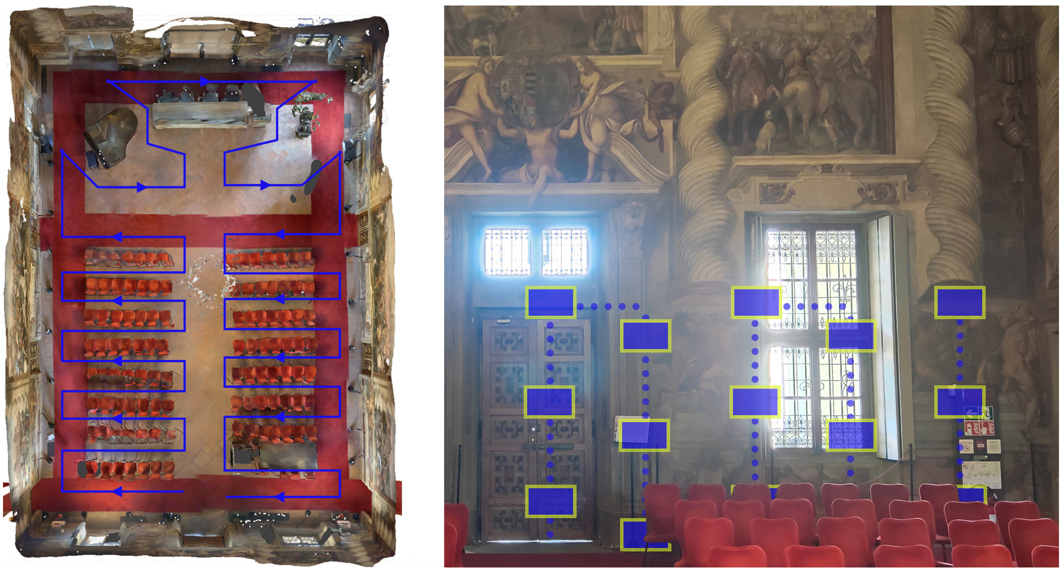


Figure 7.6: Acquisition path in Salone d'Onore: plan view and Eastern elevation

3D Scanner App

With the three modalities available on 3DScanner App (LiDAR, Advanced or Point Cloud) different results can be obtained. With the first one [Figure 7.7/A], there is no initial tweaking available, and the only customisation regard the processing quality, which was set to HD, with a 26 mm resolution.
On the second one [Figure 7.7/B], Advanced LiDAR Mode, the maximum depth was set to 5 meters, with a resolution of 15 mm, a High Confidence and No masking

applied. The processing quality was set to HD, but with no information about the resolution applied.
On 3DScanner App's Point Cloud Mode [Figure 7.7/C], there are no settings to be adjusted neither at the beginning nor for the processing quality.

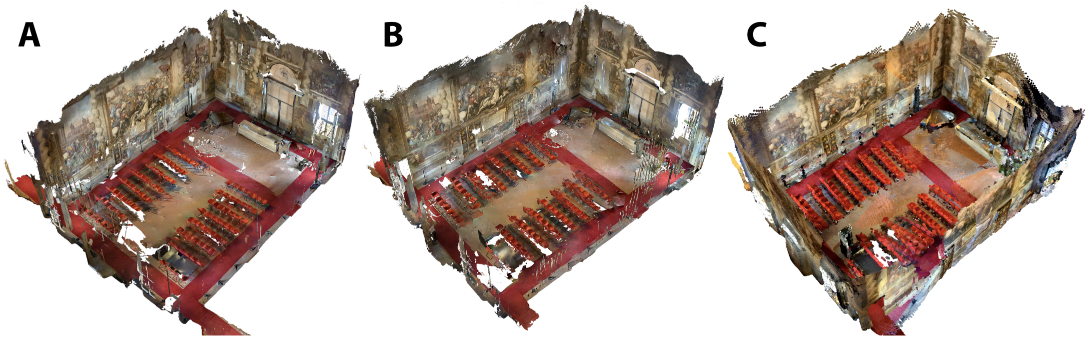


Figure 7.7: 3D Scanner App LiDAR (A), Advanced (B) and Point Cloud (C) Mode Acquisition

Dot3D Pro

Dot3DPro [Figure 7.8] does not offer many initial settings. The only available ones regard the maximum depth, which was set to 5 meters, and the one about the strong depth filtering, which was turned on. After the acquisition phase, it is possible to proceed with the optimisation phase, which does not offer any other customisation.

Figure 7.8: Dot3D Pro Acquisition

Pix4D Catch

On Pix4D's the choice is between two modalities: Device Pose or Image Overlap. With the first one [Figure 7.9/A], the distance and angle were set to 0.5 meters and 20° before the acquisition process. Advanced settings were left the default ones: Enable Mesh: ON; Save Mesh: ON; Show Cameras: ON; Show Movement Path: ON; Show Feature Points: ON; Warning Sounds: ON; Auto Focus: ON; Skip Low Quality Images: ON. The mesh colours values were set as 0.8 for Red, Green and Blue, and 0.6 for Opacity. Using Image Overlap mode [Figure 7.9/B], only the percentage of Overlap between each image can be set, and here it was set to 95%. Advanced settings were left as default just like in the first modality of this app.

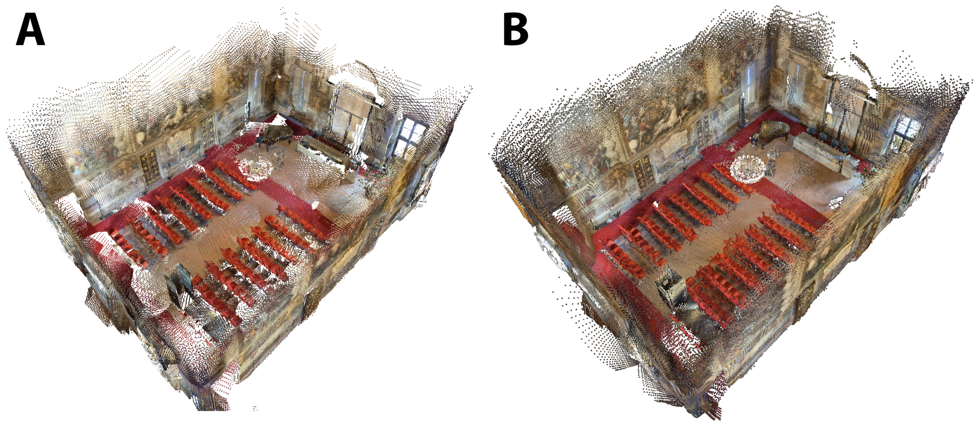


Figure 7.9: Pix4D Catch: Device Pose (A) and Image Overlap (B) Mode Point Cloud Acquisition

Scaniverse

While starting Scaniverse's acquisition [Figure 7.10] it is possible to choose between Small Objects, Medium Objects or Large Objects/Area. This choice will affect the Maximum depth, respectively being 0.8, 2.5 and 5.0 meters. To scan the Hall of Honour, the last option was selected, and location was enabled. Once the acquisition process is over, the processing mode can be selected between Speed, Area or Detail. For our purposes, the best one is Area, with a resolution of 5 mm.

Figure 7.10: Scaniverse Acquisition

7.1.3 Lying lion on the pedestal of Giuseppe Garibaldi's monument in Corso Cairoli

All the data have been acquired following the same procedure [Figure 7.11]: starting from the left and then going in a counter-clockwise patterned motion. Due to the limited range of the iPad sensor and to the height of the statue, it is impossible to reach the upper part of the monument without an external support.

Figure 7.11: Acquisition path on Giuseppe Garibaldi's monument

3D Scanner App

On 3DScanner App's Normal Mode [Figure 7.12/A] the only customisation regards the processing quality, which was set to HD, with a 14 mm resolution. In Advanced LiDAR Mode [Figure 7.12/B] the maximum depth was set to 5 meters, with a resolution of 15 mm, a High Confidence and No masking applied. The processing quality was set to HD, but with no information about the resolution applied. On 3DScanner App's Point Cloud Mode [Figure 7.12/C] no settings can be adjusted neither at the beginning nor for the processing quality.

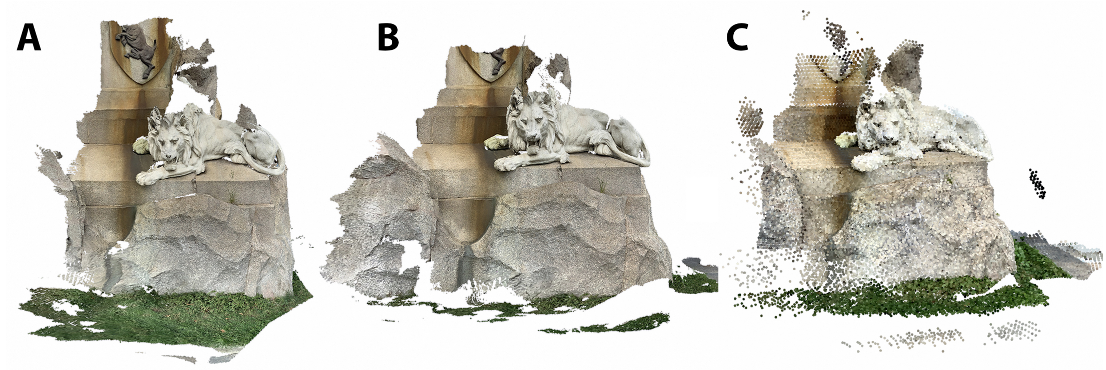


Figure 7.12: 3D Scanner App: LiDAR (A), Advanced (B) and Point Cloud (C) Mode Acquisition

Dot3D Pro

Dot3DPro's acquisition [Figure 7.13] has few initial settings available, specifically the one regarding the maximum depth which was set to 5 meters, and the one about strong depth filtering which was turned on. Once the acquisition is completed, there is the optimisation phase which has no customisation available.

Figure 7.13: Dot3DPro Acquisition

Pix4D Catch

On Pix4D's Device Pose Mode [Figure 7.14] the distance and angle were set to 0.5 meters and 20° before the acquisition process. Advanced settings were left the default ones: Enable Mesh: ON; Save Mesh: ON; Show Cameras: ON; Show Movement Path: ON; Show Feature Points: ON; Warning Sounds: ON; Auto Focus: ON; Skip Low Quality Images: ON. The mesh colours values were set as 0.8 for Red, Green and Blue, and 0.6 for Opacity. On Image Overlap Mode [Figure 7.15] the percentage of Overlap between each image was set to 95%. Advanced settings were left as default just like in the first mode.

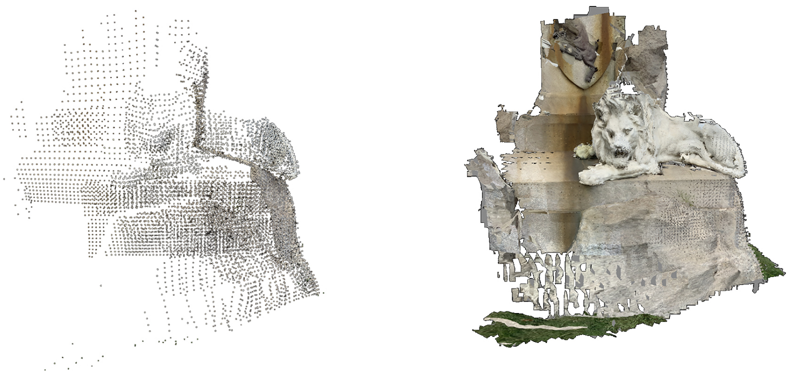


Figure 7.14: Pix4D Catch Device Pose: Point Cloud and Mesh Acquisition

Figure 7.15: Pix4D Catch Image Overlap: Point Cloud and Mesh Acquisition

Scaniverse

For Scaniverse's acquisition of the lion statue [Figure 7.16], the initial choice was between Small Objects, Medium Objects or Large Objects/Area. The last option with a Maximum Depth of 5 meters was selected, and location was enabled. The processing mode most suitable for our purposes is Area, since the statue is quite big, with a resolution of 5 millimeters.

Figure 7.16: Scaniverse Acquisition

7.2 Information about the models' geometry

The different size and nature of the scenes captured causes the models to be various and composed of more faces for complex scenarios like the large environment of Salone d'Onore, and to be formed by a small amount of pictures for smaller situations like the lion on the basement of the statue of Giuseppe Garibaldi.

Castello del Valentino's Façade

App	Mode	Number of					Scan Size
		Pictures	Depth Maps	Points	Vertices	Faces	(MB)
3D Scanner App	LiDAR	119	107	-	523k	828k	254
	Advanced	123	0	-	365k	573k	313
	Point Cloud	161	996	-	-	-	252
Dot3DPro	-	152	-	43.56m	-	-	260
Pix4DCatch	Device Pose	133	-	-	-	-	4.1
	Image Overlap	657	-	-	-	-	19.6
Scaniverse	-	-	-	-	212k	348k	24.6

Salone d'Onore

App	Mode	Number of					Scan Size
		Pictures	Depth Maps	Points	Vertices	Faces	(MB)
3D Scanner App	LiDAR	799	4790	-	996k	1.3m	1051
	Advanced	803	0	-	1.3m	1.7m	1512
	Point Cloud	658	4119	-	-	-	1001
Dot3DPro	-	719	-	198.3m	-	-	131.3
Pix4DCatch	Device Pose	451	-	-	-	-	18.8
	Image Overlap	1152	-	-	-	-	48.3
Scaniverse	-	-	-	-	264k	356k	512

Lying Lion

App	Mode	Number of					Scan Size
		Pictures	Depth Maps	Points	Vertices	Faces	(MB)
3D Scanner App	LiDAR	42	255	-	179k	285k	104
	Advanced	54	0	-	263k	467k	136
	Point Cloud	45	269	-	-	-	74
Dot3DPro	-	13	-	3.1m	-	-	3.3
Pix4DCatch	Device Pose	22	-	-	-	-	0.7
	Image Overlap	103	-	-	-	-	4.4
Scaniverse	-	-	-	-	141k	189k	60

Figure 7.17: Information about the dfferent models' geometry on Castello del Valentino's façade, Salone d'Onore and the Lying lion's statue

7.3 Data processing

7.3.1 Cyclone 3DR Scan Analysis

Model Import and Translation

The models were imported into the software Cyclone 3DR as .las point clouds, available for all the chosen apps except from Pix4D Catch, for which it is exported in the .ply format and then converted into .las through the use of the software CloudCompare [72]. Similarly to the Gabinetto dei Fiori Indorati, the first thing to be done is to align all the clouds, which initially have different placements and rotations, because each application adopts its own local reference system during the acquisition [Figure 7.18].

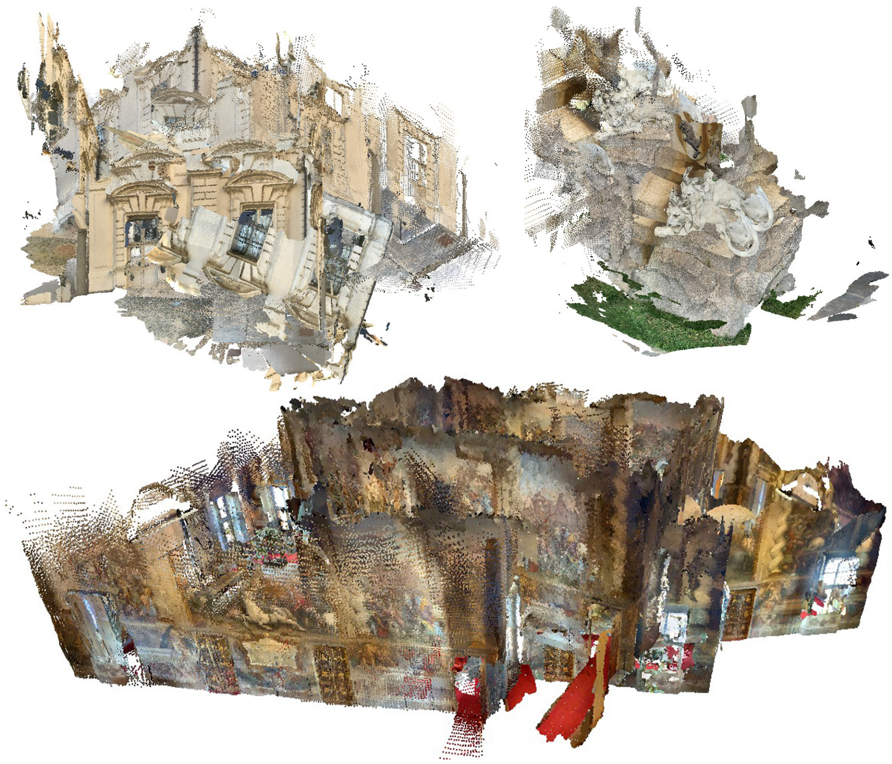


Figure 7.18: Initial Location and Position of the acquisitions in the different scenarios

N Point - Best Fit Registrations and C2C analysis

Just like in the previous test, all the clouds but the one from Scaniverse are automatically positioned roughly in the same spot, whereas this last one is located at a distance of about 50'000 meters away from the others. Once the point clouds acquired from the selected apps have been aligned with the reference one with the *N Point Registration* and then with the *Best Fit Registration* [Figure 7.19,7.20], they can be compared by using the command *Cloud vs Cloud* with the maximum distance between the two clouds set to 0.1 meters. The comparison has been done by generating the high-contrast colours one, whose colours are once again modified to display the percentages into five equal threshold ranges.

Castello del Valentino's Façade

App	Mode	Rotations [°]			Gravity Center Translation [cm]			Mean error [cm]	Standard Deviation [cm]
		Roll (X)	Pitch (Y)	Yaw (Z)	DX	DY	DZ		
3D Scanner App	LiDAR	-0.789	0.491	0.070	0.024	-0.041	0.025	8.301	12.531
	Advanced	-0.149	0.762	0.276	0.023	0.018	0.076	9.511	13.673
	Point Cloud	-0.132	0.855	-0.272	0.027	-0.017	0.082	8.721	12.646
Dot3DPro	-	-0.320	0.551	-0.597	0.022	0.042	0.070	8.757	13.223
Pix4DCatch	Device Pose	-0.825	0.588	0.065	0.011	-0.037	0.055	9.188	13.480
	Image Overlap	-0.592	0.866	-0.272	0.018	-0.060	0.101	10.370	14.575
Scaniverse	-	-0.023	0.146	1.044	0.023	-0.070	0.017	7.115	11.021

Salone d'Onore

App	Mode	Rotations [°]			Gravity Center Translation [cm]			Mean error [cm]	Standard Deviation [cm]
		Roll (X)	Pitch (Y)	Yaw (Z)	DX	DY	DZ		
3D Scanner App	LiDAR	-0.107	0.235	-0.013	0.016	0.014	0.023	3.291	5.037
	Advanced	0.266	0.382	-0.126	0.091	0.114	0.084	4.877	6.253
	Point Cloud	0.362	0.061	-0.252	0.044	0.083	0.049	5.569	7.067
Dot3DPro	-	-0.068	0.248	-0.255	-0.062	0.021	-0.008	3.883	5.282
Pix4DCatch	Device Pose	-0.232	-0.936	-0.208	0.110	-0.032	0.002	4.689	5.928
	Image Overlap	-0.053	-0.644	-1.338	0.072	0.229	-0.006	6.172	7.709
Scaniverse	-	-0.135	-0.189	0.226	0.058	0.051	0.059	3.838	5.337

Figure 7.19: Summary Tables of Alignment for the Castle's Façade and the Salone d'Onore

Lying Lion

App	Mode	Rotations [°]			Gravity Center Translation [cm]			Mean error [cm]	Standard Deviation [cm]
		Roll (X)	Pitch (Y)	Yaw (Z)	DX	DY	DZ		
3D Scanner App	LiDAR	-0.471	-1.388	-0.764	-0.002	-0.004	0.023	2.298	3.004
	Advanced	-1.412	-0.381	-0.233	-0.006	0.017	0.030	2.205	2.971
	Point Cloud	-0.362	-1.621	-0.624	0.018	-0.014	-0.006	2.644	3.391
Dot3DPro	-	0.051	-0.502	-1.099	0.019	-0.006	0.005	2.135	2.862
Pix4DCatch	Device Pose	0.379	-2.360	-0.760	-0.006	0.006	0.018	2.268	2.923
	Image Overlap	0.596	-1.467	-1.328	-0.014	0.002	-0.016	2.111	2.795
Scaniverse	-	0.129	-3.256	-2.039	-0.075	-0.102	0.098	2.432	3.186

Figure 7.20: Summary Tables of Alignment for the Lion's statue on the pedestal of the monument to Giuseppe Garibaldi

The percentages of comparison between the different apps and the reference system have been put side by side and have been summarised in a table, in which it can be seen that for the Castello del Valentino's Façade [Figure 7.22] the one giving the best results is Scaniverse [Figure 7.21/A], with the 55.1% of cloud points being aligned to the omologue ones from the reference TLS within the range from zero to two centimeters, followed by the results of 3D Scanner App in the LiDAR mode with a 44.4% of overlap, and by the Point Cloud mode with the value of 39.4%. Since Apple's sensor can acquire data up to five meters away, only a small portion of the whole façade can be obtained without the use of an external tool to reach higher surfaces. On top of that, the effect of sunlight on outdoor documentation could have affected the scanning process and the model reconstruction.

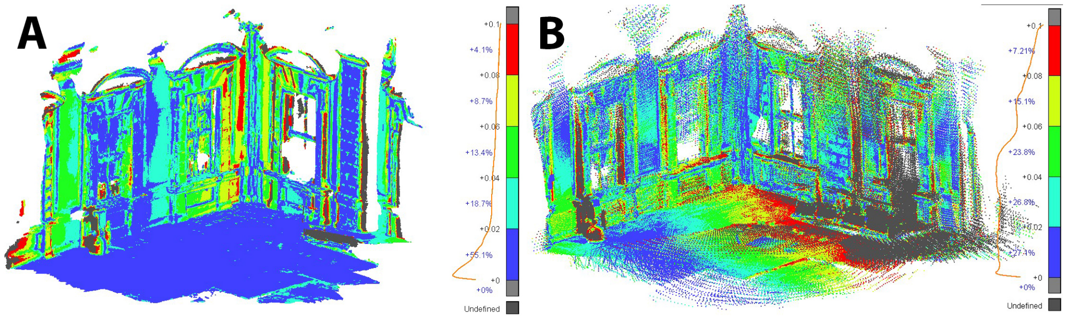
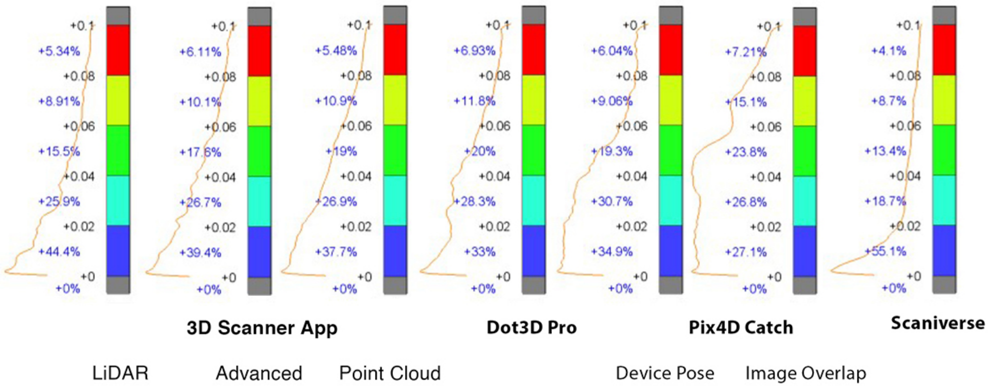


Figure 7.21: Best and Worst C2C analyses on Castello del Valentino's Façade: Scaniverse (A) and Pix4D Catch: Image Overlap (B)



App	Mode	Percentage of points of comparison in distance ranges [m]				
		0-0.02	0.02-0.04	0.04-0.06	0.06-0.08	0.08-0.1
3D Scanner App	LiDAR	44.4%	25.9%	15.5%	8.9%	5.3%
	Advanced	39.4%	26.7%	17.6%	10.1%	6.1%
	Point Cloud	37.7%	26.9%	19.0%	10.9%	5.5%
Dot3DPro	-	33.0%	28.3%	20.0%	11.8%	6.9%
Pix4DCatch	Device Pose	34.9%	30.7%	19.3%	9.1%	6.0%
	Image Overlap	27.1%	26.8%	23.8%	15.1%	7.2%
Scaniverse	-	55.1%	18.7%	13.4%	8.7%	4.1%

Figure 7.22: Results of the C2C Analysis between Apple's acquisitions and TLS on Castello del Valentino's Façade

For the second scenario, the Salone d'Onore [Figure 7.24], the app providing the best results is Dot3D Pro [Figure 7.23/A], with the 43.6% of cloud points being aligned to the corresponding ones from the TLS with a difference comprised in the range from zero to two centimeters, followed by the results of 3D Scanner App in the LiDAR mode with a 33.0% of overlap, and by Scaniverse and Pix4D Catch: Image Overlap mode, both with the value of 26.8%. The generally low overlap values are most likely caused by the size of the room and by the fact that with the iPad's sensor it is only possible to achieve information at a maximum distance of five meters. While this issue is easily adjustable for what concerns the lengths of the environment by just walking while scanning, the same can not be done for its height. In fact, all the scans acquired with the iPad are limited in height to the maximum reach of the operator's arms, from which up to five meters measured by the sensor can be added.

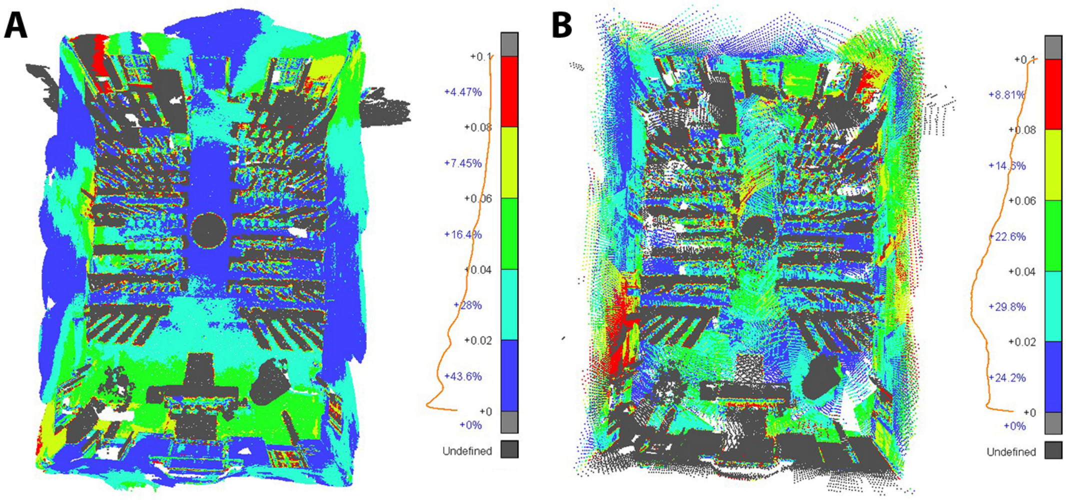
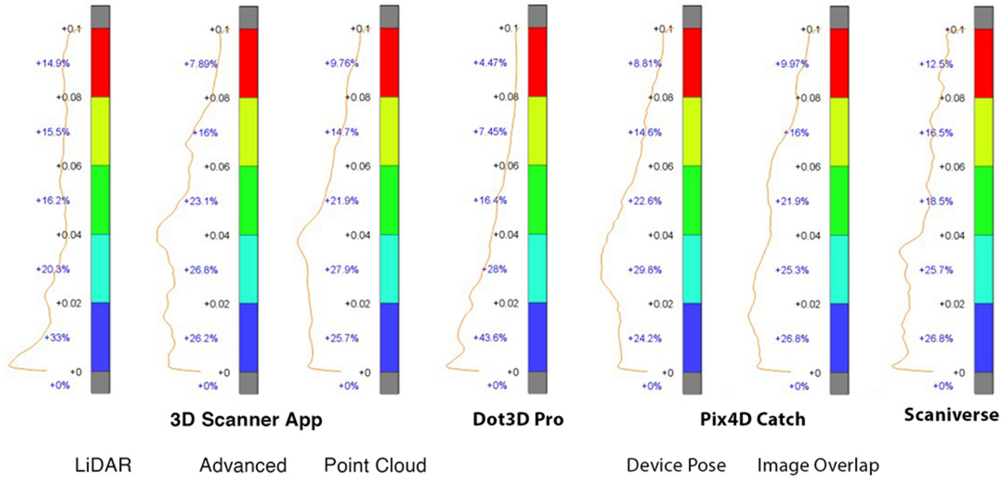


Figure 7.23: Best and Worst C2C analyses on Salone d'Onore: Dot3D Pro (A) and Pix4D Catch: Device Pose (B)



App	Mode	Percentage of points of comparison in distance ranges [m]				
		0-0.02	0.02-0.04	0.04-0.06	0.06-0.08	0.08-0.1
3D Scanner App	LiDAR	33.0%	20.3%	16.2%	15.1%	14.9%
	Advanced	26.2%	26.8%	23.1%	16.0%	7.9%
	Point Cloud	25.7%	27.9%	21.9%	14.7%	9.8%
Dot3DPro	-	43.6%	28.0%	16.4%	7.5%	4.5%
Pix4DCatch	Device Pose	24.2%	29.8%	22.6%	14.6%	8.8%
	Image Overlap	26.8%	25.3%	21.9%	16.0%	10.0%
Scaniverse	-	26.8%	25.7%	18.5%	16.5%	12.5%

Figure 7.24: Results of the C2C Analysis between Apple's acquisitions and TLS on Salone d'Onore

For what concerns the Lion's statue on the basement of the monument to Giuseppe Garibaldi, the results are quite different [Figure 7.26]. The best results are given by 3D Scanner App: Normal Mode [Figure 7.25/A], with a value of 80.9% of points overlapping within a distance of two centimeters, followed by the Point Cloud Mode and by Pix4D Catch: Image Overlap Mode, respectively with the 75.1% and the 75.0% and finally by Scaniverse with the 73.1%. For this monument, both the iPad and the TLS have the limit of having portions of the monument obstructed by the lion's statue. With an iPad, however, it is quite easy to reach those regions, since the whole scanning process requires the operator to move around, whereas with a Terrestrial Laser Scanner the acquisition is done using a stationary system.

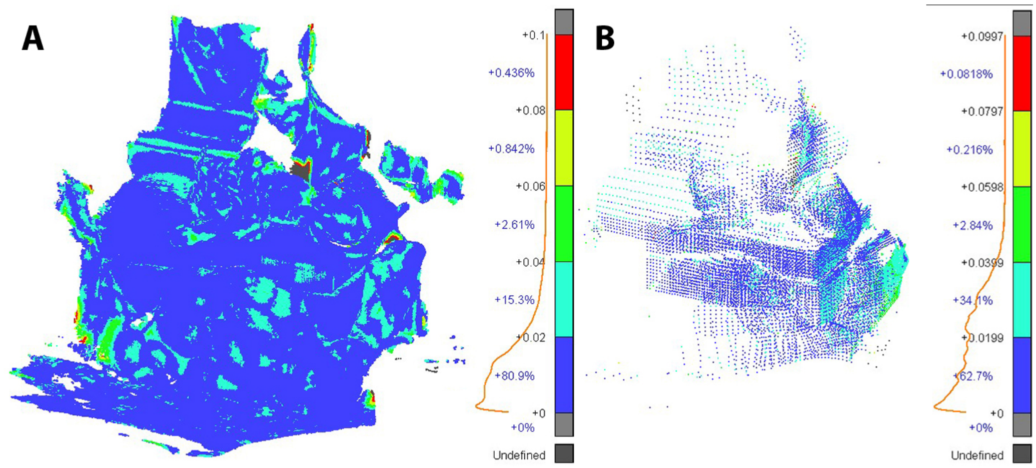
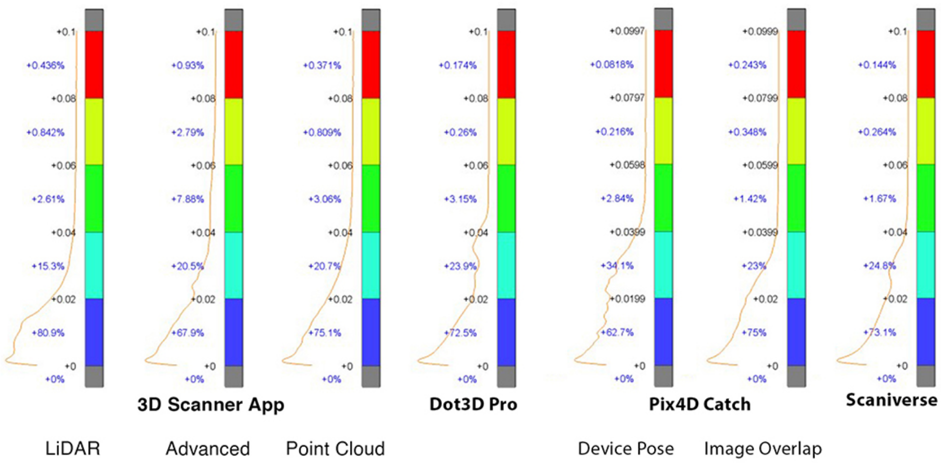


Figure 7.25: Best and Worst C2C analyses on the Lion's statue: 3D Scanner App: LiDAR (A) and Pix4D Catch: Device Pose (B)



App	Mode	Percentage of points of comparison in distance ranges [m]				
		0-0.02	0.02-0.04	0.04-0.06	0.06-0.08	0.08-0.1
3D Scanner App	LiDAR	80.9%	15.3%	2.6%	0.8%	0.4%
	Advanced	67.9%	20.5%	7.9%	2.8%	0.9%
	Point Cloud	75.1%	20.7%	3.1%	0.8%	0.4%
Dot3DPro	-	72.5%	23.9%	3.2%	0.3%	0.2%
Pix4DCatch	Device Pose	62.7%	34.1%	2.8%	0.2%	0.1%
	Image Overlap	75.0%	23.0%	1.4%	0.3%	0.2%
Scaniverse	-	73.1%	24.8%	1.7%	0.3%	0.1%

Figure 7.26: Results of the C2C Analysis between Apple's acquisitions and TLS on the Lion's statue

PointCab Section Comparison

Once the point clouds have been compared, the drifts between the models obtained with the apps and the reference system by extracting sections can be analysed. This operation is particularly significant in the architectural scenarios, since it lets us easily understand how the surfaces that make up the model are interpreted by each app.

Therefore, a plan section is defined for both the portion of the Castle's facade [Figure 7.27] and for the Hall of Honour [Figure 7.30], and starting from the models previously aligned with Cyclone 3DR, a raster image of the section is extracted using the software PointCab Origins, to visually understand in which areas the biggest drifts can be identified.

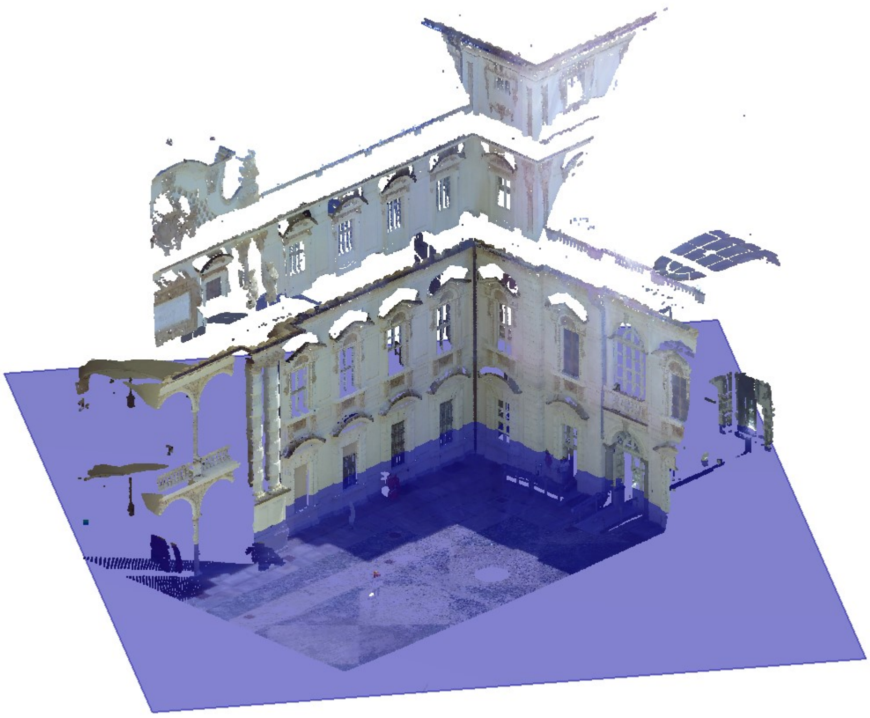


Figure 7.27: Section definition on Cyclone 3DR on the portion of Castello del Valentino's façade

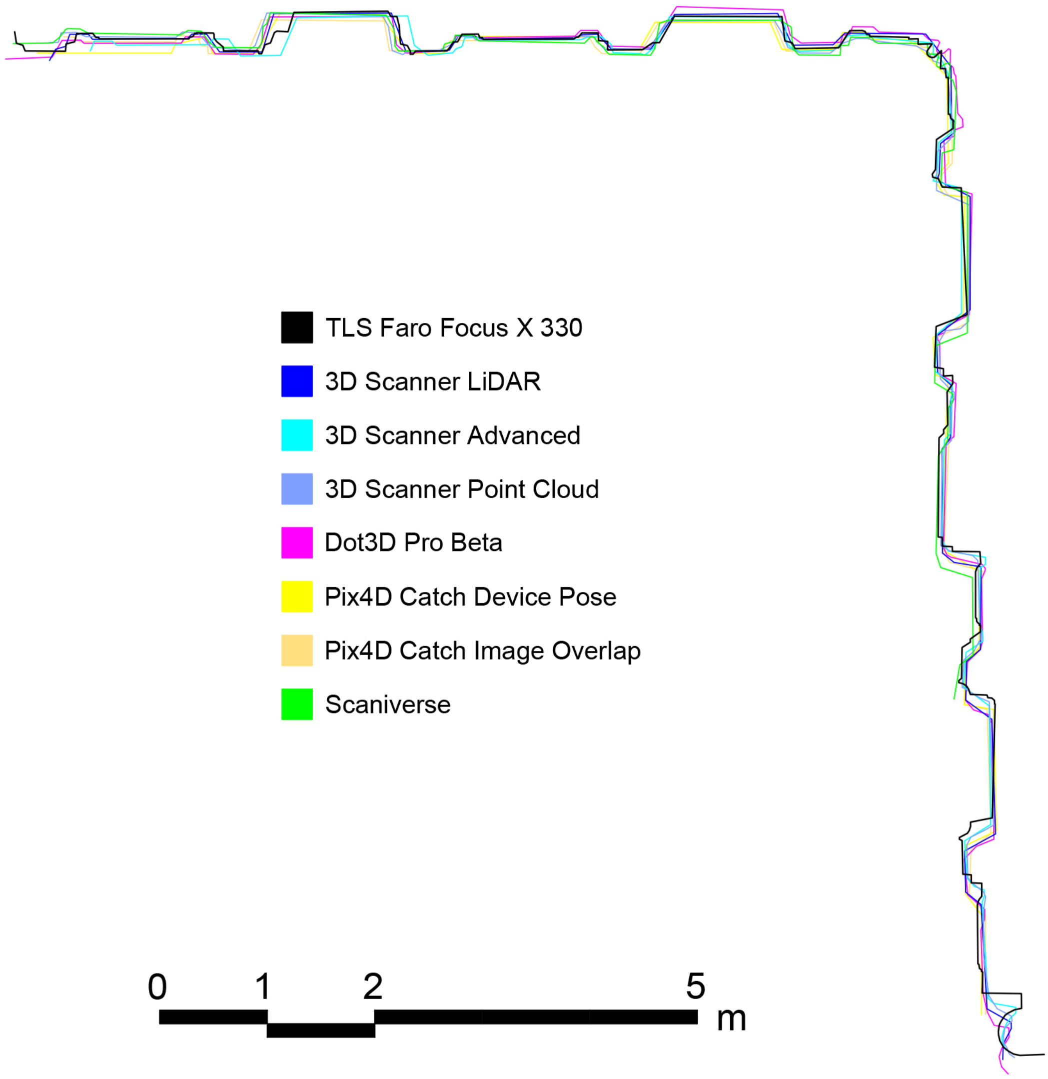


Figure 7.28: Overlap of the Horizontal sections on Castello del Valentino's façade among the seven different modalities

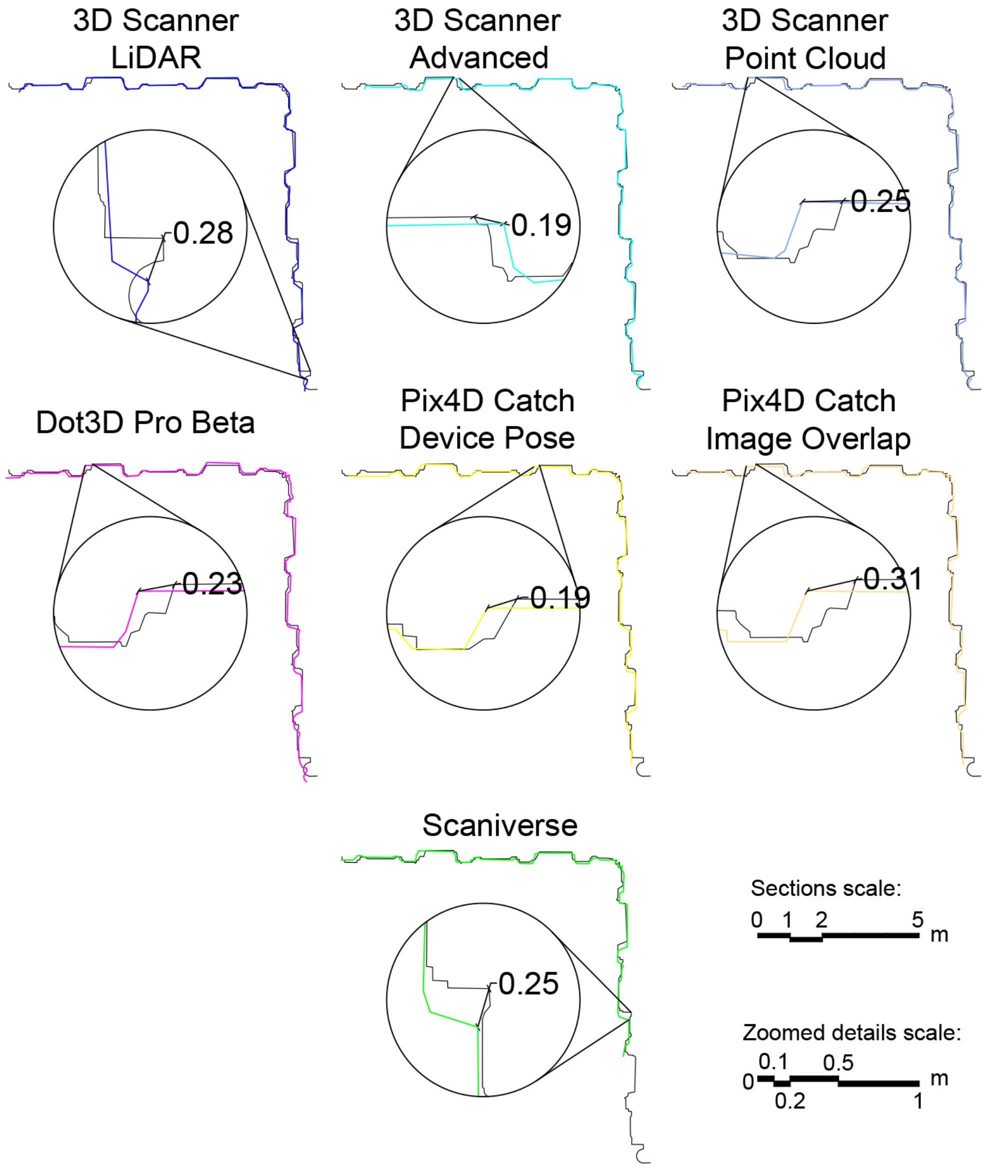


Figure 7.29: Comparison of the Horizontal sections on Castello del Valentino's façade

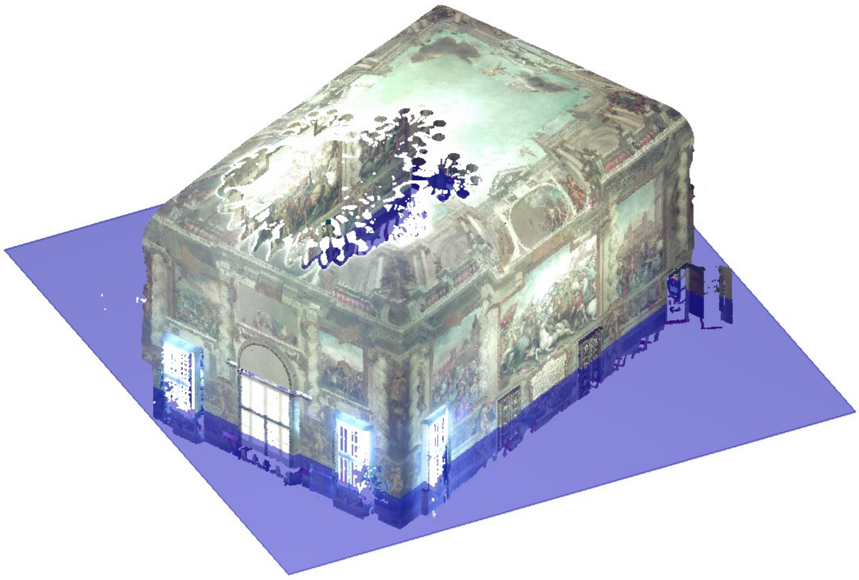


Figure 7.30: Section definition on Cyclone 3DR on the Salone d'Onore

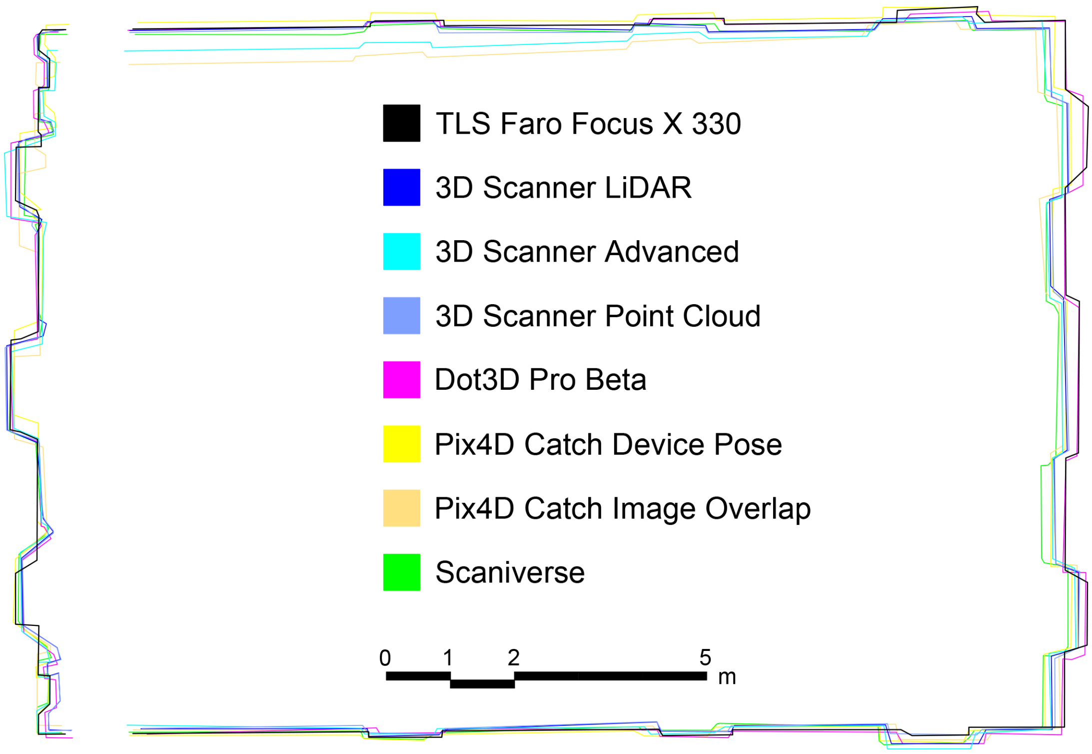


Figure 7.31: Overlap of the Horizontal sections on Salone d'Onore among the seven different modalities

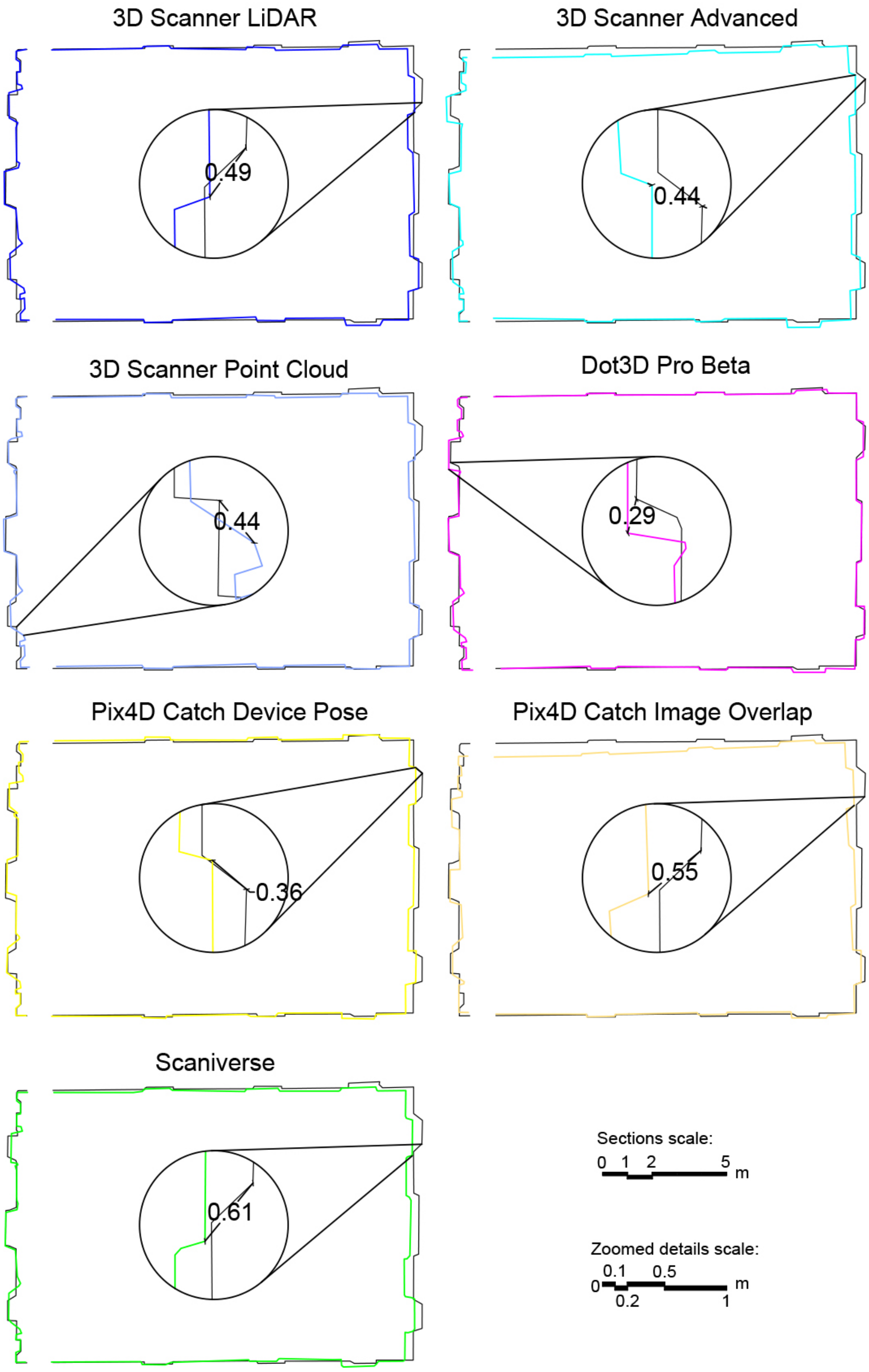


Figure 7.32: Comparison of the Horizontal sections on Salone d'Onore

Chapter 8

Discussion

8.1 Definition of the best application according to the four initial factors of judgement: Price, Shareability, Customisation and Accuracy

The different scores of Price, Shareability and Customisation for each app and modality have already been defined in the initial summary table [Figure 6.12], but to further discuss the level of Accuracy, the best range (zero to two centimeters) of the C2C Comparison have to be analysed. By extracting the results in the four different scenarios, a final table can be drawn up [Figure 8.1] to ultimately define which of the selected apps and their modalities provided the best results in the scanning process.

App	Mode	Percentage of points in the distance range 0 - 0.02 [m]			
		Cabinet	Castle's Facade	Hall of Honour	Lion
3D Scanner App	LiDAR	47.2%	44.4%	33.0%	80.9%
	Advanced	12.9%	39.4%	26.2%	67.9%
	Point Cloud	37.1%	37.7%	25.7%	75.1%
Dot3DPro	-	85.1%	33.0%	43.6%	72.5%
Pix4DCatch	Device Pose	57.3%	34.9%	24.2%	62.7%
	Image Overlap	67.9%	27.1%	26.8%	75.0%
Scaniverse	-	75.2%	55.1%	26.8%	73.1%

Figure 8.1: Summary Table of the C2C analyses in the four different scenarios, in which the three best results for each scenario are highlighted

The different levels of accuracy in the four scenarios correlate with the dimensions and complexity of the object that has to be scanned: the percentage of overlap among the scans acquired with the iPad Pro and the reference ones is greater for the small ambient of the Cabinet, as well as the statue of the lying Lion, while differences become more noticeable for big and more complex scenarios like the façade of the Castle and the Hall of Honour.

For each scenario, we have identified the three best results by considering the highest percentages of overlap within the two centimeters limit.

In the first test for the Cabinet of the Golden Flowers, Dot3D Pro provided the highest value with an overlap of 86.1%, followed by Scaniverse with the 75.2% and by Pix4D Catch in the Image Overlap mode, with a 67.9%.

The results in the other scenarios however are quite different: for the Façade of the Castle, the best results have been obtained in Scaniverse with a much lower percentage of 55.1%, followed by 3D Scanner LiDAR and Advanced mode respectively with the 44.4% and 39.4%.

For what concerns the ambient of the Hall of Honour, once again Dot3D Pro can be identified as the most accurate, with an overlap of 43.6%, followed by the results

of 3D Scanner in the LiDAR mode with a 33.0% and by the ones from Scaniverse and from Pix4D Catch in the Image Overlap mode, both with the 26.8%.
Finally, in the object scenario of the Lion lying on the pedestal of the monument to Giuseppe Garibaldi, the best results are achieved by 3D Scanner in the LiDAR mode, with a 80.9% of overlap, followed by the Point Cloud mode of the same app and by the Image Overlap mode of Pix4D Catch, with the results of 75.1% and 75.0%, and since these two results are so close to each other, the results achieved by Scaniverse are also considered, with an overlap percentage of 73.1%.
The three best results for each scenario are quite distant from the reference dataset, and while this can not be comprehended by simply looking at the comparison between point clouds, it becomes clear by looking at the distances between the section polylines obtained from PointCab.

For the first test on the Cabinet of the Golden Flowers, sections have been acquired both horizontally and vertically [Figure 8.2], with generally small drifts located throughout the whole drawing and not specifically in one defined region.
The only noticeable differences on the horizontal sections are located nearby the entrances on the walls in the left and right portions of the drawing, where the reference dataset had closed door, while iPad acquisitions were obtained without closing them, therefore these bigger drifts were not taken into account since they do not represent an error in accuracy, but a different initial environment.
For each of the three most accurate apps and modalities, a zoom on the region containing the point with the highest distance from its homologous in the reference section has been done.

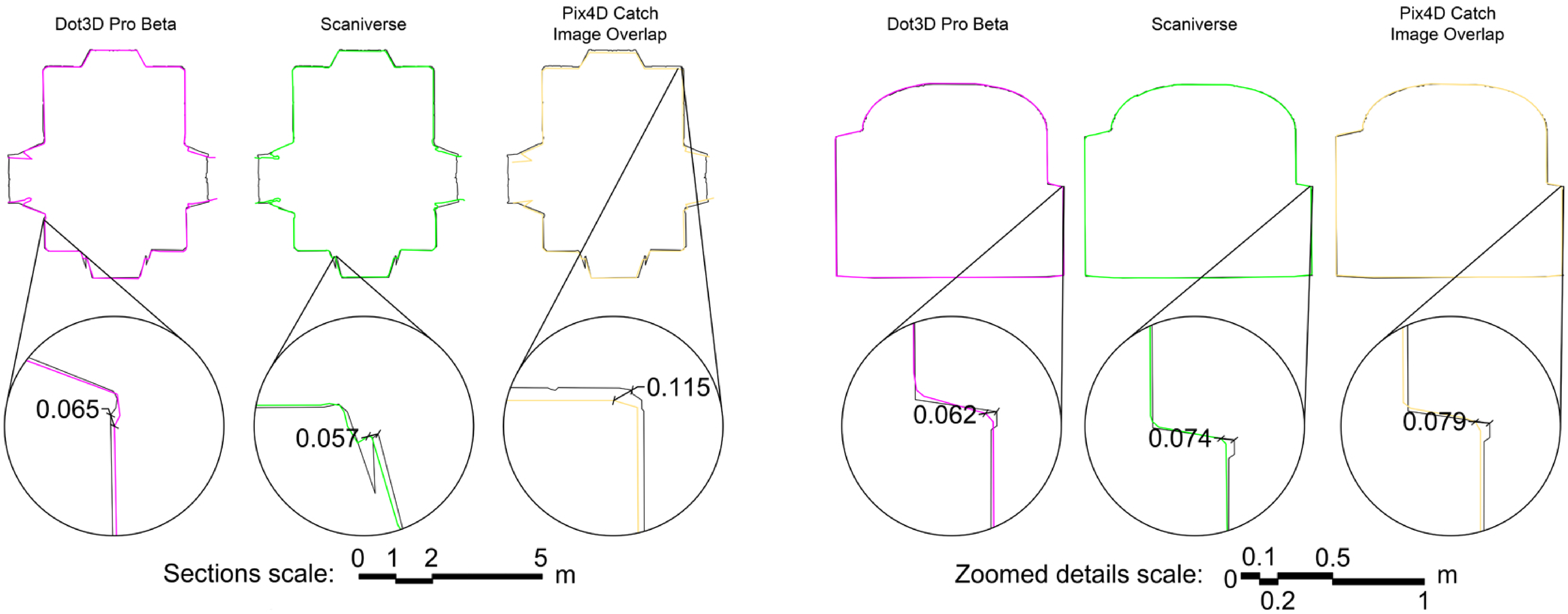


Figure 8.2: Horizontal and Vertical sections of the three most accurate scans for the Cabinet of the Golden Flowers

The app providing the best result is Dot3D Pro, with the biggest difference in the section analysis corresponding to the corner next to the door on the left portion of the drawing, with a distance of 6.5 cm. The second best result is obtained from Scaniverse, with a distance from the reference section of 5.7 cm located close to the window in the lower portion of the drawing. Finally, the third most accurate mode is Pix4D Catch: Image Overlap, whose highest difference in the section analysis is on the top-right corner of the drawing, with a distance of 11.5 cm.

On the vertical sections, on the other hand, the best three modalities generated small but noticeable drifts located all in the same position, which corresponds to the upper door jamb on the wall in the right portion of the drawing.

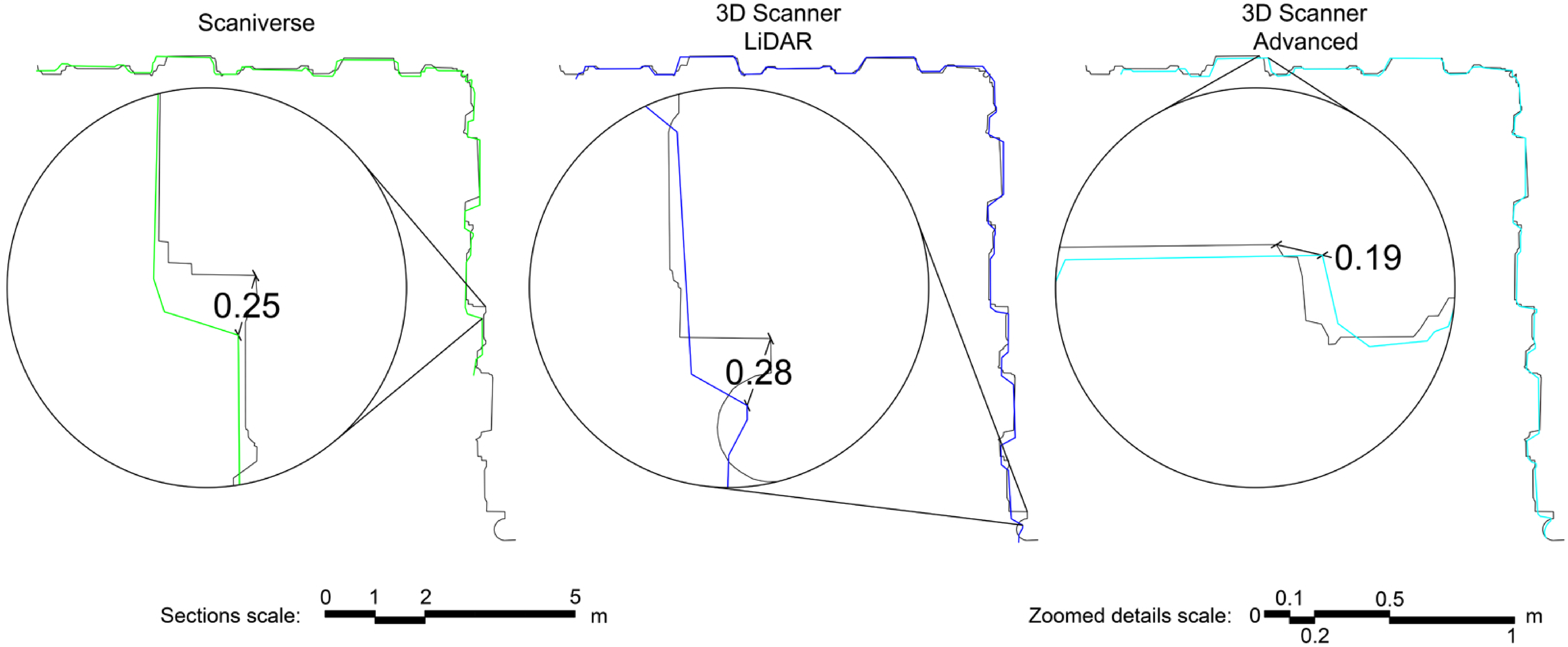


Figure 8.3: Sections of the three most accurate scans for the Castle's Façade

Regarding the outdoor scenarios, the only one on which we can extract a section line is the Façade of the Valentine's Castle [Figure 8.3], where the results of the cloud comparison were not as satisfying as the ones from the Cabinet of the Golden Flowers.

By looking at the sections, the most noticeable drifts can be identified on the right portion of the drawing, which represents the last phase of the scanning process. Therefore, it can be noted that with a rather complex surface as this one, made up of ledges and recesses, the error increases with the duration of the scan.

For this scenario, the best result for the C2C analysis was obtained by Scaniverse, and the highest distance from the reference section is 25 cm, followed by the one from 3D Scanner in the LiDAR and Advanced mode, respectively with 28 and 19 cm. Even if this last modality got the third best result in the C2C analysis, it seems to be the best one in the section analysis, not just looking at the most distant point, but in the whole polyline, since it looks more coherent with the one extracted from the reference dataset.

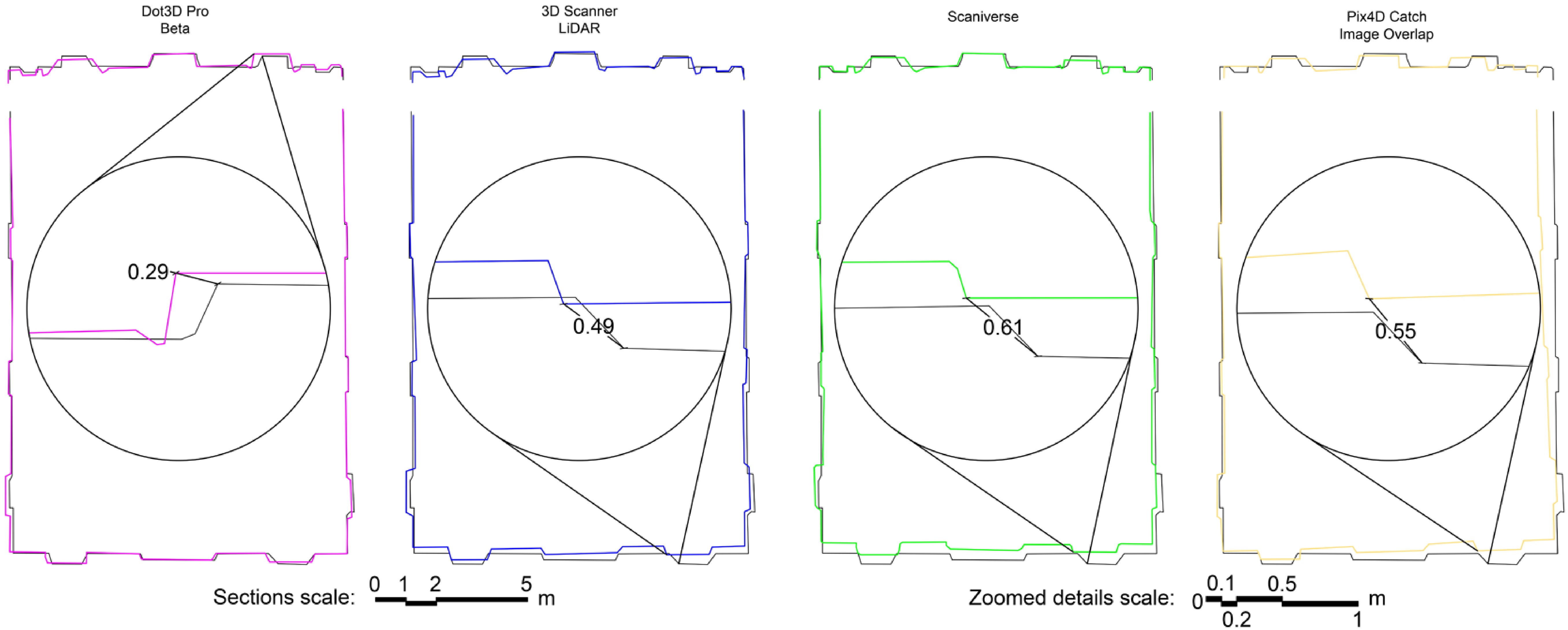


Figure 8.4: Sections of the four most accurate scans for the Hall of Honour

For the big ambient of the Hall of Honour, from the section analysis [Figure 8.4], a noticeable drift from the reference dataset can be identified in the right portion of the drawing. This may be caused by the fact that, even if this surfaces are halfway in the scanning process, there are obstructions such as a piano, a desk, a lectern and a plant, therefore the scanning path overlaps causing some distortions.

For this last scenario, the best result for the C2C analysis was obtained by Dot3D Pro, with the highest distance from the reference section equal to 29 cm located next to the door on the left portion of the drawing, while the following one are in the right portion, where there were the obstructions, by 3D Scanner: LiDAR mode, Scaniverse and Pix4D Catch: Image Overlap, respectively with 49, 61 and 55 cm.

As already stated at the beginning of this chapter, to ultimately decide which app and which modality provided the most reliable results among the four different scenarios, and to be able to sum the values from this table of Accuracy to the ones of Price, Shareability and Customisation defined in [Figure 6.12], these percentages have to be converted into whole numbers, by assigning respectively 5, 3 and 1 point to the three modalities providing the best results, and by giving 0 points to the rest of them. Therefore, the previous table can be redrawn as follows:

App	Mode	Overlap Accuracy Score				
		Cabinet	Castle's Facade	Hall of Honour	Lion	**Total**
3D Scanner App	LiDAR	0	3	3	5	**11**
	Advanced	0	1	0	0	**1**
	Point Cloud	0	0	0	3	**3**
Dot3DPro	-	5	0	5	0	**10**
Pix4DCatch	Device Pose	0	0	0	0	**0**
	Image Overlap	1	0	1	3	**5**
Scaniverse	-	3	5	1	1	**10**

Figure 8.6: Final Table of Accuracy scores in the four different scenarios

By just taking into account the levels of Accuracy provided by the four selected apps and their modalities in the four tested scenarios, it looks like the best results are achieved by 3D Scanner in the LiDAR mode, followed by Dot3D Pro who acquired the most accurate results for both the Cabinet of the Golden Flowers and for the Hall of Honour, and by Scaniverse, whose results were among the best three for all the different scenarios. However, by combining the final table of Accuracy [Figure 8.6] with the initial one for Price, Shareability and Customisation [Figure 6.12], the results may differ.

By combining these two table, we obtain the following results:

App	Mode	Final Score				
		Price	Shareability	Customisation	Accuracy	Total
3D Scanner App	LiDAR	5	5	2	11	**23**
	Advanced			5	1	**16**
	Point Cloud			2	3	**15**
Dot3DPro	-	5	4	2	10	**21**
Pix4DCatch	Device Pose	4	3	3	0	**10**
	Image Overlap			4	5	**16**
Scaniverse	-	5	5	3	10	**23**

Figure 8.7: Final Table of the four factors of Price, Shareability, Customisation and Accuracy

According to the four factors of judgment on [Figure 8.7], the best results can be identified on the LiDAR mode of 3D Scanner App and by Scaniverse with a score of 23, followed by Dot3D Pro scoring 21. From the initial situation however, Dot3D Pro has abandoned the Beta program by publishing the Stable version of the app, with a price of 49.99 $/month or 299.99 $/year. Therefore, the Price judgment has to be updated from 5 to 1, bringing the global score of the app down to 17.

Twenty out of the thirty-five available points, five for each scenario, were assigned to the judgment factor of Accuracy, which was the main focus of this work, and finally two applications managed to get the same result of 23. While this may seem just above average considering all the available points, it becomes coherent thinking at all the points that have been lost by simply placing at the second or third place in the C2C analyses.

Both 3D Scanner App and Scaniverse got the maximum marks regarding Price, since unlike other applications tested at the beginning of this research, they do not offer in-app purchases for unlocking a Pro version, a Cloud storage or an exportation format. For what concerns this last element, both apps achieved the whole five points also in the Shareability field, since they offered many exporting formats in order to adapt to the need of different software.

Regarding Customisation, Scaniverse was in line with other applications, enabling the user to tweak a few parameters, such as to set the lidar range up to five meters, to enable or disable location in order to achieve more accurate scans and finally, to choose the post processing mode and its definition, based on the size of the object that has been scanned.

3D Scanner App, on the other hand, offers three modalities with different level of Customisation: in LiDAR mode the user can only modify the processing quality and its definition, in Advanced mode it is possible to adjust the maximum depth, as well as the resolution, the confidence, which is the reduction of data based on their quality, and finally whether to enable masking on objects or people. The last modality of 3D Scanner App does not offer any customisation before scanning, but only in the post processing phase, and thereby it received a low score for this judgement factor.

Among these three modalities of 3D Scanner App, however, only the LiDAR mode was able to achieve satisfying results for what regards Accuracy. In fact, it was the best one in the outdoor scenario of the Lion lying on the pedestal of the monument to Giuseppe Garibaldi, and the second best for both the portion of the Castle's Façade and the Hall of Honour. On the other hand, Scaniverse provided top-three results for all four scenarios, and Dot3D Pro was the most accurate in the indoor ones of the Cabinet of the Golden Flowers and of the Hall of Honour.

Since 3D Scanner App: LiDAR Mode and Scaniverse received the same global score, the final decision should be up to the user. For those just wanting to achieve accurate results with a basic level of initial customisation, probably the best choice would be Scaniverse, while 3D Scanner App is more suited for both non-experienced user whose main goal is to scan in a quick and reliable way in the LiDAR mode, with little to no options to choose from, and for those at the other hand of the spectrum, the more experienced users who prefer to have full control of the initial parameters and who may achieve good results by tweaking them in the correct way.

8.2 Apple's LiDAR for Cultural Heritage Documentation

The results obtained by both 3D Scanner App in the LiDAR Mode and by Scaniverse on the four different scenarios reached quite satisfying level of Accuracy, since the C2C analysis with the referenced dataset acquired with Faro Focus X 330 were in the range from 33.0% to 80.9% for 3D Scanner, and from 26.9% to 75.2% for Scaniverse in the four different scenarios, and Apple's devices could definitely be used for CH Documentation for many different purposes, but probably Cultural Heritage metric survey with sub-centimeters accuracy representation is not one of those. In fact, Traditional Laser Scanners like the Faro Focus X 330 manage to reach errors of less than a centimeter, while Apple's solution could be more suitable for preliminary or expeditious surveys, since it grants a good level of detail at a fraction of the price.

However, since the sensor is embedded into one of the most sold smartphones, as well as one of the most powerful tablets, if a good amount of these devices' owner chose to gather information at a small scale, it would be possible to exploit these acquisitions to create a network of monuments and Cultural Heritage all around the world. Obviously, not all CH sites are suitable for this operation: information about environment with high ceiling could be completely accessed only using external tools which are usually not allowed into protected ambient such as churches or museums, and data regarding small sized object or fine details could be inaccurate, but still providing a general idea about dimensions, shapes and colours.

This network could be accessible with an app that virtually allows anybody to learn information about CH in a new and more inspiring way. Thanks to the use of Virtual and Augmented Reality apps, it is already possible to enable the user to admire the 3D models of objects generated by scanning them with Apple's sensor,

and to visualise them on the display merged with the environment in which the user is located.
The next big step would be to allow the user to access different kinds of environments and CH sites on a larger scale, such as the Cabinet of the Golden Flowers and the Hall of Honour, to create interactive models which can be explored and from which anyone can admire every single detail. This kind of experience could be very useful in many situations and for different kind of users, on top of being a fun and interactive way of learning.
In fact, when the disease of COVID-19 spread in the whole world, among the different realities which had to shut down for emergency reasons, some CH such as museums, theaters, castles and libraries were chosen by the Ministry of Culture for the project *Gran Virtual Tour* [75] to be virtually accessible from home via 360° imagery or via videos of the different environments making up the sites.
Among those sites, some are located in Piedmont, such as the Royal Theater and Museums, along with the Chapel of the Holy Shroud, the Venaria Reale and Agliè Ducal Castle, as well as a temporary exhibition in the Egyptian Museum of Turin. Most of these experiences are however quite stationary and not really interactive, since they are formed of 360° images in which one can simply zoom and move the cursor on the screen to navigate the environment, and only a fraction of them offers a VR mode, with which instead of using the cursor, people can tilt their head to look around them. Some of these sites simply redirected the user to their webpage on *Google Arts & Culture* [76], a platform which provides images and videos regarding the artworks available in a certain site, along with some virtual tours of its environment in a similar way to how Google Street View works, with arrows to be clicked on the display in order the browse trough the collection.
To look at a painting while standing in the middle of a room and zooming on it, or with a cheap VR viewer like Google Cardboard [77] to experience a 360° augmented

reality of different environments in a museum is a whole different experience than the one of walking through the environment and admiring it up close. While Google's solutions are still great for admiring art remotely, the method used by Google Street View is not enough for a museum collection, and there are very few virtual reality tours which however do not allow the visitor to fully experience the works of art available in a certain site, since they are limited to the description of the most famous and precious element of their collection, such as the *Venere di Botticelli* for the Uffizi Gallery in Florence.

For these experience to be fully interactive, the visitor could use its own device in the same way Google Arts and Culture app work, but instead of being limited to view still 360° imagery in which one has to browse, it could be possible to exploit 3D models of the whole environment and of the pieces of art in the museum collection acquired with mobile devices by the museum staff or by visitors. Obviously, for the scanning process to be executed in the correct way, museums would have to instruct users on how to properly acquire information using their iPhone or iPad Pro, and this operation could be done by visitors in exchange, for instance, of a private museum visit, since the whole environment filled with browsing tourists is not the most suitable for a clean acquisition of the different environments. A limited amount of people could therefore be employed to scan the whole museum by dividing them into small groups and by assigning to each one of them a precise room or work of art which are later assembled into a completely reconstructed museum.

This operation could allow all kind of visitors to access the museum collection through their own devices, since they would not be required to possess an iPhone or iPad Pro to download the app containing these collections. Rightly, one could say that this operation would be the death of museums, since visitors could benefit of their collection without leaving their home, but it could be a rebirth for culture, since users could choose to visit museum from across the world which they would have never visited otherwise. On top of that, this experience could also have a fee, obviously minor to the price of a ticket, to support museums or other sites, with reduced or free fruition to certain visitors.

In fact, this program could have specific sections that could benefit all those users with reduced sight or mobility, who would not have to come out of their comfort to admire collections, but also to younger users who could understand new information about art in an interactive way. By exploiting this kind of experience, in fact, children could be learning through playing and exploring different environments without having to be held by their parents or being scolded by other visitors for being too loud, and furthermore they would take advantage of the mobile devices they often already have, or their school provides them.

Finally, on top of that, museums could also allow artists to create pieces of art for virtual temporary exhibitions, which can be held into rooms that can easily be implemented into the whole museum by exploiting environments whose access would otherwise be forbidden to visitors. These exhibitions could host 3D models of physical pieces of art , as well as virtual ones like those of non-fungible tokens (NFTs) [Figure 8.8/A] or those created through the use of artificial intelligence (AI) [Figure 8.8/B], which have become very popular in the last few years.

Figure 8.8: Examples of NFT and AI generated art

Chapter 9

Conclusions

The process of Documentation for Cultural Heritage should be more accessible, since expensive and complex instruments like a Terrestrial Laser Scanner with sub-centimeter errors do not have to necessarily be exploited for all scopes. Apple's LiDAR solution is in fact a good compromise of Price and Accuracy, since the Pro version of iPhones or iPads can be acquired for as low as 1000€, and can achieve satisfying levels of accuracy when compared to dataset captured with much more expensive TLS like the Faro Focus X 330.

For this thesis, the LiDAR sensor equipped on the 11-inch version of the 2020 iPad Pro has been analysed, along with ten of the vast world of applications taking advantage of the sensor. Among these apps, only a couple of them were able to provide good results while offering at the same time a certain amount of customisation, therefore enabling the user to modify different options based on its needs and on the features of the scenario which has to be scanned.

The ten free apps available on the App Store have initially been tested on a small indoor ambient located into the Valentino's Castle and called Cabinet of the Golden Flowers, to select the four apps visually providing the best results: 3D Scanner App, Dot 3D Pro, Pix4D Catch and Scaniverse, for which a further analysis has

been carried out and the same methodology has been then applied on three other CH with different scales and levels of detail: the exterior portion of the Castle's Façade, the Hall of Honour inside the Castle and the outdoor statue of a lying lion on the basement of a monument to Giuseppe Garibaldi.
The features extracted by the four different apps in the seven available modalities were then imported into Cyclone 3DR and PointCab following the methodology defined in the first test, and by comparing the aligned point clouds and sections to those of the reference dataset, it was possible to make up a ranking between modalities for the factors of Price, Shareability, Customisation and Accuracy, by assigning a score from 1 to 5 for the first three factors, and by giving respectively 5,3 and 1 point to the three most accurate modalities for each scenario.
The outcomes of this process identified in two applications the best solutions, with some differences that could make them most suited to different kind of users: Scaniverse would be the best choice for achieving good results with a small amount of initial customisation, while 3D Scanner offers multiple modalities that could be exploited by non-experienced user since the LiDAR mode provides the best results but with no customisation, and by more experienced users who can tweak multiple parameters to adapt to the scenarios they want to capture. While the results are probably not suitable for a high-accuracy metric survey of Cultural Heritage, where TLS can achieve much lower errors, the model acquired with Apple's sensor could still be exploited for expeditious surveys, where accuracy does not have to reach the levels obtained by a TLS. Furthermore, it could benefit Cultural Heritage by allowing the creation of a network of CH models which could be accessed by all kind of devices and which could be taken advantage of by the CH sites themselves. Even if platforms like Google Arts and Culture already exist, which allow people to learn about certain exhibitions, collections or single work of arts by browsing CH via a description, HD images or, like one would do on Google Street View, by

using 360° imagery, there is a lack of interactivity that could attract more visitors to the platform.

The idea of having a 3D model of the whole CH site, which can be browsed through a mobile device, could allow all kind of users to remotely visit museum collections by paying a small fee or for free, therefore enabling people with reduced mobility or limited sight to fully experience the beauty of art, but also children which could learn by exploring without the risks of them curiously browsing around while being too loud or of damaging the collection, since the whole visit can happen in the classroom or in their home. Finally, a 3D model acquired with Apple's devices could allow museums to host exhibitions of virtual arts such as NFT or AI generated images, which have become increasingly popular in the last few years and whose potential could benefit not only the virtual world of art, but also the physical one.

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