POLITECNICO DI TORINO

Master of Science in Architecture for Heritage Preservation and Enhancement

Master's Degree Thesis

From point cloud based models to VR visualization for Cultural Heritage at risk: St. Nicola Church in Tolentino

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*"It's our **choices**,*
*Harry, that show what we **truly** are,*
far more than our abilities"
J.K Rowling

Acknoledgements

Eleanor Roosvelt soleva sempre prescriversi una *ricetta terapeutica* su come affrontare la vita al meglio: non cercando di fare ciò che infonde sicurezza e agio, al contrario la sua terapia, direi d'urto, prevedeva ogni giorno della vita di *scegliere* di fare qualcosa per cui si nutra paura, qualcosa che terrorizzi al sol pensiero. Posso ben dire, che all'interno di questo lavoro di tesi, le cose per cui ho nutrito paura e timori hanno di gran lunga superato le dita di entrambe le mie mani ma, è stato grazie a questo spirito che sono riuscita ad abbattere i miei limiti e arrivare a questa agognata pagina.

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Introduction and aim

Italian Version below

Culture, in its tangible and intangible expressions, has a civilization value and for this reason it has to be protected as a duty gesture towards whole humanity. Architectural and Archaeological Cultural Heritage is a tangible expression of culture affected by **Vulnerabilities** and environmental or anthropic hazards: this thesis path has started as an input, after the seismic events that shook the Italian territory during August and October 2016, to concentrate more attention to monuments and **Cultural Heritage at risk** that results to be limited in the visiting availability or worse to be condemned. The responsibility of **Protection** reclines on an appropriate **Documentation**, this is the reason why, the main matrix of this thesis, shown in **Figure 1**, consists of presenting the vulnerability of Heritage, the importance of documentation tools, methods and technologies of 3D metric survey belonging to the **Geomatics field** of application: from the **Survey phase** focused inside this case study mainly on **LiDAR** point cloud acquisitions and **UAV aerial photogrammetry**, passing through the models management for the extraction of 2D architectural drawings and damage visual evaluations until the last experimental step, the immersive visualization through **Virtual Reality**. The 3D model aim such as also immersive experiences are now directed towards the creation of **Reconnaissances** for visual evaluations about structural or static damages. These model visualizations aim at easy localizations of vulnerabilities through photographs having also the possibility to make real time measurements inside the model giving the non-expert audience the opportunity of a visiting walkthrough and the opportunity for the CH field audience to make a preparatory vr inspection. The added value derived from Geomatics methods especially in the Architecture and Restoration field let us have a direct connection and an architectural accuracy documentation in adherence with the real CH case study thanks to the **Reality based** approach of 3D metric survey operations. The mutual interpenetration between 3D survey tools, Architectural skills with the no-stop flowing wave of **ICTs** underlines a great interdisciplinary feature that has strongly improved, and it improves so far, **Restoration** field which acquires nowadays an important fellow in the sharing knowledge on Cultural Heritage that must be seen from a unique **Multidisciplinary** point of view and not from sectorial and separated points of view.

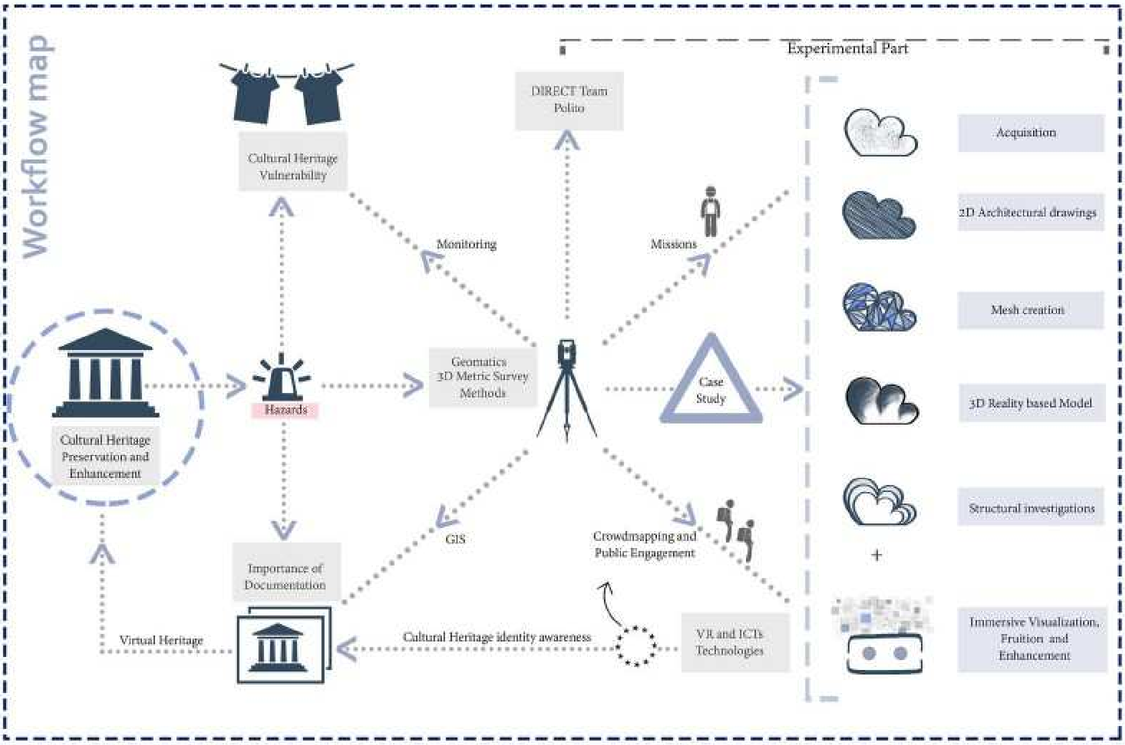


Figure 1: Thesis workflow map, Elaboration: Carla Borriello

La **Cultura**, nelle sue espressioni tangibili e intangibili, ha un valore di civiltà e per questa ragione deve essere preservata come gesto nei confronti dell'umanità intera. Il Patrimonio Culturale Architettonico e Archeologico è un'espressione sensibilmente **Vulnerabile** e affetto da rischi di tipo ambientale o antropico: in particolar modo, questo percorso di tesi è iniziato come un input, a seguito degli eventi sismici che hanno scosso il territorio Italiano durante Agosto e Ottobre 2016, proprio per concentrare maggior attenzione ai monumenti, manufatti storici e ai **Beni Culturali a rischio** che hanno delle limitazioni nella fruibilità della visita o peggio risultano inagibili. La responsabilità nella **Conservazione** si reclina su un'accurata **Documentazione**, questa è la ragione per cui la matrice di questa tesi, graficizzata in **Figura 2**, consiste nel presentare la vulnerabilità del Patrimonio Costruito, l'importanza dei mezzi per la documentazione, i metodi e le tecnologie del rilievo metrico 3D che appartengono al campo della **Geomatica**: dalla fase di acquisizione centrata in questo caso studio sul **Rilievo** di nuvole di punti da sistemi **LiDAR** e la fotogrammetria aerea con **UAV**, passando attraverso la gestione del modello per l'estrazione di prodotti architettonici 2D e valutazioni visive dei danni, sino ad arrivare all'ultimo passo sperimentale della visualizzazione immersiva tramite **Realtà Virtuale**. L'obiettivo di questi modelli 3D come anche le esperienze immersive sono ora legate alla realizzazione di **Ricognizioni** utili ai fini delle valutazioni visive di tipo strutturale o statico. Tali visualizzazioni sono mirate ad una facile localizzazione delle vulnerabilità attraverso immagini fotografiche e possibili misurazioni all'interno del Bene garantendo agli attori non esperti la possibilità di una visita e anche l'opportunità per gli attori preposti alla tutela e conservazione del Beni Cuturali di effettuare un sopralluogo virtuale preliminare. Il valore aggiunto dato dai metodi geomatici soprattutto nell'architettura e nel restauro permette di avere una connessione diretta e un'accurata documentazione in aderenza con il reale caso studio grazie al cosidetto approccio **Reality-based** tipico delle operazioni di rilievo metrico 3D. La reciproca compenetrazione tra gli strumenti del rilievo 3D, le competenze architettoniche con l'incessante onda di progresso dato dall'apporto delle **ICTs** tecnologie di informatica e comunicazione sottolinea una grande componente interdisciplinare che ha fortemente implementato, e implementa tutt'ora, il campo del **Restauro** che acquisisce così negli ultimi tempi un importante alleato nella conoscenza del Patrimonio Costruito che dev'essere visto sotto un punto di vista **Multidisciplinare** e non legato ai singoli ambiti settoriali.

Chapter 1

Cultural Heritage at Risk

The troubled term **Cultural Heritage** juridically refers to a set of cultural properties that include tangible and intangible items such as monuments, historic buildings, artworks, archaeological sites, archives, libraries and museums.
If we bear in mind the Italian description on the article number two, comma two, of the Cultural Heritage and Landscape Code [120], it speaks:

> *"Cultural properties are all the movable and unmovable things that, referring to the Italian Constitution articles number ten and eleven, show an artistic, historical, archaeological, ethnic, anthropological, archivistic and bibliographic interest and all the other things identified, by the law or following the law, as proofs having a civilization value"*

Rising from the article there's the identification of **"cultural properties having a civilization value"**: expression borrowed from the first declaration law of the Franceschini Commission in 1964 where the concept itself of "cultural property" or "cultural heritage" has existed before that moment in another reading filter. This new conception didn't find its roots only in the volunteer to underline the importance of the historic memory of past that was able to fulfil the cultural function of the public fruition of the property, but, it also aspired to definitely pass over the idea of cultural heritage considered just for the aesthetic aspects of beauty that was broadcast by the two Bottai laws in 1939 with the number 1089 about *Artistic and historical things Protection* and with the number 1497 of the same year about *Natural Beauties and Landscape Protection*[205]. Every historical building or tangible property were judged worthy of being called **"art things"** just by their aesthetic beauty [44].

An important goal achieved then, an identification basis that goes from the aesthetic criteria to the historic one [6]. Declaring a different object of protection and assigning it to a new role, it's no more only the thing itself worthy of protection, but the proof of the human civilization lifetime rooted in material and immaterial things [164].

During the Convention concerning the protection of the World cultural and natural heritage organized by the **United Nations Educational, Scientific and Cultural Organisation** (UNESCO) that took place in Paris from the 17th of October to the 21st of November 1972, the first article considered [199]:

" [...] as cultural heritage:

monuments *, architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science*

group of buildings *, groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science*

sites *, works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view"*

The convention results, though, gave an incomplete perspective about Cultural Heritage criteria that turned to cut out the concepts of *cultural landscape* and the *awareness* of our world life expressions of past and present.
The previous concepts and criteria were re-examined by UNESCO itself in 2003 during the **Convention concerning the Safeguarding of the Intangible Cultural Heritage** in the 32nd session that took place in Paris from 29th September to the 17th of October [196]. It arose the awareness of the integration of **intangible cultural heritage**, defined by the article number two, comma two, as domains in:

(a) *"oral traditions and expressions, including language as a vehicle of the intangible cultural heritage*;

(b) *"performing arts"*;

(c) *"social practices, rituals and festive events"*;

(d) *"knowledge and practices concerning nature and the universe"*;

(e) *" traditional craftsmanship"*;

But it's in the first comma of article number two of the Convention, that we perceive an important change of view about Cultural Heritage concept, that finally takes into account contextualisations and interactions linked to people, a transition from a static value to a **dynamic value** evolving with our ethical and sensibility evolution:

> *" [...] This intangible cultural heritage, transmitted from generation to generation, is constantly recreated by communities and groups in response to their environment, their interaction with nature and their history, and provides them with a sense of identity and continuity, thus promoting respect for cultural diversity and human creativity."* [196]

The juridical regulations in general, don't give their real own contributions about the definition of cultural property, indeed, they explain it thanks to other non-juridical subjects since cultural heritage cannot belong just to the culture, but also to the conscience, to the evolution rate, as already said, reached by the community or the social conscience of people [184] who want to preserve themselves essences. All this, doesn't want to be an historic-juridical *iter*, so going over every technical explanation, theoretical basics and laws, it is necessary to declare the final aim of them. Laws have showed a definition it's not always just a written notion to repeat whenever it's necessary to give explanation, it's a common concept, acknowledged and recognized by everyone.
The protection, documentation, enhancement, maintenance, secure operations and restoration processes which must be seen as a unite family in the public sphere, had and have so far, the pushing task to pass down everything is worthy of being protected from the unpredictability of nature, from time and space developments and, also unfortunately, from men themselves consequences actions.
The call for the improving management of it, lays on the **sensibility**, on the conscience of archaeologists, architects, surveyors and all the people who look at their jobs, in a micro-scale dimension a cultural gesture having in a macro-scale dimension a gesture of proof for our future world using different methods fitting the technological no-stop flowing wave of progress.

1.1 The vulnerability of the Cultural Heritage

Nowadays the connection between cultural heritage and its safety seems to appear, metaphorically speaking, like a direct thread logically wished for an ideal world. Such as the thread used for drying the laundry, several risk ”weights” are hanged up on it trying to cut this temporal continuity down.
The risk of loss changes its strength in a directly proportional way to the potential success of the danger factor. This potentiality has been investigated in a statistic approaching method under which the Italian *Carta del Rischio* (Risk Charter) turns to be the leading role.

Figure 1.1: Vulnerability of CH, Elaboration: Carla Borriello

1.1.1 Carta del Rischio

The *Carta del Rischio* (2005) [116], Risk Charter in English, is an Italian example of digital archive unification aimed to the creation of an interactive Geographical Information System (GIS) database dedicated to the Cultural Heritage vulnerability knowledge. At the centre of the charter there's the need of preservation and protection of cultural heritage and for this purpose the Geo-spatial information represent a strategic value. It has been used a statistic approach for the creation of the risk map and for the evaluation of the vulnerability.
Vulnerability factors have been divided into two categories:

1. **Individual Vulnerability** (V), it takes into account the exposition rate of a cultural property towards territorial-environmental aggression;

2. **Territorial Dangerousness** (P), a function that shows the potential level of aggressiveness of a territorial area evaluated not taking into account the presence of cultural properties;

This important tool, is not only aimed to catalogue and index case studies, but it also represents a valid support for consulting and updating the database. In the deep way, it allows to:

- Display cartography with cultural property location
- Consult the repertory of motion and motionless properties
- Consult the vulnerability document of cultural properties
- The possibility to insert new vulnerability documents
- Consult seismic documents of cultural properties
- Make statistic studies about cultural properties

1.1.2 Risk Typologies

On the base of the two categories for the evaluation of vulnerability, we generally divide two corresponding big typologies of risk depending on the *genesis* cause.

Territorial Risks that consist of:

- **Static risk** (Earthquakes, damages, floods, volcanic events...)
- **Environmental risk** (Climate problems, atmospheric pollution...)
- **Anthropological risk** (State of neglect, tourism pression, overpopulation, terrorism events...)

Individual Risks that consist of:

- **Territorial dangerousness**
- **Vulnerability of heritage during time**

1.1.3 Territorial risks

As anticipated in the vulnerability section there are three main categories of territorial risks: Static, Environmental and Anthropological ones. When we talk about cultural heritage matter, it's logic to take into analysis the most unpredictable class of them: the Static risks. Another distinction can be made on the *genesis* cause of the static hazards [198]:

- **Meteorological hazards**

  - Storm (Precipitation, strong wind, hurricane, tornado, ice storm, dust storm etc.)
  - Fire (Spontaneous coal, lightning etc.)
  - Drought
  - Heatwave
  - High sea surface temperature
- **Geomorphological hazards**
  - Volcano
  - Earthquake
  - Mass movements
  - Erosion
- **Hydrological hazards**
  - Flood (River/lake flood,storm surge etc.)
  - Tsunami

1.1.4 Environmental risks

- Astrophysics problems
  - Space weather
  - Meteorite impacts

1.1.5 Antropological risks

- Fire
  - Land clearances
  - Arson
  - Accidents
- Pollution
  - Health problems
  - Food poisoning
  - Diseases
- Nuclear
  - Radioactive accidents
- Social induced
  - Wars and Terrorism attacks

1.2 Earthquakes: a high risk in Italy

A typically peculiar risk of Italy, is doubtless, the seismic movements of the territory that every year shake people lives and their safety. It's not a causality that Italy is one of the country with the most important tectonic activity around the Mediterranean sea and with the higher seismic rate of all.
This is due to its peculiar geographical position, located in the convergent area between the African lithospheric plate and the Eurasian one [204]. Indeed, **plates** movements release a growing amount of energy, that as soon as it overpasses the resistance limit, it causes deep fractures in the lithosphere layer, they're called **faults**. The released energy produces **seismic waves** that cross the earth surface and produce the "quake", that shaking status able to cause other following consequences such as landslides or tsunami.

1.2.1 Seismicity

The **seismicity** or the seismic activity of a territory is its frequency of telluric movements and this is the reason why lots of geology and seismic collaboration studies, had let to understand and recognize all the plates and faults responsible for earthquakes. The study of spatial placement of faults is as important as the capability to have a valuation in order to reduce the disaster risk.
And thanks to the Geological Service of Italy (ISPRA) is born the "Italy Hazard from Capable fault Project", also known as ITHACA[100]. In other words, ITHACA is a database tool for operating the analysis of the seismic vulnerability, for the comprehension of the landscape evolution, an important reacting tool for territorial planning and at last, but not for importance, the disasters management process.
In the following figure, we can notice, in red, the placement of the capable active faults (FAC) in the Italian territory, or rather that kind of faults that are considered active and able to produce fractures on the topographic surface as it's read on the glossary of the italian Civil Protection[148].
While in National Institute of Geophysics and Volcanology (INGV) DISS database map, is showed the placement in the Italian territory of seismogenic faults, which are active faults as well with faster movements than the FAC ones with *"strick-slips"* jerks.

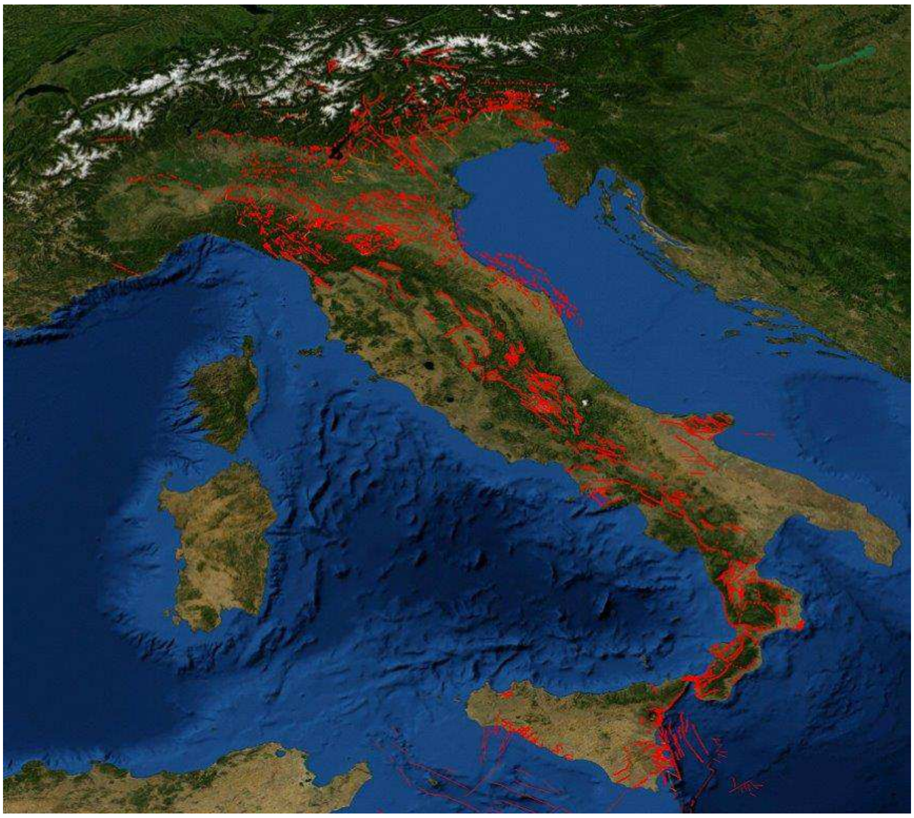


Figure 1.2: Capable faults map in Italy, ISPRA [100]

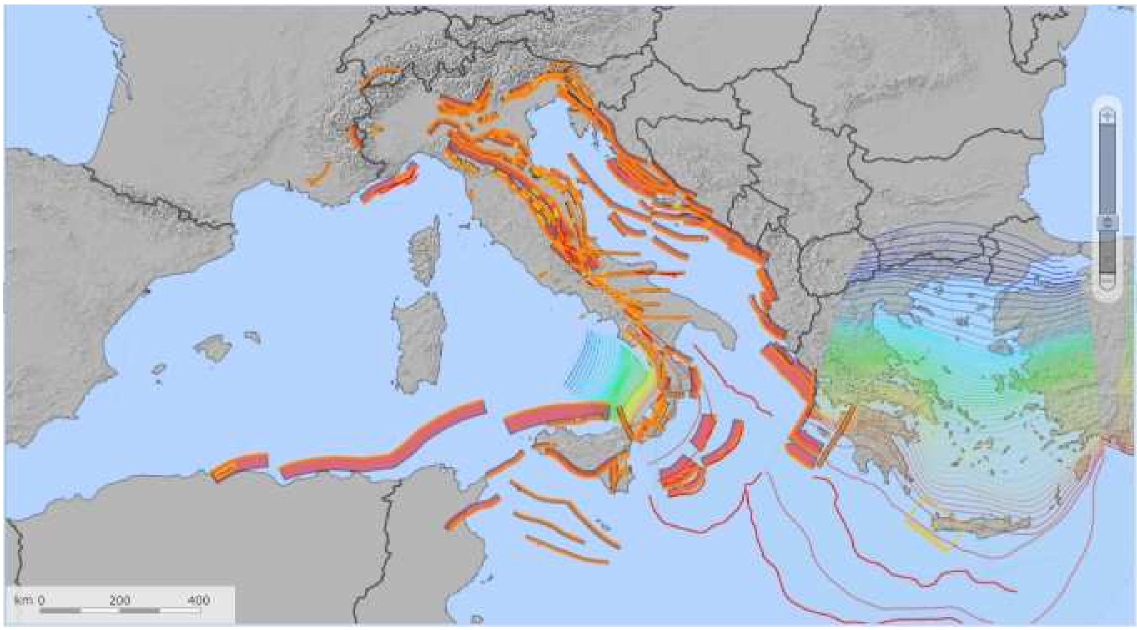


Figure 1.3: Databases of Individual Seismogenic Sources faults, INGV [94]

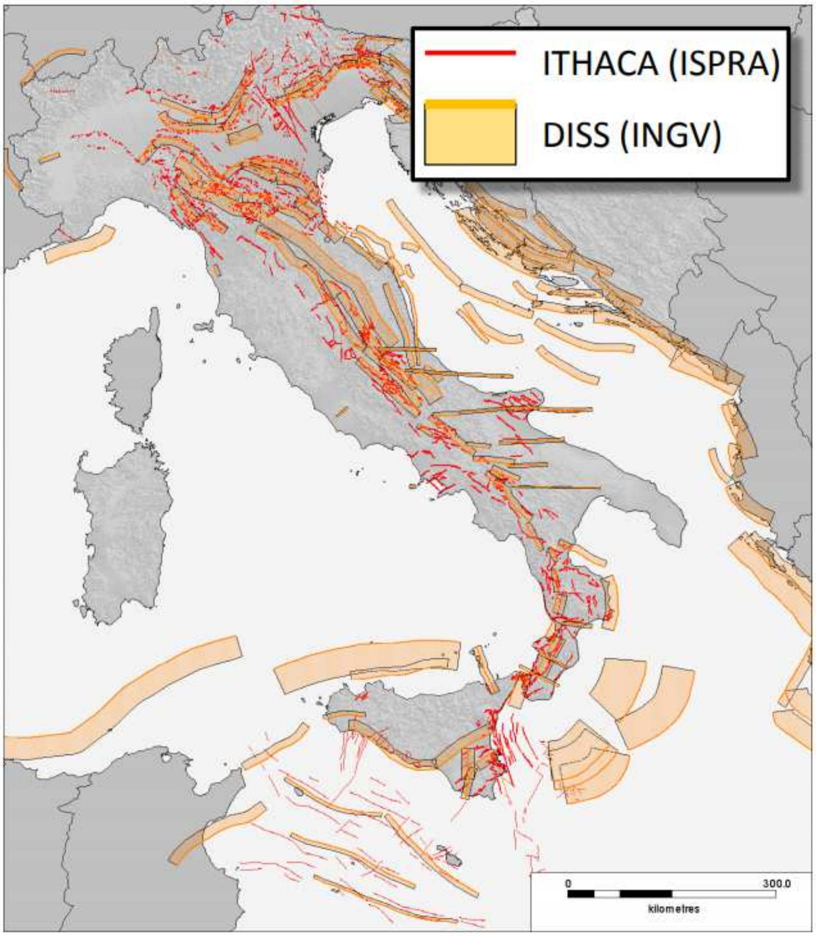


Figure 1.4: Comparison between ITHACA and DISS Database[150]

1.2.2 Intensity scales of an earthquake valutation

How is it possible to *measure* an earthquake? Earthquakes are measured by **seismograph** and thanks to the combining action of several seismographs located at different distances from the seismic wave, it's possible to evaluate:

1. **Epicentre**:*"Is the vertical projection of the focal point to the ground surface"* [68].
2. **Hypocentre**: *"Is focal point (focus) [. . .] where the earthquakes occur. Where the faults line originates"*[68].
3. **Intensity**, this last one can be valutated trought the so-called **Seismic scales** which are based on the intensity and on the magnitude of an earthquake.

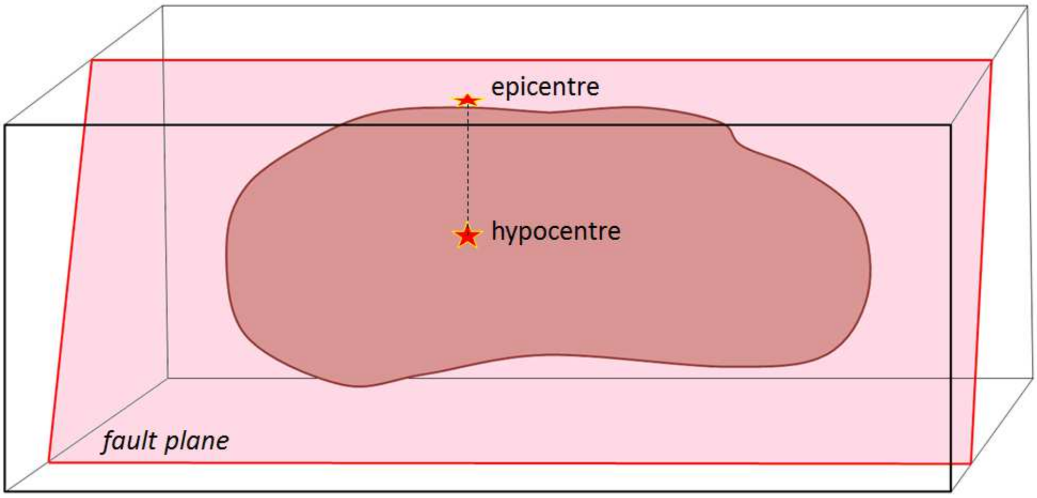


Figure 1.5: Epicentre and Hypo-centre [168]

1.2.3 Intensity Scale: Mercalli

This seismic scale, takes its name by the Italian volcanologist Giuseppe Mercalli, and it's also known today as MMI (Modified Mercalli Intensity scale). It takes into account the intensity proof of the **effects** on the earth's surface: on humans, objects, buildings and so on.

Grade	Description
I	**Instrumental** detected only by seismograph.
II	**Very soft** tremor, detected only by resting people and just in higher floors of buildings. Hanged up objects might be swinging a little.
III	**Soft tremor**, detected during daytime in houses, specially in higher buildings floor. It's like light lorries passing vibrations. Duration time evaluation. Sometimes it's not assumed like an earthquake.
IV	**Medium intensity** tremor, detected by many people in houses in daytime and by few people outdoor. At night only few people can wake up and detect it. Hanged up objects swing strongly.It's like heavy-lorries passing vibrations. Oscillations of stationary vehicles. Jingling of glasses and crockeries.Among IV and V grade wooden structures start to creak.
V	**Strong** tremor, detected pratically by everyone. At night many people can be waked up. Unstable objects overturn. Overturning of fluids. Oscillations open and close movements of doors. Movements of windows and pictures on the wall. Stop and go, beat changing of clocks. Trees shaking and fractures.
VI	**Really strong** tremor, detected by everyone with panic and the run out. People stumbling. Glasses, plates and shop windows break. Books,shelves and wall frames falling down. Alarm bells sounds, trees rustling.
VII	**Really loud** tremor. It's hard to stay standing up. Detected by transports drivers. Hanged uo objects trembling.Damages of furnitures and sandy walls. Breaking of chimney, downfall of shingles, parapets and architectural ornaments. Creation of little water waves, turbidity of waters. Strong bells sound.
VIII	**Ruining** tremor. Soft damages to anti-seismic structures, partial damages to ordinary constructions, down-falling of smokestack, monuments, columns overturning of heavy furniture,level changing in pools. Breaking of trees and fences. Deep cracks in rocks land.
IX	**Disaster** tremor. Damages also to the anti-seismic structures, loss of verticality of portable and well designed structures. Building translation from their foundations. Land, cables and underground tubes cracking. General panic.
X	**Very disaster** tremor. Destruction of the most part of wall structures. Strongly land cracking,bended railways, several landslides. Destruction of several rigid wooden structures and bridges. Serious damages to dams and river banks.
XI	**Catastrophic** tremor. Only a few wall structure resist. Bridges destructions wide land cracks. Underground tubes and pipes are out of service. Landslides and collapsing part of lands. Deviated railways.
XII	**Strong catastrophic** eartquake. Total destruction. Objects throned in the air big oscillating waves on the land surface,movements of big rock masses.

Table 1.1: Mercalli Intensity scale [83]

1.2.4 Magnitude Scale: Richter

The American seismologist Charles Francis Richter realized a different scale valuation based on the **magnitude** of the earthquake, understood as an objective measure of the amount of the elastic energy released during the seismic wave. Indeed, expressing the earthquake in a objective and damage-free way on the territory, make itself universally acknowledged and more reliable rather than the Mercalli scale.

In the table **1.2** below, it's showed the Ritcher grades correspondence to the Mercalli ones, and since the Richter scale doesn't measure the earthquake damages effects on people and objects, there's the reference in terms of

" [...]if a tritol charge exploded in the same point where the earthquake happened (hypo-centre)"[27].

Richter Grade	Equivalent Explosion	Mercalli Grade
0	0.5 Kg TNT	I
1	15 Kg TNT (2 Tons lorry crash at 100 Km/h)	I
2	500 Kg TNT (Medium mine of a cave)	II-III
3	15 Tons TNT	III-IV
4	Atomic's Hiroshima Bomb	V-VI
5	20 Kilotons	VII
6	Hydrogen Bomb	VIII
7	20 Megatons	IX
8	1000 Hydrogen Atomic Bombs	X
9	Total energy used in USA in a month	XII

Table 1.2: Richter magnitude Scale in comparison with Mercalli [25]

1.2.5 Seismic Hazard

Seismicity has a proportional directly relation with the **Seismic hazard** for which, much higher is the frequency of telluric movements on a region (seismicity), and much more will rise the probability of an occurring earthquake with an expected *"shaking value"* during a gap of expected time range on a given area.

On 20 March 2003 with the Ordinance of the Prime Minister and Ministers n.3274 published in the Official Gazette *"First elements in general criteria matter for the*

seismic classification of the national territory and technical laws for seismic area building" [72], in Italy started to rise a process of valuation of the seismic hazard of the national territory.
The scientific promoter of this study, the National Institute of Geophysics and Volcanology (INGV), collaborated with the Italian main important universities and other research centres and the result leaded to the creation of the seismic hazard map (MPS04).
This map shows the peak *"ground acceleration with a 10 percentual probability value of exceedance in fifty years, measured on a rigid and flat land in meter per squared second"* [92] 1.1:

$$\mathbf{PE} = 1 - (1 - PA)^T \tag{1.1}$$

$$\mathbf{PA} = 1 \setminus PR \tag{1.2}$$

Where:
PE= Percentual of exceedance
PA= Annual Probability
T= Period of 50 years
PR= Return period of 475 years to a degree on intensity VII MSK
As we can see in the map **1.6**, the areas of the south and the centre of Italy are the main interested in probabilities that a seismic phenomena will occur.

1.2.6 Seismic Risk

It's important not to confuse the seismic hazard with the **Seismic risk** [202] that is, otherwise, a damage-based evaluation even in terms of people, even in terms of economic costs. Seismic risk takes into account the seismic hazard, the seismic exposition and the vulnerability of the buildings. This link it's described by the following equation **1.3**:

$$\mathbf{R} = H \cdot V \cdot E \tag{1.3}$$

Where:
R= Seismic Risk
H= Seismic Hazard
V= Vulnerability
E= Exposition

And while the seismic hazard is a territorial-based component of the seismic risk and then unchangeable, the changeable part for reducing the risk lays on the value of the seismic vulnerability.

1.2.7 Seismic Vulnerability

The term *Vulnerability* is

> *"used throughout this scale to express differences in the way that buildings respond to earthquake shaking. If two groups of buildings are subjected to exactly the same earthquake shaking, and one group performs better than the other, then it can be said that the buildings that were less damaged had lower earthquake vulnerability than the ones that were more damaged, or it can be stated that the buildings that were less damaged are more earthquake resistant, and vice versa"* [83].

It's the changeable component of the seismic risk because it depends on the constructive characteristics of buildings. So, for increasing the seismic safety, it's necessary to make structures safe. In terms of measurements, after an earthquake occurred, the buildings vulnerability is evaluated through the recording of the damages taking into account the intensity scale associated.

But, before an earthquake is always hard to define it: this is the reason why, there have been approved several methods linked to statistics, probabilistic and mechanical bases. In a deeper way, the statistic one classify a given building in function of materials and constructive techniques and depending on damages that affected in the past the same building typology.

The mechanical one, otherwise, studies theoretical models to predict the real building behaviour. And at last, there are experts evaluations that study building behaviours in order to understand their influence on vulnerability.

1.2.8 Exposition

Exposition is nothing but the seismic losses that can be of different typologies such as human lives, buildings and so on. Generally the evaluation of the exposition is based on calculations depending on [50]:

- Number of people living in buildings subjected
- The occurring time of the earthquake

- Escaping or protecting possibilities
- Import of involvement
- The possibility to die after the rescue activities

1.2.9 Seismic Classification

For the the earthquakes effects reducting operations, the Italian Ordinance yet mentioned [72], has based the territorial planning by the virtue of the seismic dangerousness and calculating the seismic classification of each area. The national territory is classified by a four classes table **1.3** in increasing order:

Classes	Description
1	The most dangerous zone: Earthquakes are so strong.
2	Dangerous zone where may happen strong earthquakes.
3	A zone interested in sesimic events, but they are so rare.
4	The less dangerous zone: Earthquakes aren't probable.

Table 1.3: Seismic classification table

Each seismic classes have been attributed of anti-seismic value useful for building planning that's expressed in terms of maximum acceleration in rocks. An upgrade of the study of seismic classification, has lead to the Prime Ministerial Order number 3519 of 2006 about General criteria for identifying the seismic zones and for updating seismic zones lists in table **1.4**. It shows the peak acceleration intervals on rigid land, also known as Peak Ground Acceleration (PGA), with the probability of exeedance of 10 in 50 years [49].
For having a general view, the Department of the Civil Protection has created the Seismic Classification map of the Italian territory showed in figure **1.7**.

Seismic Zone	Acceleration with probability of exceeding equal to 10% in 50 years (ag)
1	ag >0,25
2	0,15 <ag <0,25
3	0,05 <ag <0,15
4	ag <0,05

Table 1.4: Seismic zones according the acceleration peak on rigid ground

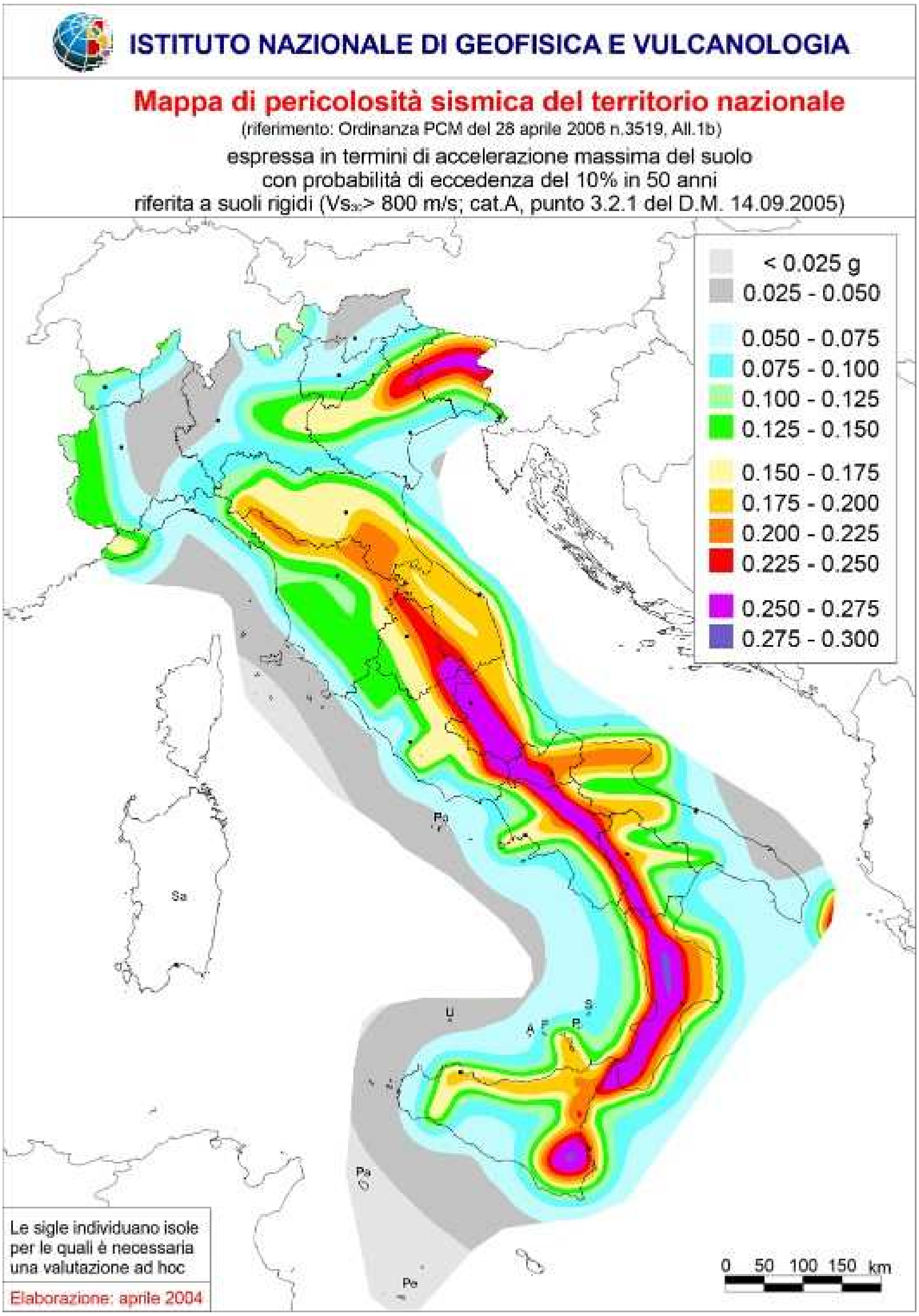


Figure 1.6: Seismic hazard map of Italy, INGV [93]

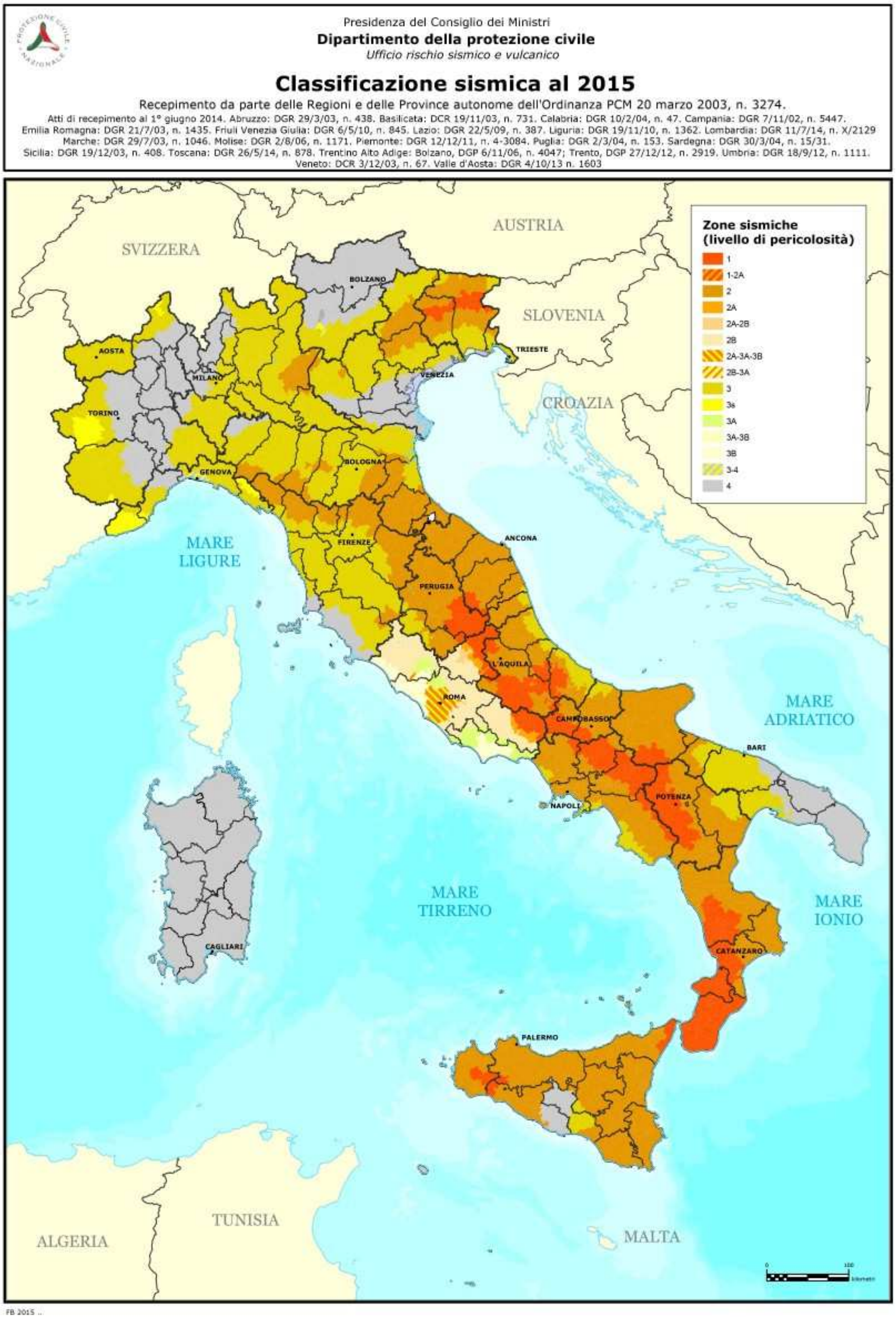


Figure 1.7: Seismic Classification map of Italy [147]

1.3 Sendai Charter for Disaster Risk Reduction

Among the two main categories, the **territorial** risks represent the most dangerous ones about disasters. With the word *"natural hazards"* UNESCO is talking about:

> *"[...] physical phenomena caused by either the rapid or slow onset of events having atmospheric, geologic and hydrologic origins on solar, global, regional, national or local scale"* [200].

But in the general acceptance the **Hyogo Framework for Action**(HFA), natural and human processed origins of disasters weren't specified. An hazard represents:

> *"A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation"* [98].

The **Sendai Framework for Disaster Risk Reduction** in line of succession is the agreement son of the Hyogo Framework of 2005 presented in Sendai, Japan on March 18, 2015 at the United Nations World Conference of Disaster Risk Reduction that aims to guide the disaster management. The charter focused its actions in order of priority [201]:

Priority 1 Understanding the disaster risk

Priority 2 Strengthening disaster risk governance to manage disaster risk

Priority 3 Investing in disaster risk reduction for Resilience

Priority 4 Enhancing disaster preparedness for effective response, and to the three B law "Build Back Better" in recovery, rehabilitation and reconstruction

The triple B policy is framed inside a wider basic concept which is, as already seen in the third priority, the **Resilience** in other words it's known as a synonymous of elasticity and it's the ability of an ecosystem, an organization, a person or a territory *"to respond to a perturbation or disturbance by resisting damage and recovering quickly"* [217].

1.4 The important role of Documentation

From the *material* loss risk is not always possible to safeguard cultural heritage entirety due to the unpredictability of hazards, but, from the *moral* loss risk there are a lot of chances to react preserving the **historical memory** passing through an appropriate documentation testifying to the value and to the existence of the

cultural heritage/property took in consideration.
The birth of contemporary Heritage documentation topic is placed in 1931 with the **Athens Charter**, also known as the first restoration charter, validated in the first International Congress of Architects and technicians for Historic Monuments. It aimed to the improvement of documentation methods creating catalogues where each cultural heritage building must have its own record document containing a photos reportage and notes. We have to wait until 1964 for an international positive feedback about the role of documentation, and the **Venice Charter** , approved by the International Council of Monuments and Sites (ICOMOS), was the *incipit* factor of it. It strongly arose, in the article 16, that in every conservation, restoration or consolidation work, the need of precise documents attached to sketches, drawings and photographies registered in public archives. Of course, everything was recommended to be published in order to be available for researcher teams [91].
Following these principles, there was a long list of other important charters [206] whose tasks were to go in depth about the several applicative fields of the Venice charter:

- 1981: **Florence Charter** about historic gardens
- 1987: **Washington Charter** about conservation of historical cities and urban city centre
- 1990: **Charter for Protection and Management of the Archaeological Heritage**
- 1996: **Sofia Declaration** on the Protection and Management of Underwater Cultural Heritage
- 1999: **International Cultural Tourism Charter**
- 1999: **Charter on the Built Vernacular Heritage**
- 1999: **Principles for the Preservation of Historic Timber Structures**
- 2003: **Principles for the analysis, conservation and structural restoration of architectural heritage**
- 2003: **ICOMOS Principles for the Preservation and Conservation/Restoration of wall paintings**

From the compared analysis of all the charters mentioned above, it's possible to notice the repetitive volunteer to build a **knowledge** made of what we are studying on to have a far-sighted view centered on the need to continue and to update documentations in order to guarantee monitoring operations, the ordinary and extraordinary maintenance and of course, the safe fruition of the cultural heritage building.

1.5 Survey climb: Sofia Declaration

During one of the yet-mentioned charters that followed the Venice one, next to the primary role of documentation of heritage, it started to grow up the awareness that it cannot exist a real complete collection of knowledges coming from different fields without investigations. Although the topic character of Sofia Declaration was mainly centred to the preservation of underwater heritage, it aspired to ensure investigations *in situ* to improve the clearness of each project.
The declaration, furthermore, underlined specially in the final part the big relevance of protecting the sources authenticity, of adopting acknowledged standards and of sharing contents with the public on web platforms, that it's getting easier and easier even technologically and economically speaking. The main topics faced in the declaration were the following:

1. **Why** recording
2. **Who**'s the recording responsible
3. **How** recording
4. **Which** are the contents of recording and how to manage them

1.5.1 Why?

In a deeper way, **recording** must not to be considered as a typical theoretical operation turned to be useful just for the field experts and just considering the architectural documentation. Beside, the survey operations must be seen much more as an *"insurance policy"* towards heritage: it arranges and assures a memory continuity of it during time, even with voluntary changes or not. Thanks to the survey insurance, the decisions quality rate about operations on heritage increases on the increasing of the value comprehension of the heritage itself involving also the population voice in this. Recording, in other words, has its own reason to exist:

- *"As the cultural heritage is an unique expression of human achievement*
- *As this cultural heritage is continuously at risk*

- *As recording is one of the principal ways available to give meaning, understanding, definition and recognition of the values of the cultural heritage*
- *As the responsibility for conserving and maintaining the cultural heritage rests not only with the owners but also with conservation specialists and the professionals, managers, politicians and administrators working at all levels of government, and with the public [...] "* [88].

1.5.2 Who?

About this last sentence reason, the topic of the **responsibility** of the recording operations speaks really clear: it's impossible to find one and only one professional profile to embody all the required skills to achieve this role. On the contrary, indeed, in the responsibility section, at the articles two and three, we read:

- *"The complexity of the recording and interpretation processes requires the deployment of individuals with adequate skill, knowledge and awareness for the associated tasks. It may be necessary to initiate training programmes to achieve this.*
- *Typically the recording process may involve skilled individuals working in collaboration, such as specialist heritage recorders, surveyors, conservators, architects, engineers, researchers, architectural historians, archaeologists above and below ground, and other specialist advisors."* [88]

1.5.3 How?

In this section is fronted the logistic problem of the **planning of recording**. First of all, before every kind of new operation of recording is prepared, it is strictly necessary to examine and analyse the *reliability* of existing sources. Only after that, it would be possible to start choosing the adequate recording method that should be

" [...] appropriate to the nature of the heritage..." [88] and its natural context, and should *" [...] use, where possible, non-intrusive techniques, and should not cause damage to the object being recorded;"* [88].

1.5.4 Which?

What do we know about survey **contents**? If in the previous section of Sofia Declaration arises the importance of the reliability of sources, here it arises the *accuracy* of identification of the building or group of buildings considered such as name, ID code, location that have to be referenced and achieved by reportage, aerial photographs, descriptions, maps, plans and architectural records. Then, it recommends to include in the record some of information contained in a considerable listing:

- *"The type, form and dimensions of the building, monument or site*
- *The interior and exterior characteristics, as appropriate, of the monument, group of buildings or site*
- *The nature, quality, cultural, artistic and scientific significance of the heritage and its components and the cultural, artistic and scientific significance of:*
  - *the materials, constituent parts and construction, decoration, ornament or inscriptions*
  - *services, fittings and machinery*
  - *ancillary structures, the gardens, landscape and the cultural, topographical and natural features of the site*
- *The traditional and modern technology and skills used in construction and maintenance*
- *Evidence to establish the date of origin, authorship, ownership, the original design, extent, use and decoration*
- *Evidence to establish the subsequent history of its uses, associated events, structural or decorative alterations, and the impact of human or natural external forces*
- *The history of management, maintenance and repairs*
- *Representative elements or samples of construction or site materials*
- *An assessment of the current condition of the heritage*
- *An assessment of the conflicts and risks from human or natural causes, and from environmental pollution or adjacent land uses.*" [88]

Chapter 2

Survey Methods Background

Surfing the wave of the most relevant world organization charters, it's doubtless that the importance of documentation has always had for man a strictly link with the necessity and the wish to *" [...] explore, to know and to represent the places where he lives"*[77]. The very first forms of the Geomatics field, such as Geography, were used

> *" Tracing itineraries to reach various places and identifying favourable sites for agricultural use [...]the beginnings of geography, which became a science in the XVI century thanks to the talent and foresight of Leonardo da Vinci".*

However, Geography has also its roots on human phenomena society, the relationships between them and the environment. Since a part of this science extends its contents to interaction, dynamics and subjective perceptions of the system, the **representation** has the task to show the perception of it in a direct and synthetic way. The architectural survey, indeed, drives through the drawing representation, to the current state of the heritage architecture case as it is:

> *"[...] its imperfections prove the techniques and tools inadequacy, its changing prove the history and its different fruition ways; its weaknesses and deformations show its health status"* [14]

exactly like a medical diagnosis on a patient. Survey is an objective representation based on scientific sciences methods that take advantages of the progressive technological tools and computer science increasing flood.

2.1 Geomatics

Geomatics is actually a science of recent birth, since it's a neologism created in the early 1980's in Canada used by the University of Laval to define all the electronic computing and equipment embedded survey and representation sciences. Its first feature lays on the multidisciplinary integration showed techniques approach based on [77]:

- *Computer science*, that processes and represent the information through the technologies (hardware) and the systems (software).
- *Geodesy*, it represents the shape and size of Earth in three ways: one more complete (Geoid),the second a little bit more synthetic (Ellipsoid) and the last it's gravitational-based.
- *Topography* first started with Geodesy, and it's *"[...] a combination of procedures for direct land survey"*[77].
- *Cartography*, it's a description of the Earth surface and its features thanks to graphical and numerical representations.
- *Photogrammetry*, it's the determination of objects position on photographical images.
- *Remote Sensing*, it's the acquisition in a remote way of data about the environment and the territory.
- *Global Positioning System (GPS)*, it's the real time providing operations of a moving object 3D position in Earth surface.
- *Laser scanning systems*, it's an operation for measuring objects and their distance by the incidence of electromagnetic radiation in the optical frequencies.
- *Geographical Information Systems (GIS)*, it's for using ESRI [60] words in 1997: *"A geographic information system (GIS) is a computer-based tool for mapping and analysing things that exist and events that happen on Earth. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies."* [2].
- *Expert System (ES)*, it considers instruments for imitating the experts cognitive abilities of, for example, abstraction, generalization and so on.

- *WebGIS*, it's about the creation and the distribution of on line databases of data and information.
- *Ontology*, it's the description of concepts and the interaction between elements of a same group.

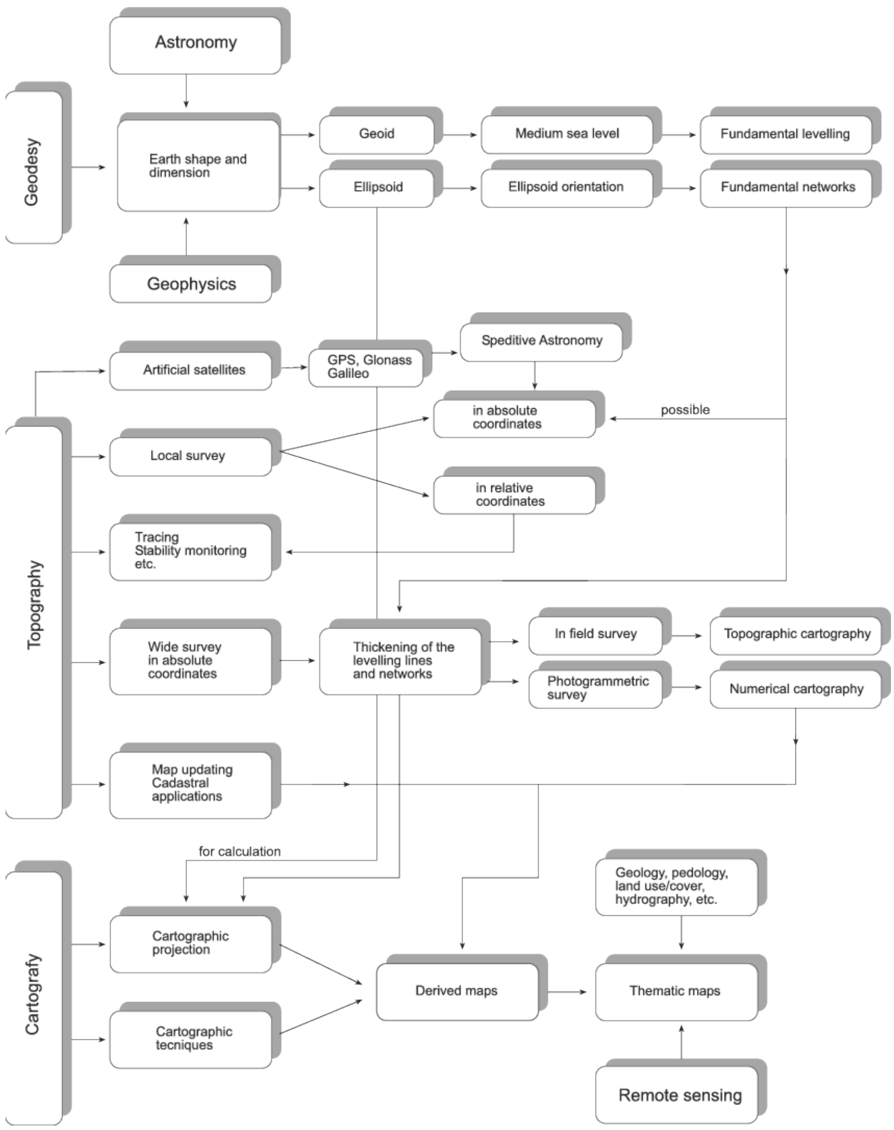


Figure 2.1: Relationship among elements of Geomatics [77]

2.2 Measurement Systems

Which are the main measurement systems? And what are they for? First of all, before answering these questions, it's necessary to be sure to have understood the concept of **measurement**. Measuring a physical quantity is a physical operation that consists in making a comparison between a quantity and another one of the same kind also called *"example unit"* after the choice of the appropriate unit of measure. Thanks to the measure, in other words, a single quality of the object taken in exam has been quantified in a numerical, and so quantifiable way. We can recognize two types of measurements [177]:

- **Direct measure**: the comparison between the physical quantity and the unit of measure.
- **Indirect measure**: it's defined by the interaction between a physical quantity and other directly measurable quantities.

Of course, due to the several measurement mistakes, it's not possible to know the effective value or measure of the physical quantity, and that's the reason why the study about the mistakes covers a big part of the researches in this field. Indeed, it presents a remarkable interest especially in the topographic and geomatics field since the accuracy measures must be extremely pushed towards high limits in order to have a precise choice about the technologies and the tools. We can recognize two system of architectural measurements, but the common aim is to reach the shape and the dimensions of an architectural object or space. But first of all we need to clarify the terms "geometry" and "dimension":

Geometry *"is a branch of mathematics concerned with questions of shape, size, relative position of figures, and the properties of space"* [218];

Dimension *"In physics and mathematics, the dimension of a mathematical space (or object) is informally defined as the minimum number of coordinates needed to specify any point within it"* [215];

Surveying is the common denominator of all types of measurements:

" [...]the technique, profession, and science of determining the terrestrial or three-dimensional positions of points and the distances and angles between them.These points are usually on the surface of the Earth, and they are often used to establish maps and boundaries for ownership, locations [...]" [222].

So, if the common aim is to reach and know the spatial coordinates of points of an architectural space or object, the systems for reaching them, change according to the methods and tools used: [181]

1. **Traditional Architectural Survey**
2. **Architectural Metric Survey**

2.3 Traditional Architectural survey

The architectural survey is nothing but the direct measurement survey applied with traditional tools for distances, differences in height, angles and so on. The two main measurements methods are:

- **Cartesian coordinates method**, or also called "orthogonal coordinates", it consists of tracing an external "support" line parallel to the side to measure: this is supposed to be the x axis. Then, the points to measure are orthogonally projected on it and the distances between every projected point are measured as y axis [53] as it's illustrated in figure **2.2**.

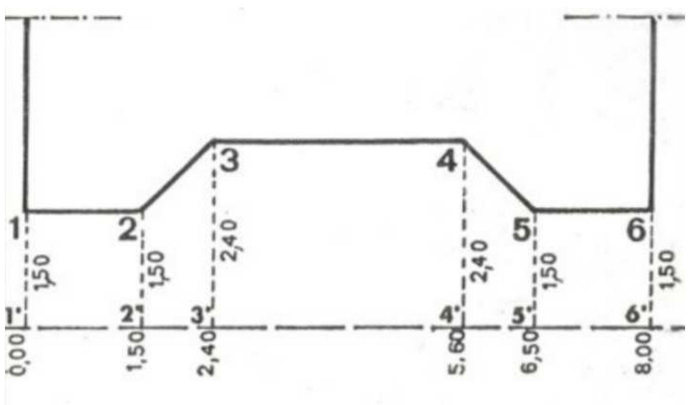


Figure 2.2: Example of the Cartesian coordinates method [53]

- **Trilateration method**, that it's based on the principle of the crushproof of the triangle. It's possible so, to define an unknown point position from two fixed points by taking measurements from that one. In pratical words it consists in choosing two known points that belong to the same reference line parallel to the object to measure. Once the distance between those points it's measured, it's enough to measure the two distances of the triangle in order to define the unknown point on the object [181]. This method is quite used for the survey of complex objects (Figure **2.3**).

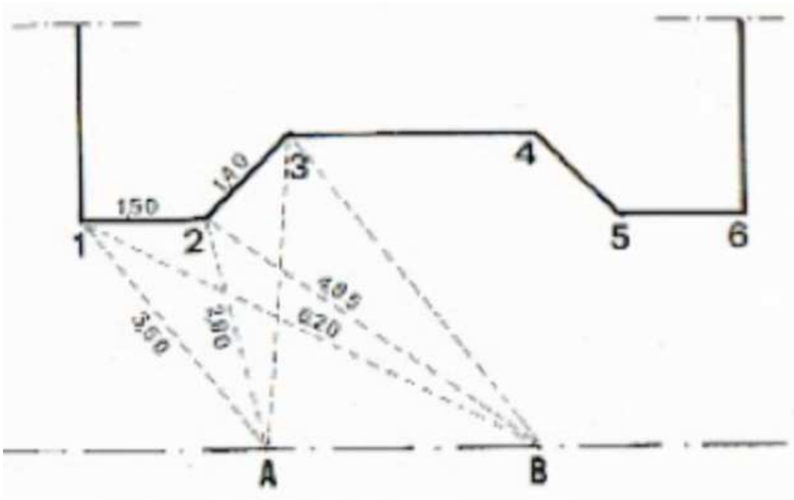
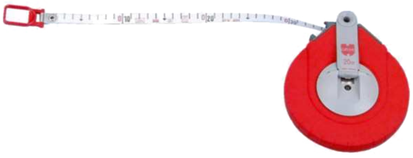


Figure 2.3: Example of the trilateration method [53]

2.3.1 Architectural survey equipments

As reguards the distances survey, we can see in the figure **2.4** the most used equipments:

- Tapes, that can be made of fiber of glass **2.4(a)** or metallic materials like steel **2.4(b)**;
- Telescopic beams;
- Plumbline poles **2.4(c)**, folding rod **2.4(d)** or half-rigid **2.4(d)** tapes;
- Laser tapes (EDM) or *Disto* **2.4(f)**;



(a) Tape in fiber of glass

(b) Steel tape

(c) Plumbline pole [11]

(d) Folding rod

(e) Half-rigid tape

(f) Laser tape (EDM) or *Disto*

Figure 2.4: Commons distance equipments [57]

2.4 Architectural Metric survey

It's an **integration** of the direct survey with topographic, photogrammetric surveys methods [181] and terrestrial LIDAR methods that are considered "indirect surveys" because the measurements are not taken directly on the object surface, but they're taken thanks to appropriate equipments and due to this, they are also considered "instrumental surveys" for their characteristics of taking advantages of other measurements descended from angular values and from intersections of visual rays. Indeed, nowadays it has been acknowledged the concept that architectural and cultural heritage buildings surveying has to be done through this complete integration that it has contributed to give to the architectural survey, the metric-numeric approach such as also the metric-photographic approach [181].
These metric approaches have brought to the determination of essential surveying characteristics like the creation of a *"survey network"* with a topographic reference system and like the *"precision"* of the coordinates points. The first task is to define the points position on the object to measure since the measurement phase will start from that: here it comes the contribute of the topography.

2.4.1 Traditional Topography

From the greek words *"topos"* that means "place", and *"graphein"* that means "writing" [223], it's the science that studies operative methods and equipments that are necessary to represent graphically and in a metric way the Earth surface features. It has a scientific and applicative character, so it's related to maths, geometry and physics.

2.4.2 Angular and distance measurements equipments

For the azimuth angle measurements or zenith distance, there are some particular goniometers that are different by their angular precision [180]:

- *"Tacheometer"* with a precision from 50^{cc} to 100^{cc};
- *"Theodolites"* with a precision from 1^{cc} to 0^{cc};

For the distances measurement there are some Electronic Distance Measurement (EDM) instruments, but as the years passed, the tacheometers, the theodolites and the EDMs have been unified in one equipment called *"Total station"*. This was a great automatic innovation, since the passage from the optic step to the electronic one, has allowed the realization of the reduction of the manual reading and transcription job of the values that was the first cause of measurements errors.

The total station

The total station is an electronic surveying device that allows the measurement and the automatic registration of angles and distances. In comparison with the mechanical-optic devices, it generates innovations thanks to the measurement of the distances and the automatism in measurements reading and registration of them. A total station is made up of four main components similar to the ones of the theodolite, shown in **Figure 2.6**:

Figure 2.5: Total station [106]

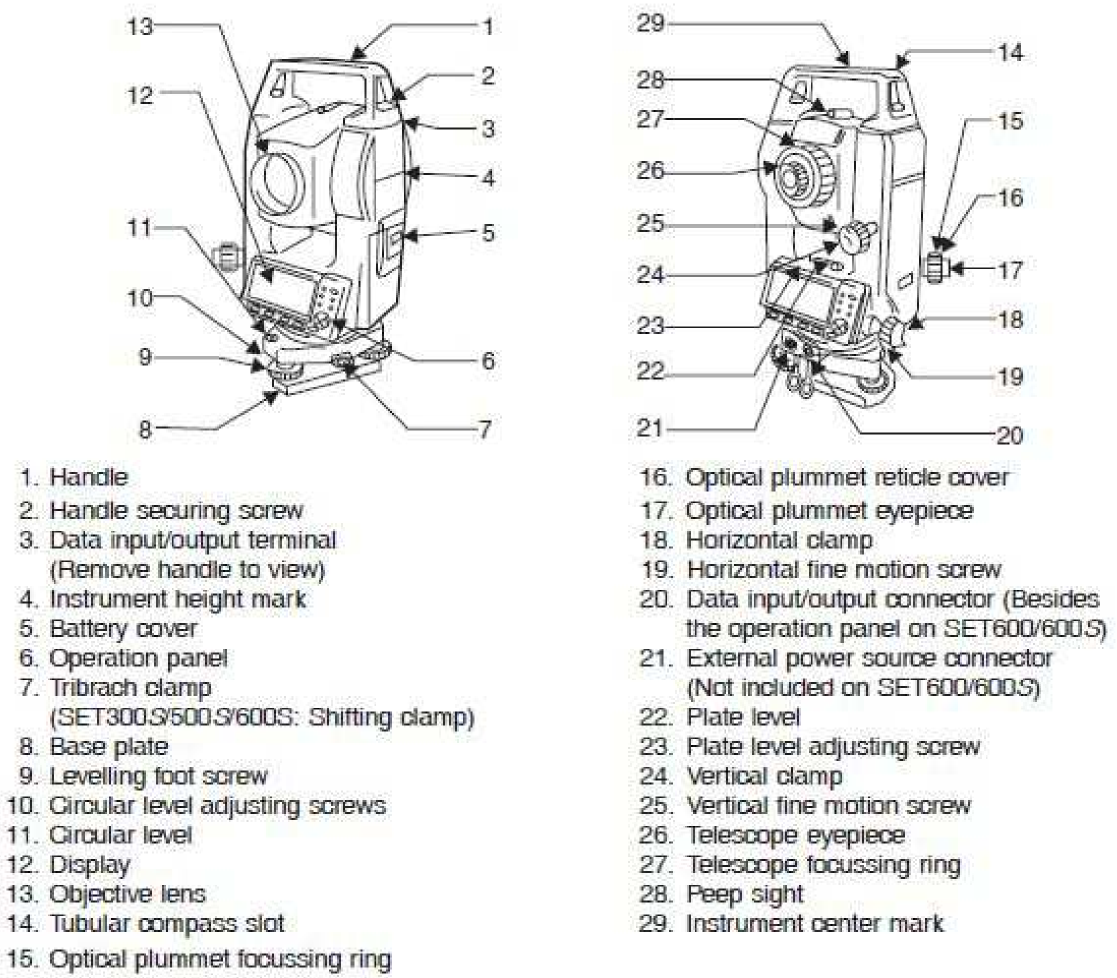


Figure 2.6: Components of the total station [38]

- A **Base plate**, number 8 in **Figure 2.6**, that is a three-cuspid element fixed on the physical support called tripod;
- A **Tribrach clamp**, number 7 in **Figure 2.6**, is fixed on the base plate and it's endowed of three levelling foot screws and a circular level;
- An **Alidade** it's an "U"-shaped element assembled on the tribrach by a little linchpin that allows itself to rotate around its axis. On the alidade are assembled furthermore, the vertical clamp (zenith) and the horizontal clamp (azimuth) with the corresponding angles shown in **Figure 2.7**;
- A **Topographical telescope**, number 26 in **Figure 2.6**, that is an optic instrument assembled between the "U"-shaped extremities thanks to another linchpin that allows itself to rotate around its axis;

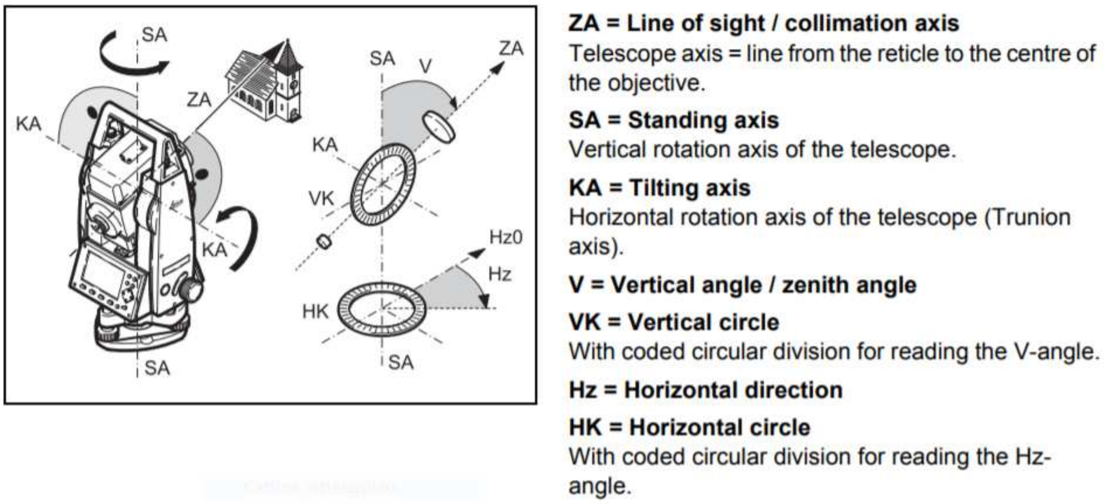


Figure 2.7: Scheme of angles and direction [105]

The geometric scheme is defined by three axis visible in Figure **2.8**:

1. **Primary axis, (a1)** it's the rotating axis of the alidade;
2. **Secondary axis, (a2)** it's an axis perpendicular to the a1 and it's the rotating axis of the topographic telescope;
3. **Third axis or Collimation axis, (a3)** it's an optic axis perpendicular to the a2 and it's included in the a1 plane.

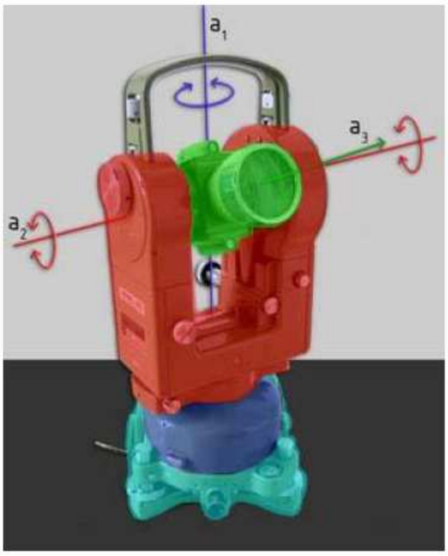
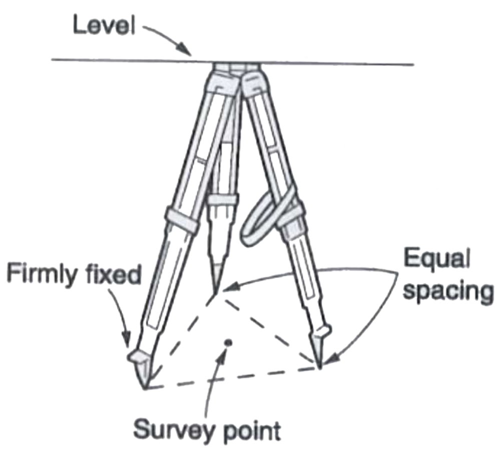


Figure 2.8: Scheme of the components and of the axises of a Total Station [180]

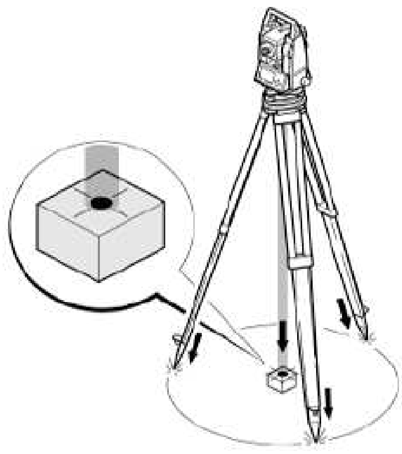
The operative phases of the total station can be sumerized in the following steps also described in **Figure 2.10**:

Figure 2.9: Operative phase [106]

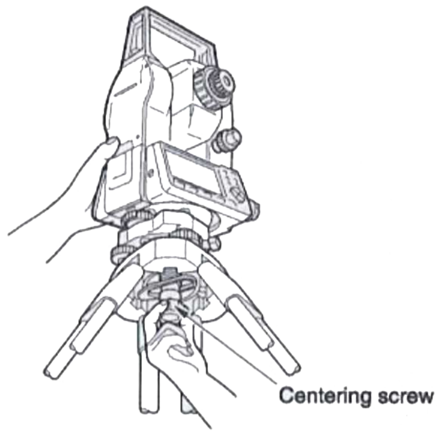
- **Station placing**: the levelling operation is quite important to reach a sufficient accuracy, it's necessary to make sure that every target is visible from the station. A necessary condition is that the primary axis of the station must be as vertical as possible and the station axis must coincide with the vertex on the terrain because from that vertex every measurement is referred.
- **Tripod setup**:in this phase the tripod legs must be equally spaced like forming an equilateral triangle and it's important to make sure that the head station should be directly on the surveying target.
- **Mounting operation**: the total station must be placed on the tripod and secure with with a centring screw.
- **Circular levelling** (tripod legs adjustment): now it's important to level the station together with the tripod, so the survey point must be centred with the optical plummet reticle and the tripods legs must be adjusted by centring the bubble in the circular level [55].
- **Plate levelling**, it's important to loosen the horizontal clamp and to turn the station until the plate level bubble centred using the level foot screws.
- **Collimation**: the collimation of a point means to have a coincidence between the collimation axis of the telescope and the point to measure [180].



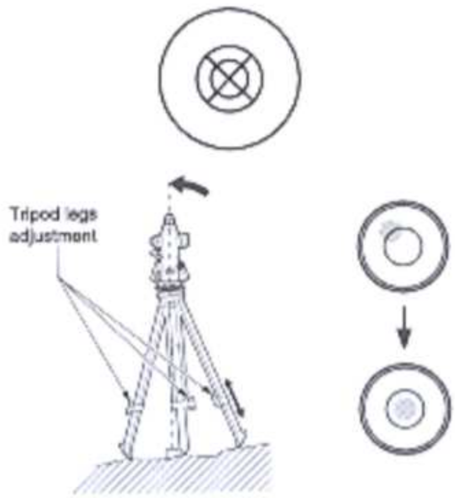
(a) Tripod setup phase [55]



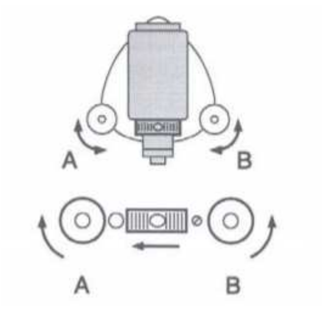
(b) Centering the terrain vertex [152]



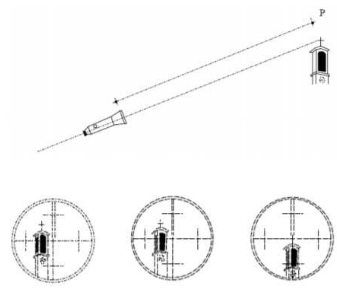
(c) Mounting operation [55]



(d) Circular leveling phase [55]



(e) Plate levelling phase [55]



(f) Collimation phase [180]

Figure 2.10: Operative phases of the total station

2.4.3 Topographic Survey methods

The term **"Survey"** defines the architectural, historical, urbanistic and geometrical features of an object or a territory area [111]. Topographic survey methods like

- Traverse

are based on the **spatial localization** of a certain number of points on the object/territory that allow its representation and its use. It's necessary to define the relative position of all the points to design a *"Relativity field"*: if the object of surveying is the territory, this one could be included in a global, national or local cartography network. Indeed, we call **vertexes** the points whose coordinates are already known in a global, continental or national systems.
The measurement operation that allow to know, in the survey area, the coordinates of some points in both systems (the relative and the global one) is called **Geodetic Control Network**.
Furthermore, it's important to consider that these topographic methods determine just the planimetric coordinates of vertex, indeed for determining the third coordinate (the difference of height) it's necessary to operate the Trigonometric Levelling method [179].

Traverse

Traverses segments have a geometric scheme that consists of a segmented line that links together several unknown points to survey but with starting and final coordinates points already known. We can recognize two kinds of traverses networks:

- **Geodetic traverse network**, if the segments measured are not more than 10 km;
- **Topographic traverse network**, if the segments measurements are from few kilometres to 10 m;

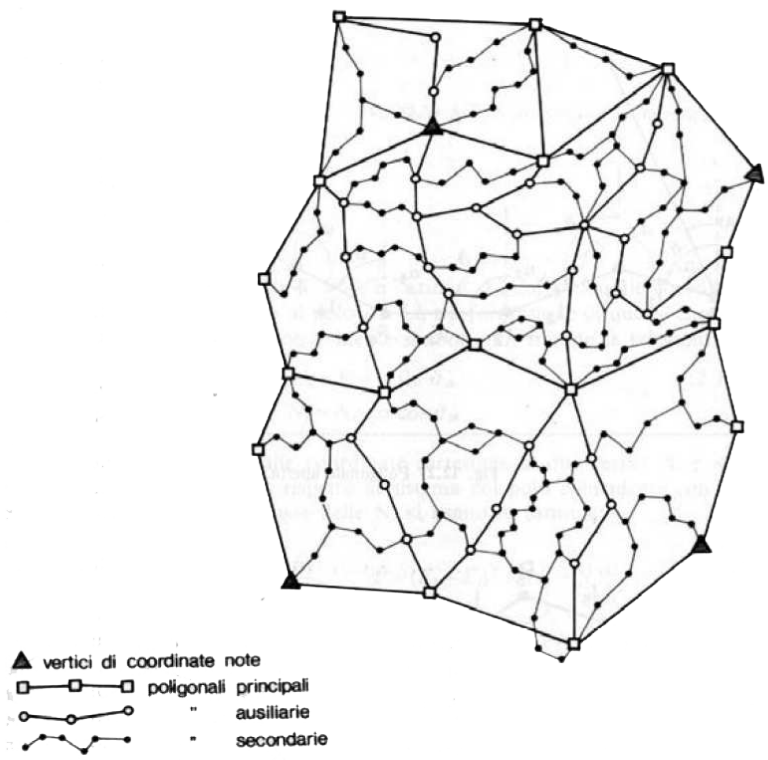


Figure 2.11: Traverses network example [179]

2.4.4 The traditional Topographic method

With the term "traditional" in Topography I'm talking about the creation of the topographic network for the measurement process of the vertex thanks to total stations.
The main role of the topographic network is to provide a **Unique Reference System** for the entire surveying mission [179]. There's to consider that for the measurement and the calculation of the topographic vertexes it's always used the the calculation of the determinations thanks to the Bessél rule repeated more times. This helps to reduce the systematic errors influence.

2.4.5 The modern Topographic-Photogrammetric method

In a schematic way the integration between the topographic- photogrammetric method is made up of four fases:

1. **Creation of a Geodetic Network** that is a GPS network linked to the National Geodetic Network IGM95;
2. **Creation of a High Precision Geodetic Network (HPGN)** that is a high density GPS network supporting the first one;
3. **Ground Control Points Network**
4. **Detail Metric Survey** that leads to the photogrammetric restitution and its phases can be sumarized by:
    - Survey and calculation of the Geodetic Network for the reference system definition;
    - Survey and calculation of the elective high precision geodetic network;
    - Detail survey;
    - Digital plotting of plans, sections and fronts.

2.4.6 LIDAR technology

Laser scan systems or commonly known as **Light detection and ranging systems (LIDAR)** are reaching nowadays high levels of application and diffusion thanks to the big automatism component and to the short times of acquisitions even in cases of complex objects. This new generation method marks an important methodological overturning in comparison with the topographic and photogrammetric techniques and it'll induce in future great changes in the 3D modelling field [36]. According to the object to survey many operative conditions are on:

- **TLS**: Terrestrial Laser Systems
- **ALS**: Aerial Laser Systems

LIDAR derives from the measurement system of the distances through electromagnetic waves (EDM) but it's based on the laser ray incidence on objects. The **Laser** (Light amplification by stimulated emission of electromagnetic radiation) it's a monochromatic and then composed by only one frequency of light. Furthermore, it's coherent (spatially and temporarily), that in the optic field it means that the signal moves towards a unique defined direction (unidirectional) by waves of the same frequency and of the same phase that adding together create a ray of light.

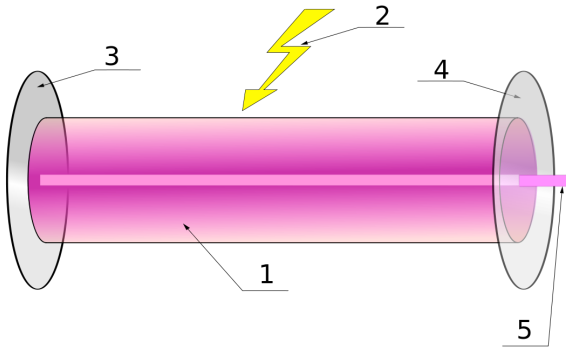


Figure 2.12: Laser components [220]

- 1. Optic means
- 2. Energy stimulating the optic means
- 3. Mirror
- 4. Half-reflect mirror
- 5. Laser ray

The introduction of the parameter **Acceptable Emission Limit (LEA)** helps to consider different classes of dangerousness about the lasers: the one used for the LIDAR methods is included in the class number 1 of the table **2.1** below.

Class	Dangerousness
Class 1	In this class are included all the socalled "intrinsically safe"
Class 2	It's important not to watch to the laser ray
Class 3A	It's important not to stare at the laser or to whatch directly witj optic devices
Class 3B	The sight at the laser ray is always dangerous
Class 4	It's important to avoid the direct or reflect eye and skin contact to the laser ray

Table 2.1: Laser dangerousness table [174]

Laser scan systems are divided into two categories:

1. **Distance systems**
2. **Triangulation systems**

(a) 3D Focus distance Scanner

(b) Handyscanner

Figure 2.13: TLS Scanners [64]

The **distance system** or **range scanner** (Figure **2.13(a)**)uses the same measurement principle of the total stations, in other words every point is measured by the direct measure of two angles and a distance. This one is determined by the measure of the **Time of flight (TOF)** or by the measure of the **Compensation of phase** between the radiated and the reflected wave.
The **triangulation scanners** (Figure **2.13(b)**) are based on the principle of measure of the photogrammetry: a point object is measured by the intersection of two straight lines with a known direction in the space.

Time of flight

The laser emanates several impulses (through a double rotating mirrors system) towards the surface to survey and the time between the transmitted signal and the received one is measured. The distance between the centre of the instrument and the object point hit by the laser is determined by the TOF.

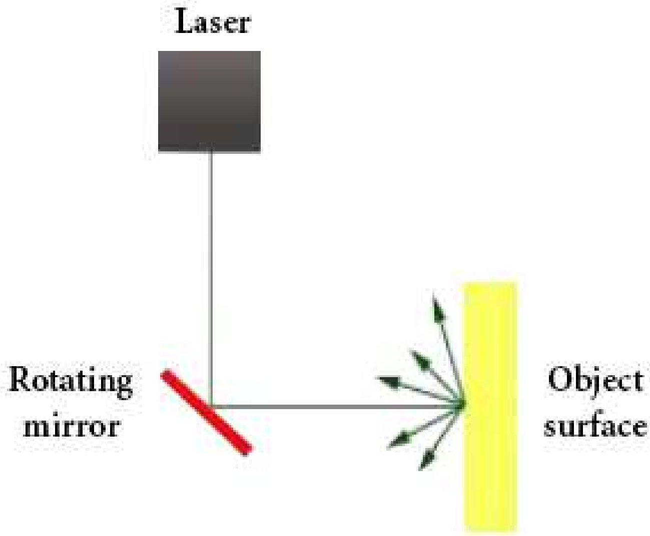


Figure 2.14: Time of flight [174]

Compensation of phase

It's a similar method of the TOF. The distance is indirectly calculated by knowing the wave length and by measuring the difference of phase between the initial wave and the final thanks to a phase compensation device.

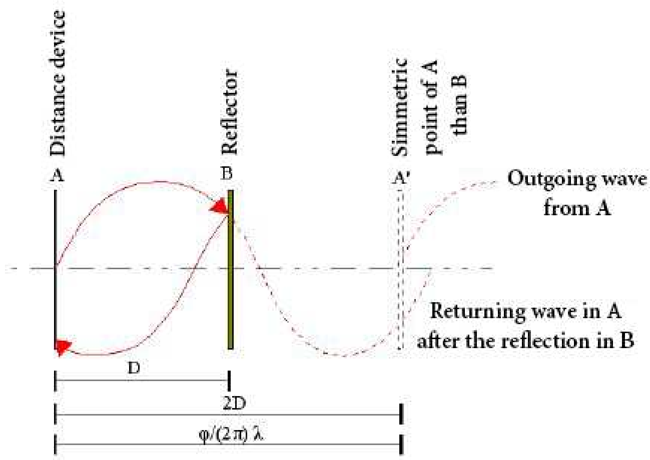


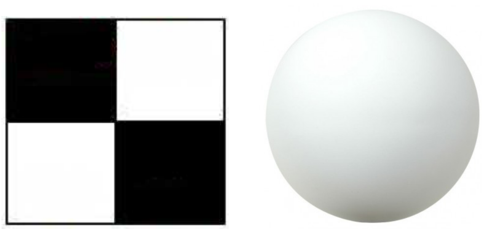
Figure 2.15: Compensation of phase [174]

2.4.7 LIDAR acquisition

The acquisition system is totally independent from the object characteristics: the object points are practically defined by certain and constant angular distances in order to record exuberant amount of information and points. Indeed, in laser scan systems the measurement of points is performed through spheric coordinates and the difference with the topographic systems is the lack of collimation telescope, so it's no more the user required to choose the number of points to survey. It's just important to choose the right positions of recording for a complete coverage of the area to scan.
Now it's possible to:

- Define the inclination of the rotating mirror in the wanted direction;
- Define the interested area of the LIDAR mapping;
- Define the points density to record (in other words the distance of the scans);

And since the position of recording for each scanning is different, this determines the need for the **point-clouds** to be **registered**. The sufficient condition for the **transformation** (the scan position and the orientation) is the presence of at least three common points for each scan.
The coordinates are assigned to a chosen reference system for the registration that can be the system of a particular scan chosen as reference, or an external system extracted from the topographic network. For operating the spatial transformation or in other words, the **roto-translation** of the scans in another reference system is important to mark particular reference points or objects.
Infact, the common references are natural features like corners, angular points, geometrical, visible parts and they are highlighted by square chess-boarded papers o spheres called **targets** (Figure **2.16**).



(a) Chess-boarded target **(b)** Sphere target

Figure 2.16: Targets typologies

Targets can be measured by topographic ways: this technique, important for the geo-reference operation, requires long times of acquisitions and registration for each target for the identification of shapes and contrasts, but doubtless it guarantees higher accuracies [174].
The point-clouds treatment consists of few steps that will be treated in a specific way in the case study chapter.

- Naming the targets for each scan;
- Filtering the point-cloud with a reduction of the number of points;
- Alignment and registration of all the scans;
- Geo-referencing operation;
- Segmentation of the point-cloud;
- Integration with other survey contents;
- Modelling;

2.5 GPS/GNSS Systems

GPS is the acronym for **Global Positioning System** a *"space-based radio-navigation system"* [219] and its aim is to determine the position (Geo-location) and time information of every point on the Earth's surface by the position of several satellites. The **measurement operation** of a Global Position System consists of determine the time that takes the satellite signal to reach the terrestrial GPS receiver. A GP System is made up then of different segments:

- **Space segment (SS)** composed of 31 satellites of the GPS constellation orbiting on unmovable orbits around the Earth at 20.000 km of height. For each satellite it's known the position in matter of *X, Y, Z* geocentric coordinates.

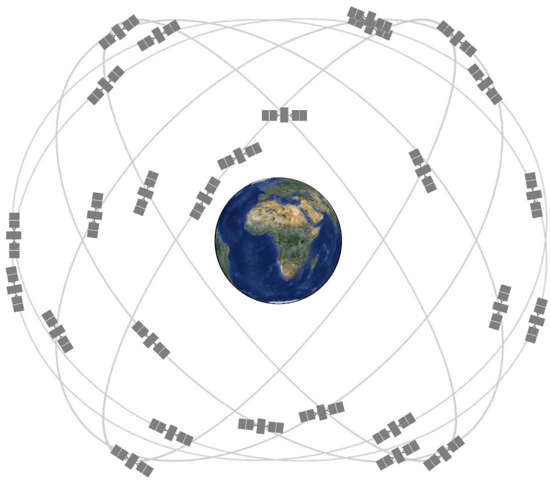


Figure 2.17: GPS satellites constellation [129]

- **Control segment (CS)** composed of monitoring terrestrial stations whose aim is to supervise the satellites positions, since the distance between the Earth's point position and the satellite is known only by knowing the satellite itself correct position and the determination of the real orbits of them[175].
- **User segment (US)** that are GPS Receiver devices for determining for each satellite **Si**, the state of out-phase of the time Δ_{Ti} that results on the receiver device and the time travelling with the signal received by the satellite.
  GPS receivers are made up of an antenna that is tuned to the satellites frequencies, a receiver-processor and a high precision clock. Sometimes they provide also a graphical screen to give users information about the geolocation and the speed.
  The distance **D** between the satellite and the GPS receiver device is obtained by multiplying the out-phase of time and the speed of propagation of the electromagnetic waves of the satellite signal (**2.1**).

$$D = \Delta_{Ti} \cdot v \tag{2.1}$$

The current GPS satellite group counts of 31 active satellites out of 71 firstly launched and it belongs to several satellite constellation for the Geodesy field. But there are also other examples of other different satellites constellation:

- **Navigation and Geodesy**
  - GPS, owned by the US government and operated by the US Air Force;

- GLONASS, or Global Navigation Satellite System (GNSS) is owned by the Russian Federal Space Agency;
- Galileo, is currently created by the European Space Agency (ESA);

- **Telephones services**
  - Iridium communications, owned by USA;
  - GlobalStar, similar to the Iridium;
- **Remote Sensing**
  - Disaster Monitoring Constellation for International Imaging (DMCii), operate for Algerian, Nigerian, Turkish, British and Chinese governments [216];
  - RapiEye, is a five observatory satellite constellations owned by Germany;
- **Messaging service**
  - Orbcomm is an American company offering internet communication services;

2.5.1 Determination of a point coordinates

The determination of the coordinates of a point on Earth's surface (Figure **2.18**) comes from the signals **satellites intersections**. It's possible to solve a three equations system, where the variables are the coordinates of the point P.

$$\begin{cases} D_1 = \sqrt{(X_P - X_1)^2 + (Y_P - Y_1)^2 + (Z_P - Z_1)^2} \\ D_2 = \sqrt{(X_P - X_2)^2 + (Y_P - Y_2)^2 + (Z_P - Z_2)^2} \\ D_3 = \sqrt{(X_P - X_3)^2 + (Y_P - Y_3)^2 + (Z_P - Z_3)^2} \end{cases}$$

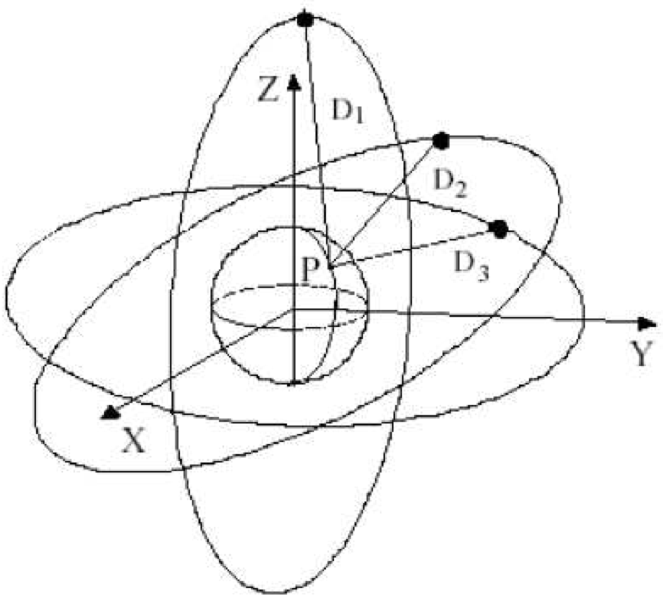


Figure 2.18: Point position on Earth's surface [175]

While, the constant terms of the system are represented by the satellites coordinates and the distances between each satellite and the point on Earth's surface .

$$\begin{cases} S_1 = X_1; Y_1; Z_1 \\ S_2 = X_2; Y_2; Z_2 \\ S_3 = X_3; Y_3; Z_3 \end{cases}$$

$$\begin{cases} D_1 = \frac{\Delta_{T1}}{v_1} \\ D_2 = \frac{\Delta_{T2}}{v_2} \\ D_3 = \frac{\Delta_{T3}}{v_3} \end{cases}$$

From a geometrical point of view, after having determined the distance (D_1) from the first satellite, it's sure to consider that the point P belongs to a sphere with ray D_1 (R_1) and centre in the centre of the satellite itself. If we measure a second satellite distance (D_2 or R_2) the point P will belong to the intersection between the two spheres. A third distance D_3 (R_3) and the intersection of a third sphere lead to the determination of two possible locations for the point P.
For this reason it's important to determine with accuracy the point P location by fulfilling the ambiguity and the precision with a fourth intersection of a fourth

satellite. With use of calculation software that takes into account all the systematic and accidental errors, the precision of positioning of a point could be of few centimetres.

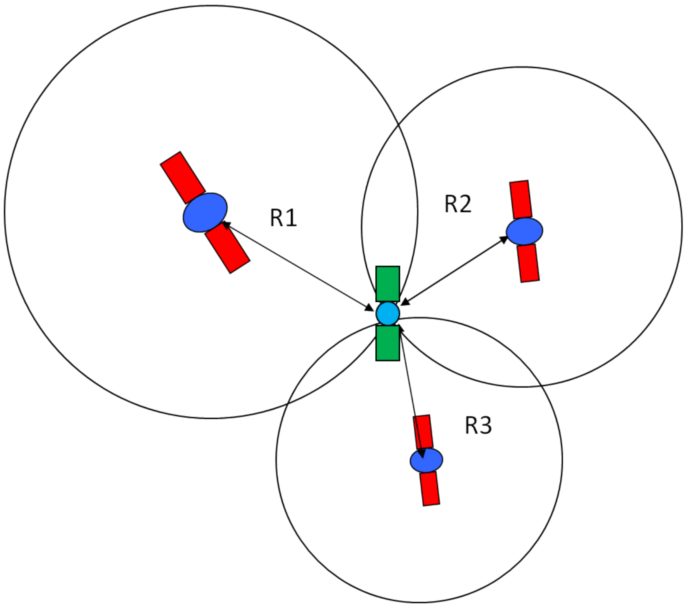


Figure 2.19: Intersections of satellites sphere for determining a point position [130]

GPS Errors

The main GPS errors typologies can be summarized in:

- **Ephemerides errors**, it's the orbits variation rather than the designed orbits;
- **Time Biases**, errors or distortions of the resulted information due to the satellites clocks;
- **Delays due to the Ionosphere and the Troposphere**, it's a slowing down of the transmission speed of the electromagnetic waves due to the density difference of the atmosphere;
- **Selective availability**, these are deliberate errors made by the Defence Department for security reasons: in 1990 indeed, the US military started to avoid the possibility for the enemy forces to use the accuracy positioning of the global GPS signals by offsetting, in a intentional way, satellites clock signals of a random amount to make them loose the realistic positions [214];
- **Multipath signal**, the signal could not reach the GPS receiver but it could be reflected or split due to some obstacles;

2.5.2 Differential Global Position System (DGPS)

Many of the yet-cited errors can be solved thanks to differential GPS technique. It's an improvement correcting method to the GPS in terms of location accuracy (from the 15 m of GPS to the 0,10 m of DGPS [214]) and speed of transmission.
For determining, for example, the position of a group of points, such as in a **topographic network** for a cartographic survey, it's commonly used simultaneity a two receiver devices system (Figure **2.20**):

- **Base Station or Reference Receiver** whose coordinates are known.
- **Rover Receiver or Project Point** whose coordinates are unknown.

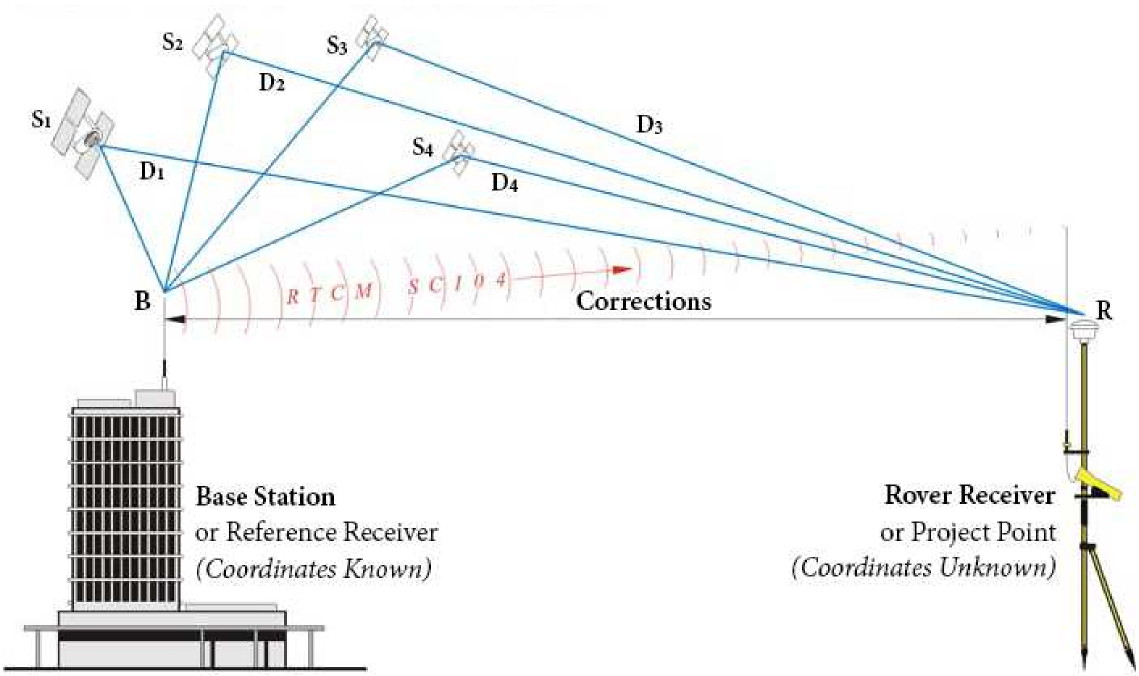


Figure 2.20: Differential GPS method [137]

The correction values are used to calculate, post survey or in remote mode, the exact position of the unknown point. The positional accuracy is about $\simeq 2$ m. This method can be used in a **static mode** [175] or **movable mode** with mobile rovers such as boats, air-planes or surveyors with rover receiver for land survey. But also in the 3D metric survey missions, this method has found a great use for the ease of GPS system for the realization of triangulations or geodetic networks.

2.5.3 Real Time Kinematic (RTK)

The RTK satellite navigation is a satellite technique used to improve and correct the other satellites precision about the the time and location information derived from navigation and geodesy satellites constellations as GPS, GNSS and Galileo. For the measurements it uses the position of a point in time of the signal of the electromagnetic carrier wave rather than the content of the wave itself. Then thanks to the reference station the corrections are provided in real time (Figure **2.21**) for calculating the unknown point. The positional accuracy is more precise thank the DGPS, it's about $\simeq$ 0,02 m.

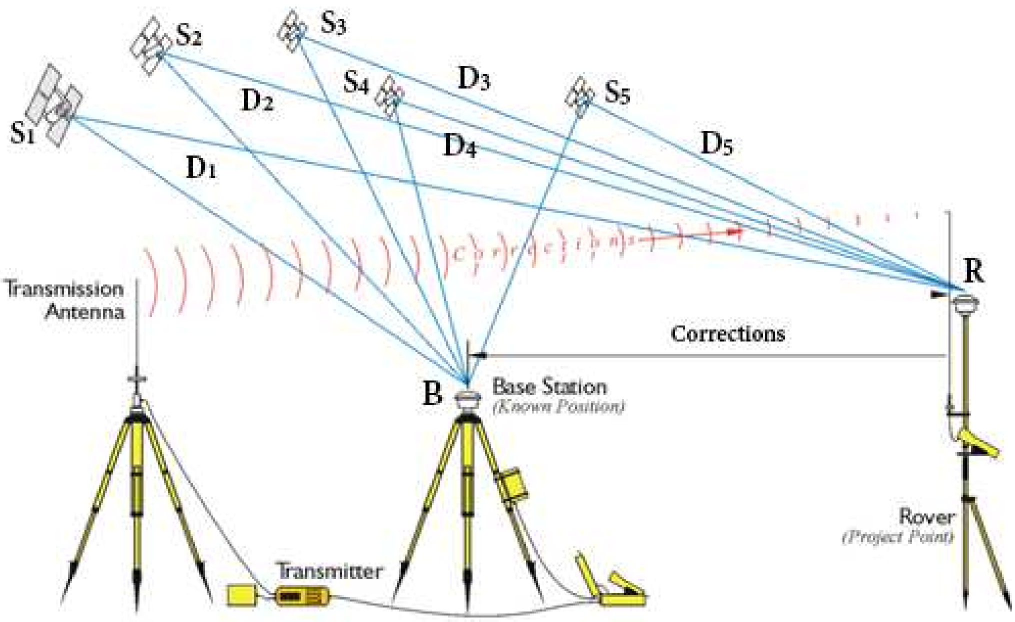


Figure 2.21: RTK method [138]

2.5.4 Photogrammetry hystoric framework

Photogrammetry is:

"a technique that allows the measurement of an object without touching it. Measurement can be performed in two and three dimensions (2D and3D) exploiting both photograms (analogical images) acquired by traditional photogrammetric cameras and digital imagery" [77].

In first place it was born for architectural surveys, but nowadays it's spreadly used for topographic aerial mapping and for military services. It all started in 1839 when Louis Jacques Mande-Daguerre impressed for the first time real object on a photography film. But *”the step from the ground photography to the aerial photography was made by G. Fèlix”* [77], he was one of the first to understand the big possibilities of the aerial photography applications. Indeed, in 1856 he equipped an aero-static balloon to perform the first acquisition on Paris and he is also known to have used this kind of unconventional method for **military spying services**. Other first military services methods, were about the use of pigeons (**2.22**) that were equipped with cameras and trained to fly back to the starting point. But the birth of the photogrammetry as technique is for merit of the French colonel Laussedat who in 1859 presented to the Academy of Sciences a research about the possibility of extract the coordinates of points from a pair of photographs and basing this assumption on geometrical intersections and properties[77].

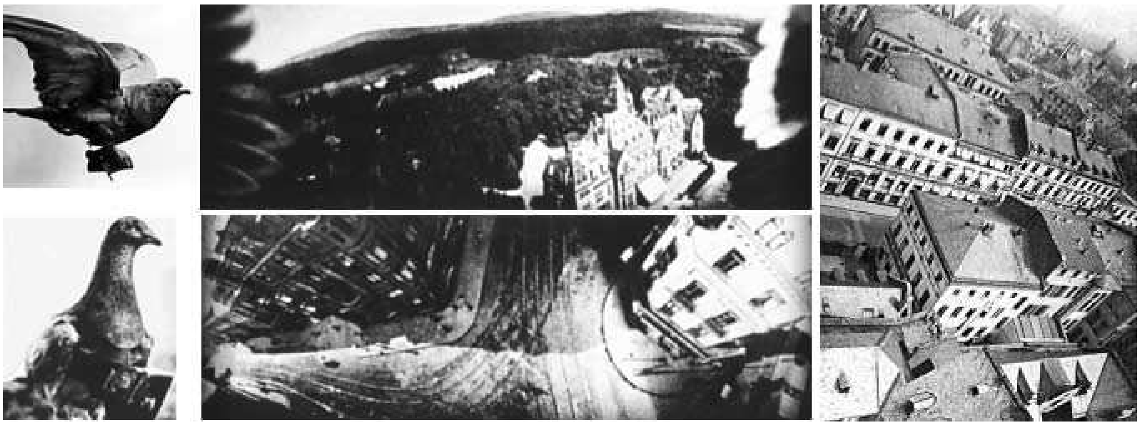


Figure 2.22: Aerial photography with pigeons [136]

2.5.5 Photogrammetric phases

In general and in a schematic way the photogrammetric method is made up of three phases. Furthermore, it’s important to have an external topographical network for allowing the orientation of the system.

Image acquisition it’s the recording moment of the frame images;

Orientation phase its aim is to determ the parameters of the analytic interactions between the object points and the image points;

Plotting phase it includes several operations:

- Measurements on the stereoscopic model
- Determination of the 3D coordinates of the object points;
- Control of survey contents;
- Graphic final elaborations;

2.5.6 Geometric concepts of Photogrammetry

The traditional photogrammetry has always considered that the images, called *frame images* are generated by a single **central perspective geometry** and are used for metric aims (Figure **2.23**). Whatever is the location of the two geometric elements, the central projection produces a mutual correspondence with the object points (3D) and their 2D projections (image points). The analytical relation between homologous points (correspondent points), changes according to the geometrical conditions of the object in exam, to the centre and to the plane of projection [178].

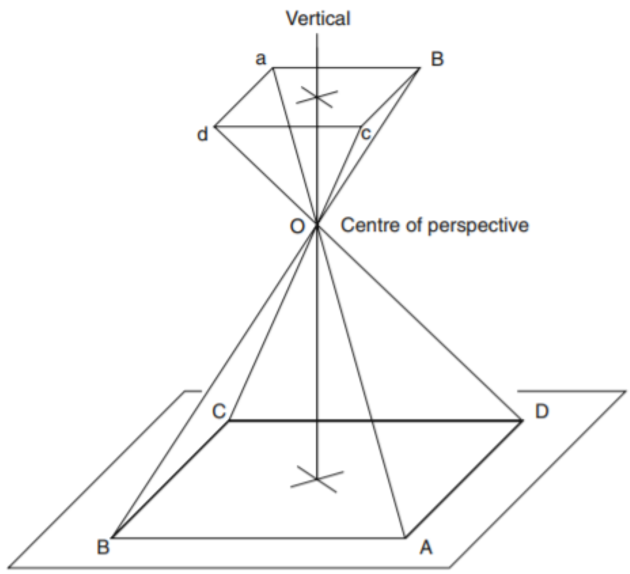
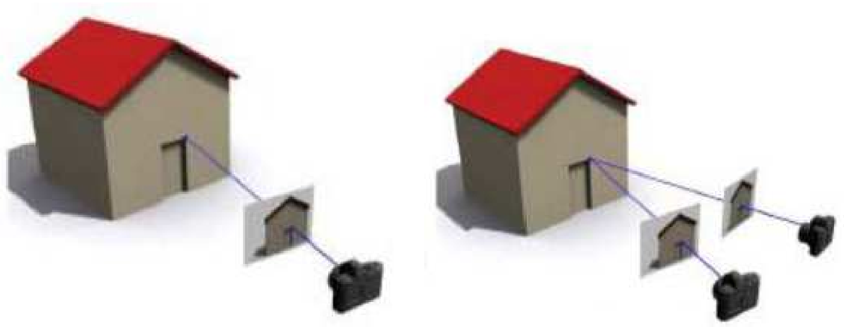


Figure 2.23: Central perspective that takes in relation object and acquisition[77]



(a) (b)

Figure 2.24: Frontal image (a) and stereoscopic acquisition (b) [178]

It can be distinguished in:

- **Aerial photogrammetry** it's performed by above the Earth's surface. So, the camera can be on an aircraft or other aerial vehicles. In this point of view, indeed, the aerial or satellites belongs to the **Remote Sensing** in other words measurements techniques that allow the acquisition with any physical contact. Today the main applicative fields of the aerial photogrammetry can be itemized in the table **2.2** below.

Aerial Photogrammetry
National cartography (1:25000 and for the charts at the scales 1:50000 e 1:100000)
Technical regional cartography (scales 1:5000, 1:10000)
Technical urban cartography (scales 1:500, 1:1000, 1:2000)
Tematic cartography at different scales (ex.. Geologic, Hydrologic, or land use)
Numeric cartography and GIS databases
Orthophotos
Digital terrain models (DTM)

Table 2.2: Main applicative uses of the aerial photogrammetry [178]

- **Terrestrial Photogrammetry** or **Close-Range photogrammetry**, if the images are referred to the Earth's surface and it's performed by using cameras that generally are positioned at the ground level. In table **2.3** is possible to have a synthesis of the common uses, but in general the use of terrestrial photogrammetry has many advantages for object located at inaccessible or hardly accessible for limited time periods sites such as archaeological sites or post emergencies sites.

Terrestrial Photogrammetry
Close range photogrammetry
Architectural and archaeological photogrammetry
Engineering photogrammetry for structural monitoring and hazard emergencies
Mobile mapping

Table 2.3: Main applicative uses of the terrestrial photogrammetry [178]

According to the **data representation** source, we can recognized three types of photogrammetry that correspond also to the three historical phases of this technique:

1. **Analogical Photogrammetry**, also called **Stereo-photogrammetry** it used particular devices, *stereo-plotters* (Figure **2.25**), optic-mechanical devices, thanks to them the frame images are arranged in analogous and similar positions to the ones of the acquisition moment phase. This spatial position is intentionally reached in a as similar human-eyed mode as possible: the stereoscopic mode.

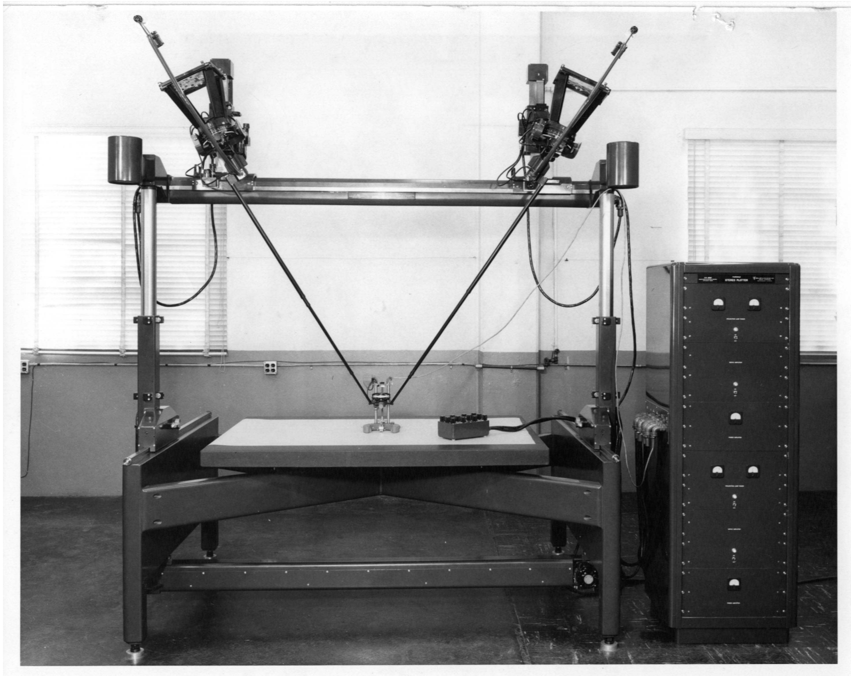


Figure 2.25: Analogical Stereo plotter [190]

2. **Analytical Photgrammetry** is defined the calculation of the *X, Y, Z* coordinates of a object point in function of the X_1, X_2, X_3 2D coordinates of the image frames on films that are translated in numeric matrixes thanks to an *analytical stereo-plotters* equipped with collimation microscope (Figure **2.26**).

Figure 2.26: Analytical Stereo plotter [190]

3. **Digital Photogrammetry**, the latest phase that has developed not only due to the performing wave of digital images and dedicated *work-stations*, but also thanks to the new developments in the computer science fields and the consequent creation of algorithms for the automation of the photogrammetric processes [178].

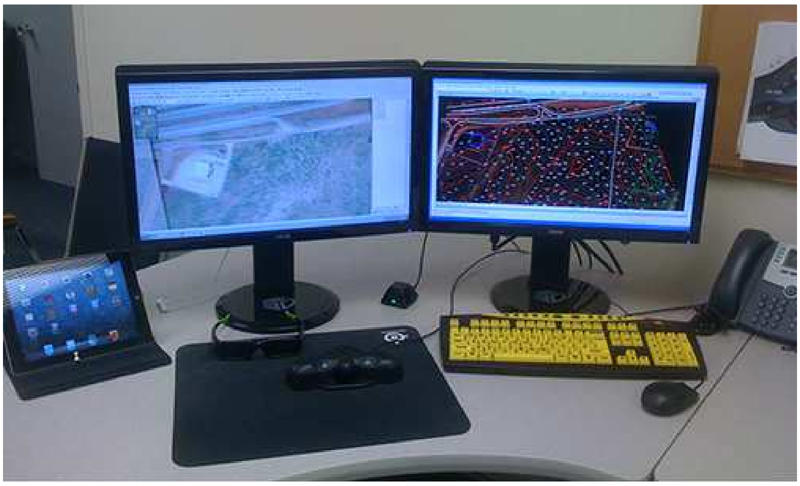


Figure 2.27: New generation work stations[190]

The digital photogrammetry innovations in comparison to the Eighties and the Nineties consist of the exclusive use of **digital images** and no more image frames. Another advantage is in the restitution phase: it's no more necessary to have expensive devices but now the calculation process is managed by software in personal computers with digital devices for the restitution. And as a consequence, calculation processes are much easier than before.
The digital image is made up of **numeric information** (radiometry): the **Raster** representation, in **Figure 2.28**, is divided into elements of set dimensions called **pixel**. Every pixel included the number that represents the radiometry for that part of digital image [178].

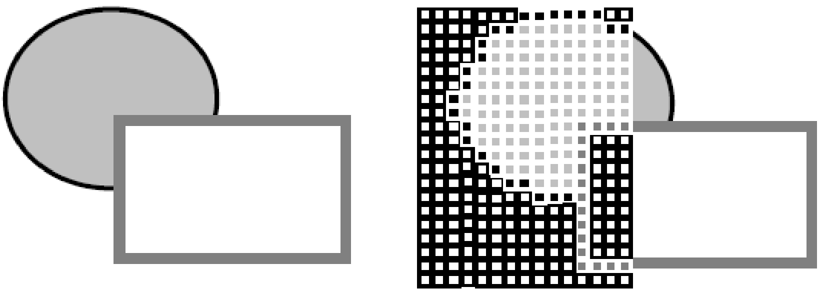


Figure 2.28: Comparison between an image frame (left) and a raster image (right) [178]

So, since the pixel has set dimensions (D_x, D_y), it's possible to have a mutual correspondence between the pixel position on the digital image and the coordinates couple *x, y*.

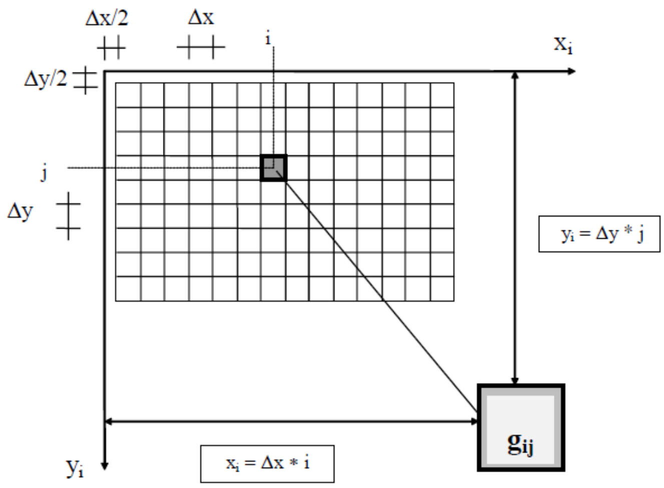


Figure 2.29: Pixel calculation [178]

Thanks to the numeric origin of raster images that allowed a fast developments of computer vision fields and automation processes, it has been created artificial intelligence procedures such as **algorithms** in photogrammetry for the auto-correlations of images and their orientation.
Indeed, the **Image matching** and the **Features extraction** algorithms, such as *SIFT (Scale Invariant Feature Transform), SURF (Speed Up Robust Feature)*, operate an homologous points auto-correlation that consist of a statistic comparison of the radiometry contents of pixels in the point neighbourhood in several images of the same object.
The great innovation of Image Matching elaboration [29] relies on the possibility to create a 3D point-cloud based model and a realistic textured mesh of the object starting from the digital photogrammetry [176] as the **Figure 2.30** below shows.

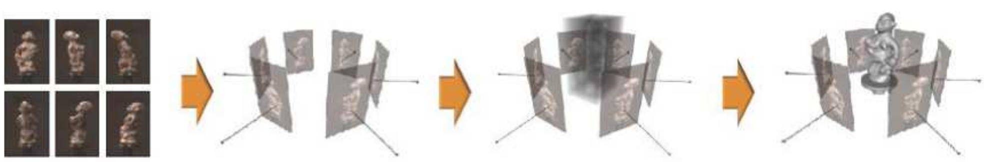


Figure 2.30: 3D surface model from photos acquisition [176]

The true innovation breakthrough in elaborations is the implementation with the so called **SfM (Structure from Motion)** technique [30]:

> *"[...] traditional photogrammetry derives calibration parameters of the camera and the camera poses mainly from well-distributed GCPs and tie points, a Structure from Motion (SfM) approach computes simultaneously both [...] it extracts corresponding image features from a series of overlapping photographs captured by a camera moving around the scene"* [208].

If we think carefully that the action of correlating homologous points from different shooting position images of the same object, has always been carried out in the past manually with the analogical and analytical photogrammetry.
However, despite the conventional photogrammetry, in SfM the camera locations and the object geometry are reconstructed at the same moment with an iterative bundle block adjustment process because the automatic features matching procedure works without specifying a priori the targets network [30].
But with the birth of semi automation and automation algorithms the digital photogrammetry has marked a *"second revolution"* [30] revealing everyday incredible potentialities in the CH documentation and VH fields and, more important, easy using modalities that have recently produced growing applicative chances for everyone as compared to the past, when the research in the photogrammetry field needed specialized skills and furthermore it wasn't able to reach the range sensors 3D point clouds quality and accuracy [163].
Bearing in mind the Geomatics approaches rather than the Computer Vision ones, as [30] have underlined, it's important not to underestimate the role of GCPs and the georeferencing process for verifying the accuracy of the following reality-based products which have **metric value** and in the VH documentation field these parameters must be controlled.

2.5.7 Terrestrial and Aerial equipments

Since the first years of the birth of the photogrammetry techniques, several equipments have been investigated to find out which one could balanced different aspects of acquisition (range, weight of the device,technical settings, manoeuvrability, physical performance in difficult conditions and so on) especially about the aerial equipments.

Terrestrial equipments

Starting from the requirement that the generic photogrammetry technique establishes its existence on the presence of photographs taken by cameras, in the recent years a new terrestrial applicative use of them has been broadcast.
The **Terrestrial mobile Mapping** consists of positioning an acquisition device (a 360° digital camera, a terrestrial laser scanner device) on a mobile vehicle that records a series of longitudinal and transversal scans: the third dimension is provided by the vehicle movement through the trajectory with the support of satellite (GPS), inertial (IMU) and localization systems (GNSS) [178].

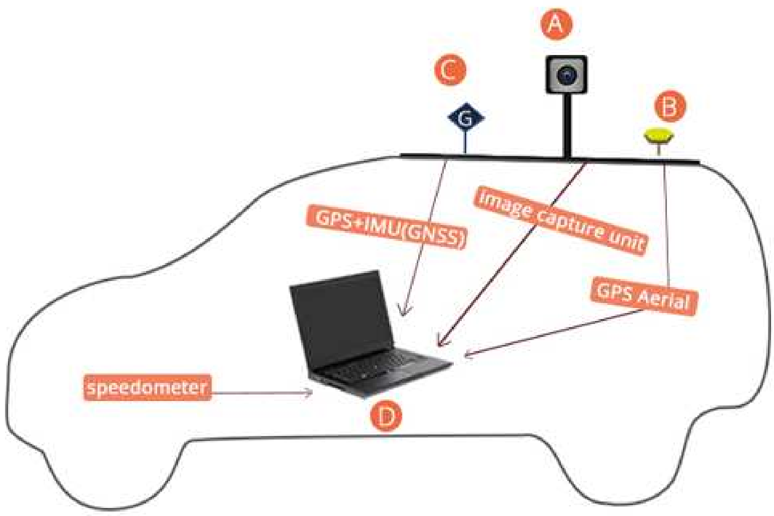


Figure 2.31: Terrestrial mobile mapping system [56]

Aerial equipments evolution

The photogrammetric documentation has reached so high levels of accuracy and definition, that pushed into the use of newer and newer technologies or methods even in difficult context to survey or to reach physically. The aerial survey has always been one of the most experimented field and all experimental attempts have taken place during the history from the past most strange methodologies to the current most conventional-unconventional ones.
We have already seen the first prototypes of **non-motorized** aerial photography with **pigeons** (Figure **2.32(b)**) that, of course produced extraordinary acquisitions possibilities thanks to the training-friendly behaviour of the birds, the flying abilities

and their resistance to long distances but they were also extremely unsure for big possibilities for the animal to get eaten or catch by other predators during the flight. Before the pigeons there were used **motorized** aerial photography methods (Figure **2.32(a)**) that consisted of sending pilots with cameras to take photos from **planes**.

(a) Plane photography [190]

Carrier Pigeons Take Aerial Photos With New Camera

IT IS no longer necessary to send planes over enemy lines to get photos of troop operations—carrier pigeons have now been pressed into service for this hazardous task.

This unusual feat is made possible by the development in Germany of a new diminutive aerial camera which is strapped to the pigeon's breast, as illustrated in the accompanying photo. Two hundred views may be taken while in flight, the shots being made possible only after the bird has left the ground. Each bird also carries a message tube strapped to its leg.

The German government has opened a school to train carrier pigeons for service in aerial photography.

(b) Article in *Modern Mechanics* dated February 1932 [13]

Figure 2.32: First aerial photography prototypes

The **aero static balloons** [69], **kites** (Figure **2.33(b)**) and **telescopic arms** [113] were just few of the experimental ideas for the aerial acquisitions: two of the most commons negative characteristics were doubtless in the manoeuvrability of the systems and the image stability that resulted really difficult to reach, especially, in case of bad atmospheric conditions or strong winds (Figure **2.33**).

(a) Aerostatic balloons [151]

(b) Kite aerial photography [9]

Figure 2.33: Aerostatic and wind aerial photography

"The advantage of aircraft acquisitions derives from the large flexibility, adaptable to every specific need, especially temporal." [77].
But in general, the presence of the pilot, who had to take aerial pictures and at the same time drive the flight to the right directions wasn't so safe.
That's the reason why among the current unconventional equipments figure **Unmanned Aerial Vehicles (UAV)** and **Remotely piloted Vehicles (RPV)**: classes of aircraft born in 1950 for military purposes since they were able to be remotely programmed and to fly without any pilot on-board. Their use results really decisive to carry out long and dangerous missions in order to improve the monitoring operations without risking human losses. They are characterized by a good flight autonomy in terms of time and by a good manoeuvrability even in presence of wind.

(a) Fix-winged mapping aircraft **(b)** Fix-winged Ebee drone

Figure 2.34: Aerial fix-winged remotely vehicles [191]

(a) Quadcopter drone **(b)** Hexacopter drone

Figure 2.35: Drones [54]

Acquisition modality

The prerequisite of the acquisition phase is that every part of the object to survey must be photographed from two consecutive points of acquisition in order to have a common part, on two consecutive images, called: **overlap zone**. This principle's valid for both types of photogrammetry: terrestrial (Figure **2.36**) and aerial (Figure **2.37**).
In the aerial case, for example, the flight is planned according to straight lines parallels to each others. Along the flight directions the UAV took pictures in sequence and at given time gaps. The photographs sequences are called **stripes**. All the technical and geometrical data are included in the **flight path plan** (Figure **2.38**).

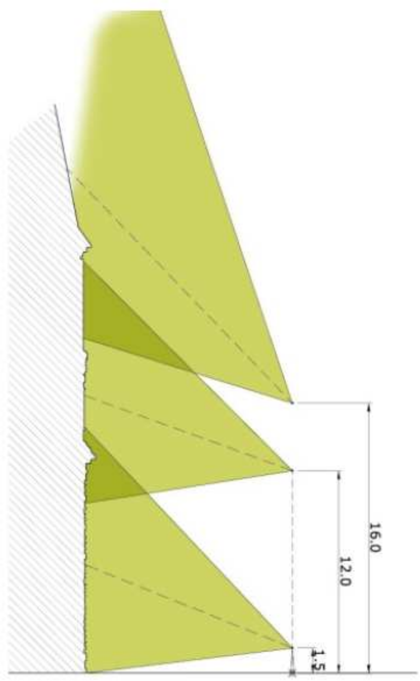


Figure 2.36: Terrestrial acquisition: in dark green the overlap zones [178]

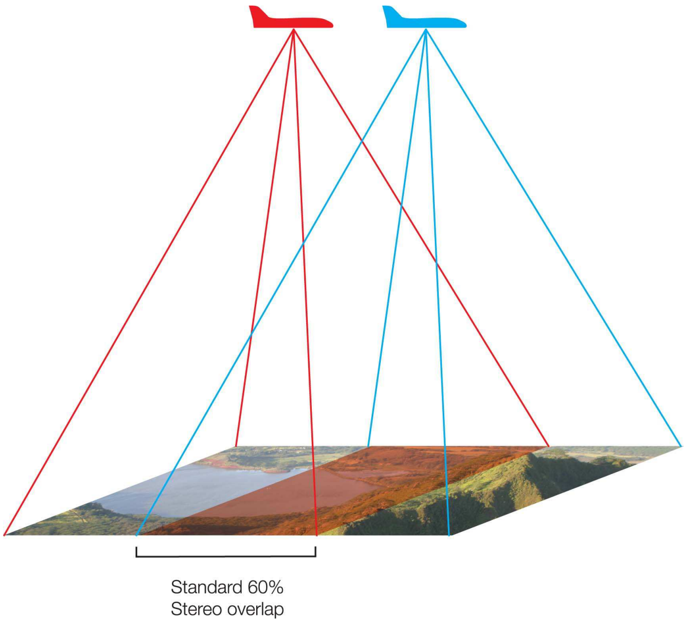


Figure 2.37: Aerial acquisition: in red the overlap zone [89]

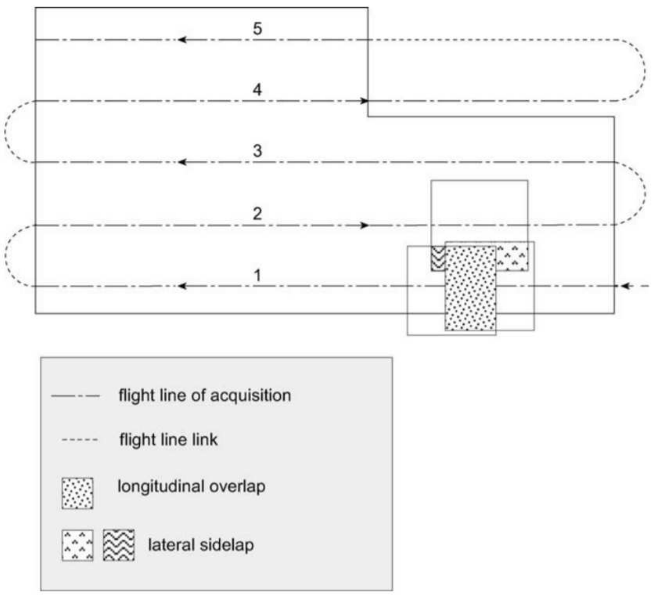


Figure 2.38: Aerial acquisition: Flight plan [77]

Chapter 3

VR: the *"Big Bug"*?

Nowadays, our society seems to be involved more and more in a long-term digitalized growing path. There's no field we could think about that cannot be solved or improved with technological, digital or informatics methods: the only limit is the one we set.
As the Big Bang had marked an universe explosion creation, its expansion and progressively developments I feel to mark another big "explosion" of the human universe, the moment of the first overturning about our lives: the ***Big Bug***.
Why "Bug"? The unexpected accident, the bugs of the system have always constituted the first "bricks" of the **evolution** wall.
And as old as time is the evidence that every pretty big overturning changes, the new, the diversity, the unthinkable, were, and are so far hardly to be imagined and to be accepted due to fears. But it exist, it's vivid, and it was vivid even during the introduction of Information and Communication Technologies (ICT) in architecture field when the architects community was strongly conservative and traditionally linked to the "old style method" of communication.
But the truth is, according to the Co-founder of Iris VR [97], Shane Scranton, that the unacceptable bug that shocked the conservative society, already did it many years ago, the first time the word *"drawing"* was put together with the word *"computer"* and when the words *"computer aided drifting" (CAD)* were introduced in our quiet lives [5].
Even the main antagonistic expression of the immateriality form, that's **space**, has been converted.
"Real": *"Actually existing as a thing or occurring in fact; not imagined or*

supposed" [134].
"Virtual": *"Not physically existing as such but made by software to appear to do so" [135].*
In other words, real it's for antonomasia everything is already executed, something existing which doesn't allow imagined or supposed parts. Otherwise, virtual exists only in a cyberspace, not physical. We'll se there's no too much difference considering space, physically and geometrically speaking, boundless places characterized by three physical dimensions where it's possible to know the exact coordinates of a point as much as the virtual one.

3.1 The *"Reality-Virtuality Continuum"* [119]

Has someone made a mistake in writing the oxymoron "virtual reality"?
How can a reality be defined as virtual?
Dear folks, welcome to the era of the computer aided paradox technologies: **Virtual Reality** is the latest visualization and communication technique spread among several discipline fields which have to communicate data over the written words or the voice tool. As Tufte underlined:

> *"We envision information in order to reason about, communicate, document, and preserve that knowledge — activities nearly always carried out on two-dimensional paper and computer screen. [...] Still, all the history of information displays [...] is entirely a progress of methods for enhancing density, complexity, dimensionality, and even sometimes beauty"* [194].

The *"Reality-Virtuality Continuum (RV)"* defines a *"spectrum"* of classes, showed in **Figure 3.1**, of displaying the world which goes from the physics laws-based world to the computer laws-based synthetic one.
Within the two opposite extremities of the continuum, the **Mixed Reality (MR)** environment put together objects from the real and from the virtual world and it includes the **Augmented Reality (AR)** and the **Augmented Virtuality (AV)**.
With Augmented Reality is defined the act of *"augmenting natural feedback to the operator with simulated cues"* [119] where participant's head-set is transparent and shows a *"[...] a clear view of the real world"* and just for this feature it's considered as a form of virtual reality by Paul Milgram, since in the VR environment participants are totally immersed in a synthetic world (completely

modelled world) which may or may not have physical laws, time and materials properties according to the modelling settings.
The information we could actually know about objects and the environments in which they are displayed is explained by the **Extent of World Knowledge (EWK)** depicted in **Figure 3.2**.

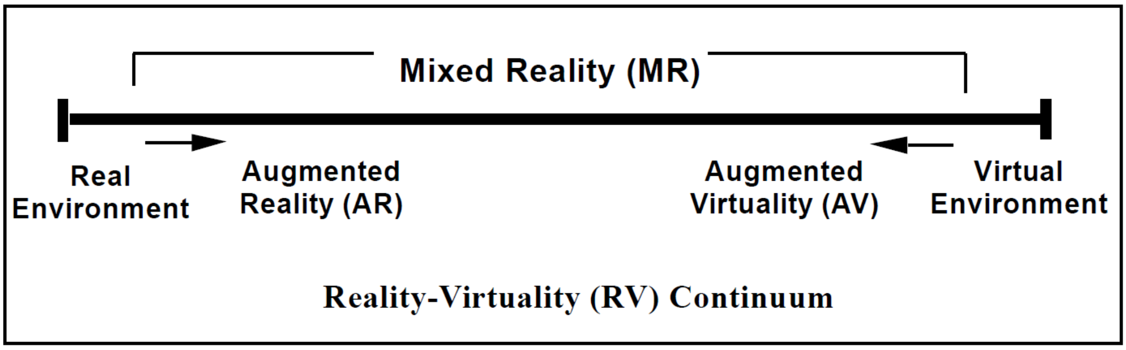


Figure 3.1: Representation of the *"Reality-Virtuality Continuum"* [119]

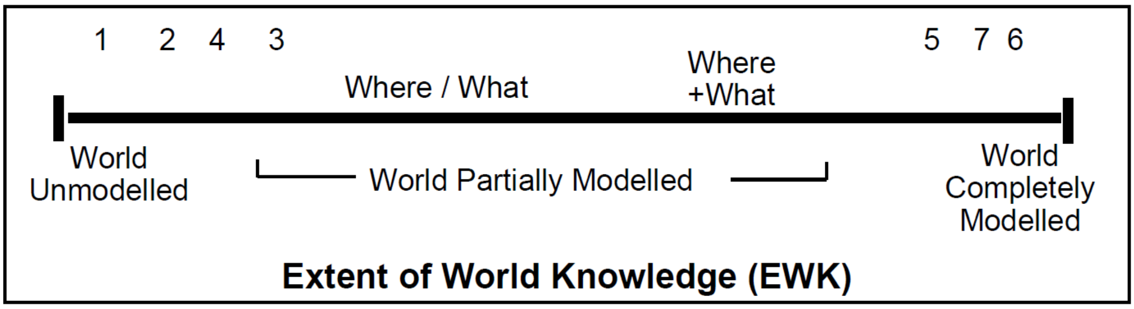


Figure 3.2: Representation of the *"Extent of World Knowledge"* [119]

What's Virtual Reality

A good starting definition for the *"Virtual Reality"* (VR) meaning could be the one that emphasize the interaction of participants and no more in terms of class of visualization, but in terms of **class of immersion**, putting in opposition the *"view"* and the *"experience"*:

> *"[...] the component of communication which takes place in a computer-generated synthetic space and embeds humans as an integral part of the system"* [154]

and equipped with the five **"i"**s interaction-friendly features of VR: *"[...] intensive, interactive, immersive, illustrative and intuitive"* [173]. The enormous

advantage of virtual reality is *"[...] the sensorial immersion that let us perceive realistic proportion and dimensions, let us have everything is impossible to realize with a 2D drawing..."* [5].
People in the 50's were trying to find this kind of immersion that could be greater than the usual cinema or theatre experience. It all started in 1963 with *Hugo Gernsback* and his *"teleyesglasses"* shown in **Figure 3.3** (the first prototype of the modern headsets with separate screens for each eye, it could display stereoscopic images [90]), with the development of realistic video-games and it continued with the great products of cinematographic industries wanting the world to get familiar with the potentialities of the droid and virtual-made worlds: *Robo Cop* (1987), *Tron* (1982), *Videodrone* (1983), *Terminator 3* (2003) were great VR candidates to give through the scenes an immersion as realistic as possible [172].
Indeed, the component of the **realism** of the scene isn't really capable of let the customer think that the space might be abstract, because of the change of direction in the perspective visualisation that characterizes the natural mechanism of the sight that moves according to the head's movements in real time like the latest **Headsets mounted display (HMD)** (**Figure 3.4**): from the low-cost ones such as *Google Cardboard* in **Figure 3.4(f)** and *OpenDive* to the expensive ones with *Oculus Rift* in **Figure 3.4(a)**, *Oculus Go* (arriving in 2018 with no Pcs or wires showed in **Figure 3.4(b)**), *Samsung Gear VR* (**Figure 3.4(c)**), *Google Daydream view VR* in **Figure 3.4(h)**, *Playstation VR* (aka Morpheus project in **Figure 3.4(d)**), *HTC Vive* in **Figure 3.4(g)** and *Microsoft Hololens* for mixed reality shown in **Figure 3.4(e)**.
Furthermore, the real time movements revolution hasn't restricted its action limit to the single recreation of the head sight, but it has spread out with devices that recreates the movements of the **whole body** which are projected into the virtual world and are capable of enhancing our self-awareness of the interactive experience. Indeed, we can find handy-controllers, joysticks, wands or sensors-equipped gloves *" [...] designed to stimulate the perception of different stimuli such as Control VR, bracelets etc."* [66]. Thanks to the creative wave of all these sensors based on the perception of pseudo-real *stimuli*, the future appearance of "sensorial jackets" capable, for example, of inducing perceptions of temperature to the explorers (the cold, the hot and so on) according to the real time environment weather conditions of the VR experience, it wouldn't even be a "wow factor" anymore.

Figure 3.3: Hugo Gernsback, Ph: Alfred Eisenstaedt for Life Magazine Collection [90]

(a) Oculus Rift [132]

(b) The new Oculus Go without computer and wires [133]

(c) Samsung Gear VR [171]

(d) The Sony Play Station VR [141]

(e) Microsoft Hololens for Mixed Reality [117]

(f) Google Cardboard [79]

(g) HTC Vive [84]

(h) Google Daydream VR [80]

Figure 3.4: Virtual and Mixed Reality most common Headsets mounted display

3.2 A thousand and more of virtual possibilities

Many people today, thanks to the constant mobile media advertising pressure, are getting more and more familiar with the term ”virtual reality” even though the half part of them conceive it just in the games industry field and in general when it’s associated with the entertainment. When it comes to understand the thousand possibilities of this kind of technology the uncertainty, of running into latest urban legends, science fiction applications and so fake ones, gains the upper hand.
When it comes to speak of **virtual** possibilities, which are **real**?
Doubtless, beyond the **games** application which covers a big slice of the ”cake” of uses, there are a lot of other ”slices” [211]:

- Entertainment
- Cinematography and Media
- Telecommunications
- Education
- Heritage and Architecture
- Construction
- Engineering
- Scientific visualizations
- Medicine
- Sport
- Business
- E-Shopping
- Fashion
- Space
- Jurisprudence
- Military

Entertainment and VR

After gaming industry, the entertainment is the second most fascinating use of the VR technology which has the primary aim of the **audience engagement**.
This field is also strictly linked with the Architectural, the Art and the Heritage fields through the wide spread of entertainment experiences of **4D Cinemas**, **Virtual Tours**, **Virtual Museums**, **Art galleries and interactive exhibitions** that

provide the explorers full immersions inside their movies. art collections or historical buildings.

Cinematography, Media and VR

Films have been the best experimental science fiction contexts for the use and introduction of virtuality in everyday life, envisioning sometimes also the pros and contros of technology. The success in this industry lies in taking advantage of the **”Computer generated imagery” (CGI)** and 3D computer graphics effects to amplify, to exaggerate the potentialities of the virtual technology making these computer generated worlds as realist as possible in order to let the customer suspect and hesitate about which the real and the virtual worlds really are.
As already cited, many science fiction films since the eighties were great candidates for this technology and few ones such as **Tron** (1982) have embraced the virtual world inside a computer as the **central plot** element of the entire storytelling and even now the latest movie **Ready Player One** (2018), which takes inspiration from the homonym Ernest Cline’s book, proves the constant world spreading interest on these themes.

Telecommunications and VR

Mobile communications have simplified our everyday social lives if we bear in mind live chat, video callings and so on. They have enabled also new and easy access to VR communicative projects: this is also the same principle used in the Medicine fields simulations.

Education and VR

Education lies in the same importance plot of land of entertainment since the primary aim is to support the teaching in a way that should be also easy and fun to learn at the same time by students. Virtual reality teaching allows to envision and to interact with complex information that results hard to explain just in the 2D dimension. An example of fun teaching-learning is the solar system application that allows student to envision how abstract concepts work in a 3D way which makes it easier to understand [211].

Heritage, Architecture and VR

This is a new type of experience in comparison with those of galleries, museum and visiting tours: virtual reality has allowed to create immersive ***walkthroughs*** around **architecture buildings** during the planning phase, around **virtual heritage sites** no more accessible, or **archaeological sites** at risk, **historical buildings**,**monuments** destroyed by hazards, **sculptures** and so on.
This field is strictly linked also to the scientific visualization of **cultural heritage** in general which, thanks to the accuracy of scientific methods and technologies of survey and 3D modelling, have brought to create a new frontier of heritage protection and enhancement that I will accurately face in the next chapter: **virtual heritage**.

Construction and VR

The collaboration between construction industry and virtual reality seems to be, as the heritage field, extremely promising and useful in the future. In the current present already, the virtual environment, instead of a 3D render, provide many benefits not only in the envisioning part but also in the experimental part of the designed spaces: the **testing phase** of factors without any cost, without waste of time in order to reduce the number of error in the complete construction [211].

Engineering and VR

In the same mode of operation wave of constructions, here it comes the engineering field which covers other fields of knowledge such as the design cycle, rail and car design etc. Virtual reality shows itself as an efficient partner in time, money and quality saving process, in terms of safety conditions for workers and in terms of maintenance.

Medicine and VR

Recently medicine field, but also in general the health-care field has spotted an increasing number of adopters of virtual reality. The proof lies in the creation of several software of **human body simulation** or **virtual diagnostics** software. One of the most popular use is the **virtual surgery simulation** or **robotic surgery** that allow the surgery doctor to perform surgeries also *”at a great*

*distance (**telemedicine**) [...] or to help a less experienced surgeon during interventions with high difficulty (**telementoring**)"* [82], without risk of health complications for the virtual patience.
Unbelievably, virtuality can also act like a tool for mental health disorders: a sort of therapy for stress, panic disorders, phobia, fears or autism disabilities.

Sport and VR

Also the sports industry has welcomed with great expectations the virtual reality potentialities in the **training process** and for the measurement of the athletics **performances technique** [211]. Furthermore, all these kind of virtual measurements have gave birth to another use concerning the **sport manufacturing** industry: virtual reality is used to simulate human body movements during the sport activities in order to design all the equipments with scientific accuracy, innovative and ergonomic principles to gain more speed, strength, endurance and so on.

Business and VR

The virtuality has been embraced by the business field thanks to its time and money saving quality that allows to test the success of several prototypes without the development. It's increasing the number of companies using this kind of technology also in the data analysis for gaining the edge over the competitor companies [211].

E-shopping and VR

Words like "e-commerce", "on-line shopping" aren't a surprise anymore in 2018, but the next step of progress aims to amplify the traditional on-line experience [211]. Several mobile applications provide virtual tours where the shoppers can comfortably have a real-time virtual walk to explore the entire store: a practice example is the new experience of virtual real-time shopping inside the IKEA stores [196].

Fashion and VR

Fashion industry uses VR technology in ways that include also the possibility in the future to create a virtual fashion portfolio. Another potentiality is the creation of a 3D **fashion avatar** to help with the clothes design process [211].

Space and VR

In the space field, NASA has embraced virtual reality technology to control robots on other **planets explorations**. Another use was about sharing the experience of astronauts on a spacecraft [211].

Jurisprudence and VR

Another innovative potentiality is the 3D **virtual analysis** of a crime scene instead of the analysis of bi-dimensional photographs taken. This new way allows to also re-create the crime phases dynamics in order to understand the relevant from the irrelevant details [211].

Military and VR

The USA military services (army, navy and air force) has always adopted virtual reality for **soldiers training** purposes. **Battlefield and wars simulations**,**virtual boot camp**, **flight or vehicle simulations** indeed, are really helpful to prevent risk of injury or death. As already written, VR is also used for post-traumatic stress disorders (PTSD), fears or panic attacks of soldiers that suffered from the battlefield traumas [211].

Figure 3.5: Military simulation in virtual reality [211]

3.3 Architects and Virtuality

Figure 3.6: VR interior design visualization [5]

As I wrote before in the introduction of this chapter, the acceptance of the introduction of digital revolutions in the architectural community have had a difficult path. According to the co-founder of *”Arch Virtual”* company [8], Jon Brouchoud, we have five years to get used to work with the ”virtual family” that will become in future the most communicative way architects will go through projects [5].

Virtual reality has been known since the Fifties, but at that time the computational power of workstations, central processor units (CPUs) as well as the lack of the quality interfaces in terms of high definition (HD) displays and in terms of graphic processor units (GPUs) weren't enough. And at last, the most important reason, there were no appropriate engine software or platforms for the management of complex virtual models or environments [102].

There's no much surprise if we think of **Gaming industry** as a springboard for the virtuality development since the game experience of all those game-addicted players required a certain speed of reaction on inputs, more scene realism in terms of lighting, shadows, Physics world laws and interaction with the player itself.

Today indeed,

> *"GPUs are capable of handling several hundreds of millions of textured polygons per second, have a storage capability of several gigabytes and a memory bandwidth of hundreds of GB/sec, are highly parallel structures based on a unified shaders architecture. Shaders are small programs that run on the graphics card and are primarily used to calculate rendering effects (like reflections, depth of field, atmospheric effects, automatic mesh complexity modification) in realtime"* [112].

As well, there's no much to turn up the nose from the current situation where many architects and designers are widely approaching the use of **Game Engines**, instead of architectural software for the real time rendering of models, just because is a commonplace talking about *"augmented reality"*, *"mixed reality"* without thinking only about gaming and fun applications.
This is also a belief that Microsoft, in partnership with Cambridge University and Trimble, are trying to erase in favour of new professional fields that goes from the architectural ones to the infrastructure ones [118] taking advantages from the risk-free and saving-money characteristics of the virtual dimension.

3.4 Virtual *"Archviz"*

Architectural visualizations or for short *Archviz*, is a well known made computer generated process for showing the result of any structure before the real construction: 3D models, hand sketches, renders and post productions. In this way, the client has always been absolutely aware about the expectation of the final structure to buy and even if visual contents are better than words, in the era of the possible of impossibilities, bi-dimensional visual information aren't and won't be enough anymore in future.
The current trend isn't about watching a render of a space or a physical 3D model from an external view, now it concerns the possibility to enter the 3D space or an extra-terrestrial 3D environment, to **experiment** it in **first person**, to have a preview with **virtual animations**, to have a real-time **virtual *walk-through*** in order to understand and try how it feels and how it'd feel to be there for real.
Technologies from the mixed reality family as virtual and augmented reality will completely change the way to design or to take decision about the architectural

planning phase taking advantages from several game engines software: among the most common we can find *Unreal Engine*, *Unity 3D*, *Lumion*, *Stingray* and so on.

Figure 3.7: A first person virtual walk-through [1]

3.4.1 Is there ”home” on Mars?

Mars City project is an example of how, thanks to virtual reality, architects, and in a particular way Kieren Timberlake, found the way to overtake the traditional architectural visualizations for having new possibilities and chances to design even in extra-terrestrial environments and test them.
It was an hard work because *” [. . .] to create a self-sustaining habitat without water, without food for 100 people, the architects worked with Kerry Joels”* (former NASA physicist) *[. . .] to determine which materials and technologies would work best on Mars”* [153] in order to test them in virtual reality mode. Mars City has become an educational virtual game which simulation video is available on line on Vimeo as showed in the image frame (**Figure 3.9**). where student can easily wear headsets and walk through the corridors of the project, shown in **Figure 3.8**, the planet base testing out solutions of survival.

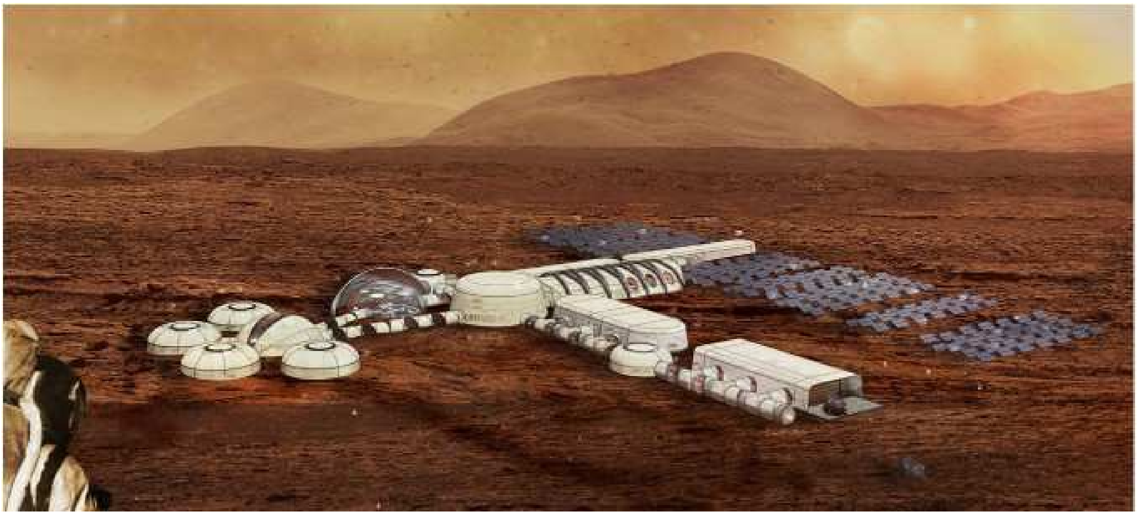


Figure 3.8: The virtual Mars City Base [153]

Figure 3.9: Image frame extracted from the Mars City simulation video [209]

Chapter 4

Tu quoque, Virtual Heritage?

If Cultural Heritage, as we knew it fifty years ago, spoke to its future evolute product, son of the digitalization and immateriality generation called Virtual Heritage, maybe he wouldn't even recognize it. It's like the generational gap between a father and a son: the change is still trying to be acknowledged by the traditional society and its spread can't be stopped by the far-sighted one. Virtual Heritage places itself like the heir of a new frontier of protection, restoration and enhancement of Cultural Heritage.
The passage from the materiality to the immateriality feature is supported by the **Information and Communication Technologies (ICT)** which aim to document with extremely accuracy the safety *status* of Heritage [159] that's mostly *"[...] undervalued in spite of the growing scientific evidence"* [62].
ICT do not provide the Heritage field, only to a scientific documentation thanks to the Geomatics and 3D metric Survey tools, but also to faster and better monitoring operations for the restoration phase and for the availability of the Heritage itself that can be enhanced and promoted with social sharing on-line platforms which will give people new possibilities far more than the past ones.
This is the challenge the European Commission wants to aim inside the **Horizon 2020** project frame about the call for the work programme by *"Promoting the European Public and Cultural Space"* [62]. That's the reason why the European Commission has asked an integration approach to Cultural Heritage for Europe seen as a *"shared resource for everyone"* that needs to adapt to the innovative changes society and to meet the potentialities of **digital** dimensions.

4.1 From visual to virtual communication

The architectural field, and more in general, all the graphical-visual embedded profession fields, are based on **drawings**, **images**: the primary ingredients of the history of the *"recipes"* of communication *"kitchen laboratory"*.
The 2D representation reveals itself as a tool that makes an object, a story readable by different layers of meaning. What combines an image and a drawing is the selective filter about data visualization according to their tasks [14]:

1. **Describing**, It consists of collecting and putting in order all the complex data characterizing the object in consideration.
2. **Illustrating**, is a synthesis action that aims to show the previous order of lines, volumes with a hierarchy: deleting the secondary or accessories elements made of decorations and others and let the primary elements, such as the structure, rise high.
3. **Representing** introduces the necessity to have a precise interpretation but also a universal understanding graphic code. Furthermore, representation passes through two action ways:
   - The choice of the density of information to represent
   - The choice of the form of visualization to represent

But beside the 2D representation, historically speaking the **3D models** had always helped and followed the 2D architectural representations that changed the purposes of communication during the centuries of course. In ancient Greece for example, inside sepulchral graves there have been discovered several 3D architectural models of domestic houses as simple architectural representations and maybe communicative proof of the social or economical *status quo* of the dead soul. While, during the Roman Emperor the 3D models were brought to the triumphal demonstrations to give power and emphasis to the conquer missions [46].
The Renaissance period has seen the use of models for the projects communication and also as a guide to the final result for the workmen, but it was doubtless that the binomial made up of 2D architectural representations and 3D models was complementary and efficient: where the 2D representation could not show correctly, the 3D fulfilled communicative task especially during the designing phase and during the choice of materials [18].

Virtual Models

Today, the concept of architectural model has changed radically, since it doesn't mean to be a physical one anymore: the **Virtual Models**, the **Immersive Virtual Environments (IVEs)** [22] are spreading widely among the architectural and heritage fields thanks to:

- The **interoperability** among different kinds of **sources**, kinds of **unconventional fields** of application like game engines, serious games, cultural learning, reality-based methods of Geomatics towards projectual experimentations or already existent ones like heritage buildings;
- The projectual task to show the committee the final result of an experimental building exactly like a bidimensional render, but with the advantage that now the experience is totally **3D immersive** in order to navigate and explore in first person the designed space;
- The **Cultural Heritage Learning** with its didactic task of showing the audience the original asset of ancient archaeological sites destroyed by time or hazards with the ri-creation of virtual models or for the **Cultural Promotion** of Cultural Heritage **at risk**;
- The **Enhancement** of cultural heritage through the comprehension, the heritage awareness of the building authenticity, history and value;
- The adaptability for the model to be transformed into physical, into real models through stereo-lithography and **3D printing techniques**;
- The possibility to offer a guide for the restoration operations in a fully risk-free and not invasive way;
- The chance of **testing** and of course of **simulating**, without any real risk, in the virtual dimension the stability and the material structures, their interaction with chemical products before the real application on the structure [17];
- The opportunity to create **Virtual Museums (VM)** for collecting the archaeological researches and for Cultural Heritage **availability** giving audience new possibilities of exploring knowledge in terms of lack of economical resources, lack of time, lack of possibilities to travel long distances;
- The development of the new frontier of travelling enhancement thanks to the **Virtual Tourism** through **virtual tours** that act like ”previews” of the

expected experiences or in other yet mentioned cases like an opportunity for a better understanding of the present, for maturing the respect of our cultural, sociological roots because VR experiences aren't supposed to replace the real travel experience at all [183];

- The creation of educational **Serious games**, influenced by the gamification process, which have "place" in 3D virtual heritage reconstructed buildings or environments for immersive and interactive experiences of cultural learning for everyone while having fun;

4.2 Cultural Heritage Enhancement

Protection, **Preservation** and **Enhancement** should be three correlated realities but many of the National and International laws push towards the idealistic view of the protection and the preservation processes seen as *Cultural Phenomena*, while the enhancement is seen as a high *"Trendy Rate"* business process [167].
And this kind of duality between the conservation and the enhancement spheres has been highlighted by the different accepted meanings that are the roots of the Eestern and the Western culture. In the Eastern approach is fully vivid the volunteer to preserve because

> *" [. . .] conservation manifests itself in the preservation of the historic monument"* [207]

treating the enhancement with a "Business approach". In the other hand, the Oriental culture

> *"tries to use the monuments to preserve the very spirit they present."* [207]

So, it isn't just about the enhancement as we conceive it in the Occidental world in terms of economical and touristic trades, heritage shows an **essence** and its enhancement must refers only to ethical values of **memory**, **identity**, **history**.
Indeed, the memory of the past, and the enhancement of it, survives thanks to the comprehension and to the availability of the cultural heritage buildings entity. The past can be highlighted and enhanced not only with the traditional editorial media of disclosures but also surfing the web wave made up of sharing-platforms and information envisioning.
The power of the technology allows to reach every kind of people: from the less involved into the discipline to the most involved ones and of course, it allows to

have a constant real time updating about discovers, critics, restoration processes in order to create a cultural **database**.

4.3 The Future of virtual past Enhancement: VH

Virtual Heritage (VH) is the combination of the memory value of Cultural Heritage with the increasing power of the Information and communication technologies (ICT) about virtual models or virtual reality environments: in other words it's the future of the past enhancement background methods. As already written, there are a lot of increasing reasons for the social *"boom"* of this new horizon of visualisation and immersion but at the same time, there are still vivid many questions about the technical rigorous of visualisations.
The **London Charter** recognized, by the virtue of the wide range of VH applications, that a set of principles was needed to promote not just the mere visualisation applied for envisioning arts but an illustrating computer-based visualisation of Heritage corroborated by its *"intellectual and technical rigour"*, its scientific value in relation to *"[. . .] intellectual integrity, reliability, documentation, sustainability and access"* [108]. That's the reason why, from this standpoint, the *"Reality-based spatial data"* [35], derived from Geomatics methods have more than a point of advantage for the geometrical and radiometric data thanks to

> *" [. . .] accurate reproduction of objects, as well as, the uniqueness and the specificities of each cultural asset impose a very careful choice of the needed approximation"* [149].

Furthermore the charter recommends, in a **scientific** way, to set a visible distinction between all the reality-based spaces and all that ones that may be hypothesized in order to ensure the reliability of documentations.
This was also the vertex of discussion, at its birth, of the **ICOMOS Ename Charter, for the interpretation and Presentation of Cultural Heritage Sites**. The term *"Interpretation"* refers to a

> *"full range of potential activities intended to heighten public awareness and enhance understanding of cultural heritage site"* [87].

But one of the most important values highlighted was the **Respect of Authenticity** of the Cultural Heritage by

> *" [. . .] communicating the significance of their historic fabric and cultural values*

> *and protecting them from the adverse impact of intrusive interpretive infrastructure, [. . .], inaccurate or inappropriate interpretation"* [87].

And here it comes into the play, the necessity to produce virtual contents and models that are faithful to the original through scientific bases, reliable and not just mere visualisations of "likeable" envisioning contents that the audience is expected to see. This also means the possibility to abandon the usual vision of the **perfection** concept in favour of the **authentic imperfection** one that expresses, after all, the properties **uniqueness** of each culture, object or heritage.
To pursue that rigorous standards without sacrificing the quality visualisation, the development of a **collaborative virtual environment (CVE)** based on both **reality point-cloud** and **game engines** software to support the stages of design context is one of the hardest challenges of this new era of interoperability among sources from different disciplines in a way that would be not possible using the only architectural software contribution [125].
Furthermore, the introduction of the **context** to the content of the reconstruction such as new games tools, has changed completely the vision of Virtual Heritage models:

> *" [. . .] from a means of communication to an environment that affords a variety of real-time activities"* [28]

a visiting experience which gives you the form of an **Avatar** in order to transform *" the model from an abstraction into a lived place"* [28].

4.4 The European challenge in Horizon 2020

As already mentioned, *Horizon 2020* is one of the biggest EU Innovation programme that started in 2014 and will last until 2020 for facing, through several measures, the societal challenges of Europe future that touch different fields:

- **The Science**
  - Emerging technologies
  - Infrastructures
- **Societal challenges**
  - Health and demographic changes
  - Bio-economy and sustainable agriculture
  - Energy efficiency

  - Smart and green transports
  - Climate action, environment and raw materials
  - Europe in a changing world: inclusive, innovative and reflective societies
  - Secure societies: protecting citizens freedom and security
- **Social Sciences and Humanities**

The societal challenges we're talking about, regard the "inclusive, innovative and reflective" aspects of the future European societies, in a particular way the **Call for Promoting the European public and private spaces** for a better understanding of Europe cultural and social past [62] about:

1. *"**Participatory approaches** and **social innovation** in culture"*;
2. *"Cultural heritage of European coastal and maritime regions"*;
3. *"European cultural heritage, access and analysis for a richer **interpretation** of the past"*;
4. *"Virtual museums and social platform on European digital heritage, **memory, identity** and **cultural interaction**"*;

This will *"inform the reflection about present challenges/opportunities and help to find solutions for shaping Europe's future"* [62].
The challenge set today, is to give emphasis to the meaningful **narrative aspect**, to the interpretation and to **story-telling** tools of collections which may cover the latest demanded technologies such as augmented and virtual reality experiences. It's also a vivid hope by the European Commission to believe this kind of approach will open a dialogue about the collaborative partnership between scientific progress and digital cultural heritage knowledge.
As soon as the European Commission has highlighted the necessity to give emphasis to the interpretations of past and storytelling aspects, it's pretty quite inevitable to think about "narration" as a communicative vehicle to spread a message that has to be received from a "recipient" in the exact dynamic of working of sound waves propagations. The dissimilarity element concerns the human reception seeing as how it processes the information to a sort of personal codifying that is the **interpretation**, until it arrives to the **comprehension**.
Of course, the Horizon challenge means also to create a **public engagement** towards every kind of citizens who show curiosity for art, culture and heritage, but also and especially for those who don't at all. To start really from the less involved or not interested in culture is a great incentive for the solution-raising call about

the search for social innovation strategies turn toward **involvement approaches**, really because they are the hardest to involve: keep in mind, for example, how it's hard sometimes to talk to young aged children about theoretical and scholar subjects. They need visual inputs full of colours, surprise effects during the narration maybe making up funny stories around an important information just to support the natural **learning** of that info.
In other words, the sustainability and the affordable digital access to researches and heritage contents must create a common sharing platform to give everyone like journalists, policy makers, researchers and curios people the possibility to open dialogues, to make and answer questions, to share interpretations, to improve solution of participatory partnership with scientific progress and, the most important aim, to promote a **better comprehension-acquisition** of knowledge about our European heritage history uniqueness.

4.4.1 Learning and Gamification in Virtual Heritage

When it comes of "learning" the situation is always spiny, but even spinier when it comes of "cultural learning". For this reason, Ibrahim [85] illustrated in a graphic, shown in **Figure 4.1**, the five most common research fields that will increase the attention and sensibility of Cultural Learning in Virtual Heritage:

Wayfinding , in the architectural field and in particular way in the VH field, it refers to orientation and path choosing of problematic experiences within the the virtual environment.

Interpretation of cultural heritage through virtual contents or environments. Heritage interpretation is an *"[. . .] educational activity which aim to reveals meanings and relationships"* [189] (Architecture/Archaeology point of view) and it doesn't come out just from the visualization of the given object, but it has to be connected also with the personal experiences of the audiences (Hermeneutic point of view).

Evaluation of Virtual Heritage is a young field in growing since there's no a standard technique or method to be developed.

Meaningful contents expressing **cultural value**. We don't have to forget that, even digitally or virtually, we're always talking about mankind Heritage which have values and reasons to be protected and enhanced.

Immersion experiences or **cultural presence** as Ibrahim call it. This is the area that more represents and translates into practice the learning task about the cultural learning in virtual heritage environments. Four are the key words that characterize the educational experience: **interactivity**, **definition**, **realism** and at last, but not surely for importance, the **engaging activity**. For this last purpose, as we'll see in the following lines, **game-based** activities and **task-based** ones will collaborate together to give birth at something bigger.

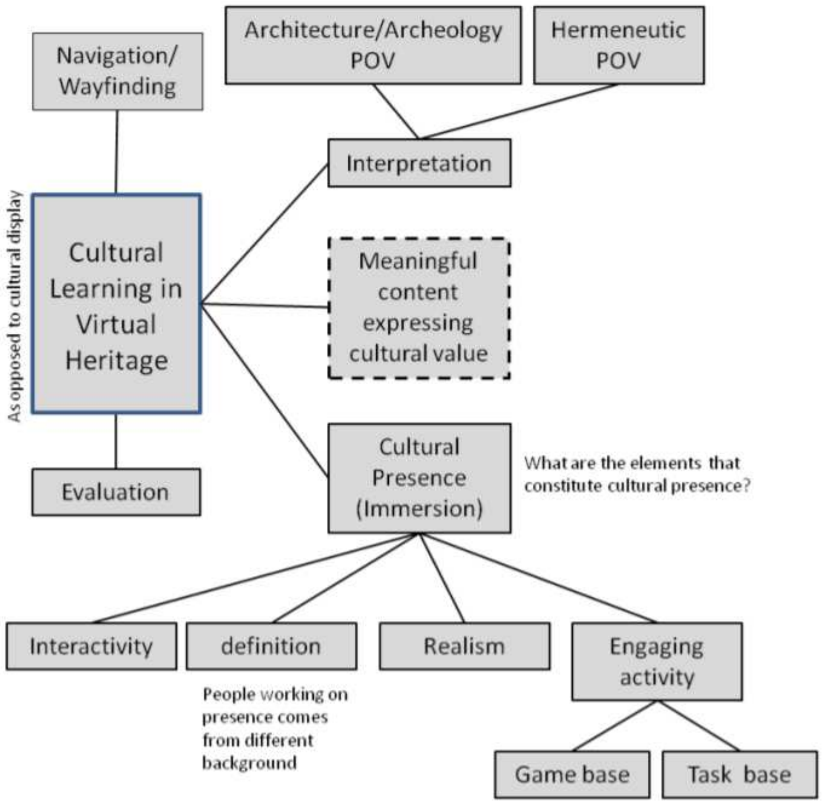


Figure 4.1: Cultural learning in Virtual Heritage [85]

As highlighted by the EU commission, it's necessary to give easy access of Virtual Heritage and increase the engagement activities for promoting a better understanding and learning about EU history and heritage complexity.
How to connect then, **cultural learning**, **public engagement** and **virtual heritage**? How to pursue the aim of involving audience in heritage keeping the attention level high and at the same time maintaining the audience focused on the topic or simply let the audience become interested in the given topic?
Well, first of all it's important to remember the Cultural Heritage isn't static but

it's defined by the society taken in example, because society and the consequent value of heritage tend to evolve constantly through space and through generations during time. In opposition with the 3D cultural collection storages for a mere cultural visualization, it comes the **cultural presence or immersion** of 3D heritage for the protection processes and for the people awareness of past culture that is proposed now with appealing and modern methods in line with the new generations [85]. Children have always been the *"testbed"* and like I wrote before, they really are needy with a constant request of inputs that let them enjoy the experience and, at the same time, let them learn things and built their own knowledge.

This is the key principle lying at the roots of the **Edutainment**, that is semantically a fusion of **Education** and **Entertainment**, to explore, to **learn while having fun**. So the concept of "playing" is not so far from the "learning" one and considering also the explosion in the Nineties of several audio interactive books for children, educational video-games learning based for the first computers and so on, the "learning by playing" motto isn't a new concept certainly.

The message the society want to give can be clarified through the tv spot quote by Samsung in the 2017 promotional campaign launching on market of their VR headsets (**Figure 4.2**):

"The impossible for a generation, is the normality for the next one." [171]

Figure 4.2: Samsung TV Spot 2017 "The reality for the new generation" [171]

It discloses the future attitude for everyone to get used to this way to envision information, to see the world around us and visually speaking, it has a strong impact too showing these young students, with their eyes staring at a dinosaur and experiencing the real time **virtual learning**.
Here it comes consequently the concept of **Gamification** which has its own meaning according to the field taken in exam but it's really close to the concept of **Education**. For using Deterding words:

"Gamification is the use of game design elements in non-games contexts" [48]

which means, the design programming matrix, game elements and interactivity are the same of games but the purpose of the entire interaction changes according to the player context and to the field of application.
The introduction and the use of **Serious Games** (SGs or games with educational purposes) into the cultural sector has automatically created a collaborative field between Edutainment and Gamification.
Despite of the traditional edutainment methods, the static installation of exhibitions and the lack of heritage awareness the new generation of serious games for virtual heritage, the virtual and the augmented immersions for visits of cities, natural landscapes, archaeological sites, architectures, **virtual museums**, **virtual tours** and so on, *[...] are designed to augment a real experience and engage players with the cultural content encountered along their tour* [126].

4.5 Virtual Museum

> *"The Virtual Museum (VM) is not a real museum transposed to the web, nor an archive or a database of virtual digital assets but a provider of information on top of being an exhibition room"* [62].

The concept of the **"Museum"** itself has been completely overturned: from a particular idea of a simple "objects container" of past, the same past that found its symbol in museums, art galleries defined as targets of destruction of the ancient tradition by the *"Futurism Manifesto"* [20] of Marinetti, to a general horizon of *"Museum outside the Museum"*[121] extending this concept to a large-scale like environments, sites, ecosystems and so on. Thanks God, there's no need to destroy our "heritage containers" to pursue the futurist exaltation of the era of the "technology", but it could be, instead, a powerful fellowship. Technology indeed,

integrates many objects which in reality reside in different locations, additional information which are proposed now in new attractive guises since:
"[...] visitors interact with the museum contents via multimedia systems (projection, hologram, app, robot, etc.) and in a variety of ways (touch, free action, voice), either on-site or remotely" [75] [96].

4.5.1 Virtual Tours

Virtual Tours, 360° tours and street-view tours are the new trend about the museums experience fruition from the audience who can widely access to Heritage in a **Remote** way without any problems concerning the availability of contents like the latest **Google Art Project** or the **British Museum** website, the **Smithsonian National Museum of Natural History** and the **Vatican Museums** and others. The first to design a virtual tour experience was Colin Johnson, a British engineer that created in 1994 a *"walk-through"* of the Castle Dudley 3D reconstruction [224].

Google Art Project

Google Art and Culture is a google-powered project (**Figure 4.3**) launched in 2011 in cooperation, at its birth, with seventeen museums and it consists of an **on-line**, **free fruition** platform "where" each museum partner has given access to a several numbers of artworks in a high resolution. It's, in other words, a virtual tour art platform like the already known technology of *Google Street View* (**Figure 4.5**) used in *Google Maps* (**Figure 4.4**). Today the platform, has met the agreements of over forty-six museums all over the world with a total amount of thirty-two thousands of collections (**Figure 4.6**).

Figure 4.3: Google Art and Culture on-line platform [78]

Figure 4.4: Google engineers during capturing operations at the White House [47]

Figure 4.5: Google Art exploring Street View sites tours[78]

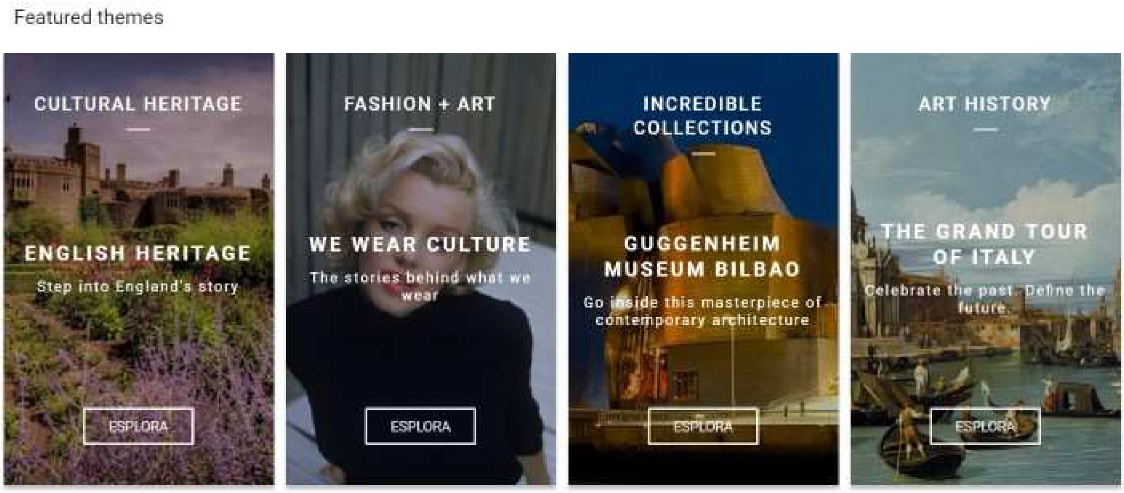


Figure 4.6: Google Art exploring art collection tours [78]

The project aim is to make art, architecture and all kinds of culture available to everyone, free of prices, free of obstructs like distances or limited mobility: a *"Democratization of Culture"*.
Everywhere, **anytime** and **anyone** without lack of time, without closing times is able to enjoy the world's best exhibition of art, architecture or cultural heritage *"without leaving their seats"* [47], directly with a mobile smartphone, a laptop or a workstation. On the other hand though, few criticisms include arguments in terms of **security risks** for the museums that can be easily mapped out and the creation of the so-called **"armchair tourists"** [47].

Louvre Museum

Louvre museum, as the most iconic museum in France, has embraced the new technology of fruition for the visitors engagement towards art, architecture and heritage in general.
The museum website offers free and easy 360° experience tours of the entire building history visible in **Figure 4.7**, of all the exhibitions, artwork collections from which the explorers will have additional information about history or curiosity facts.

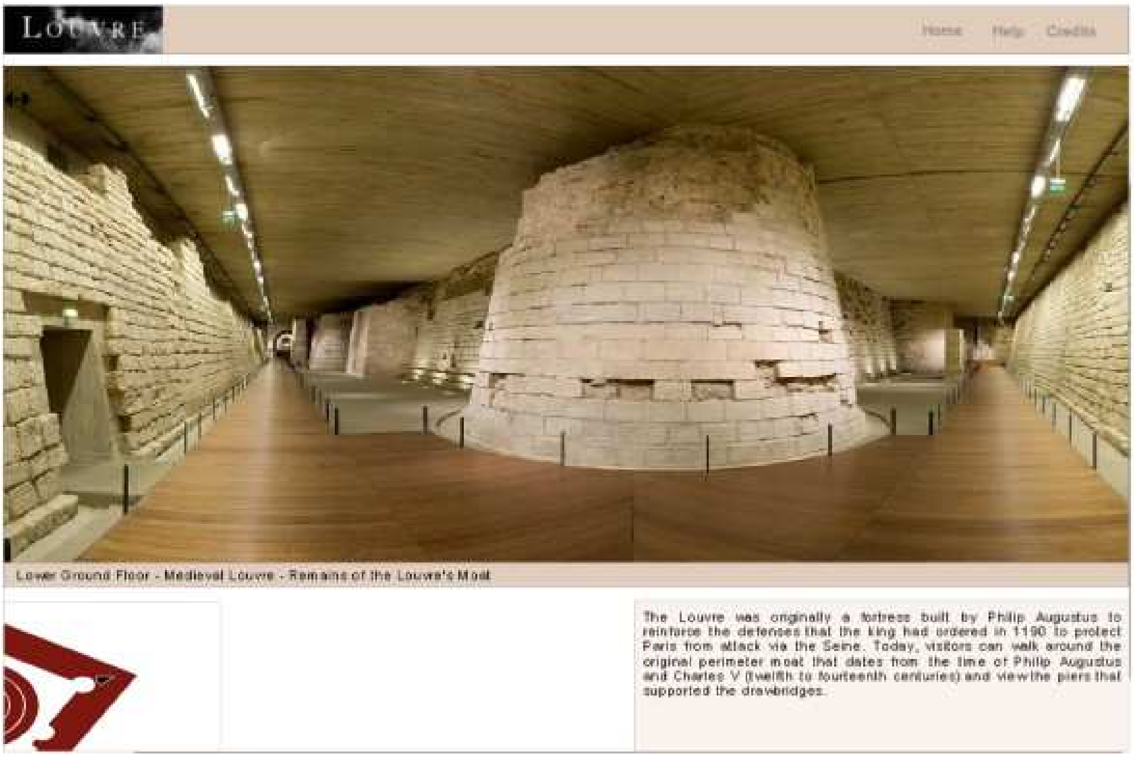


Figure 4.7: The Louvre Museum 360° virtual tour experience [109]

Solomon R Guggenheim Museum of New York

Thanks to Google street view and virtual tours, now it's possible to have a 360° visit (that was performed by the integration of the recording results of small drones, tripods and trollies) and walk along the famous Frank Lloyd Wright's spiral ramp, **Figure 4.8**, and discover over a hundred and twenty artwork collections of contemporary art.

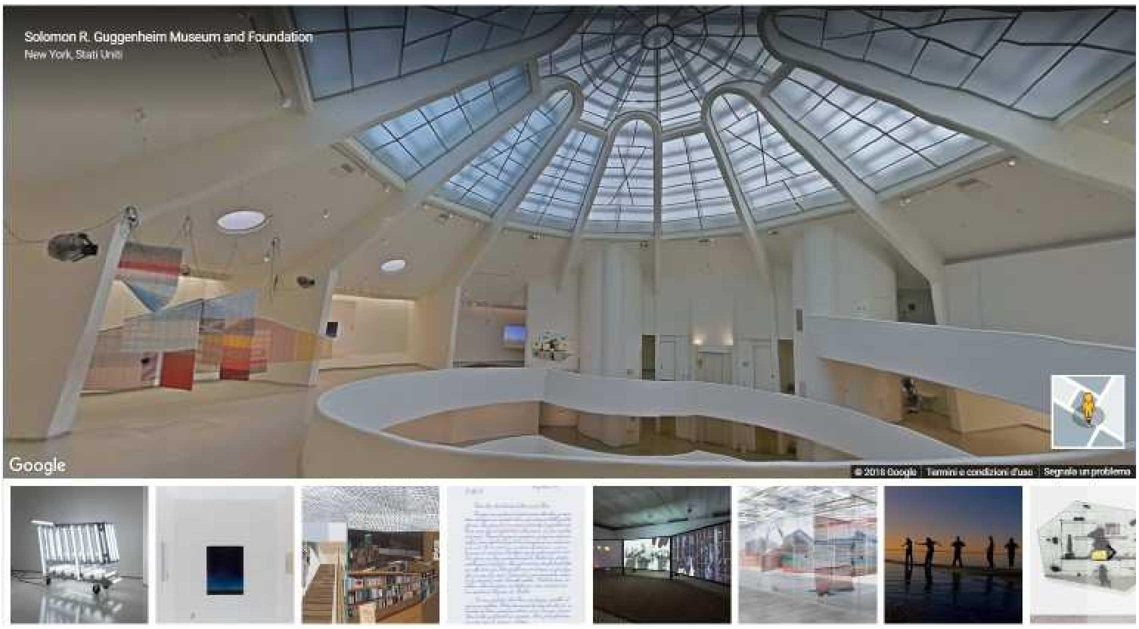


Figure 4.8: The Solomon R Guggenheim Museum in New York street view tour [81]

British Museum

The British Museum is recently working in partnership with Google and Google Art and Culture project to make the **heritage accessibility** the key words for all the people all over the world who want to discover and have a connection with heritage and history of other cultures thanks to a new **Web GL** (Web Graphics Library) experience on mobile or on workstation desktops as we can see in **Figure 4.9**.
That's the reason why, **The Museum of the World**, shown in **Figure 4.10**, is a complete and interactive experience that features the most fascinating human-made objects collections from the five continents.
It starts from a chronological line exactly like a time machine where the only thing to do for the explorer is to jump in, connecting time and space.

Figure 4.9: The British Museum street view exploring experience [185]

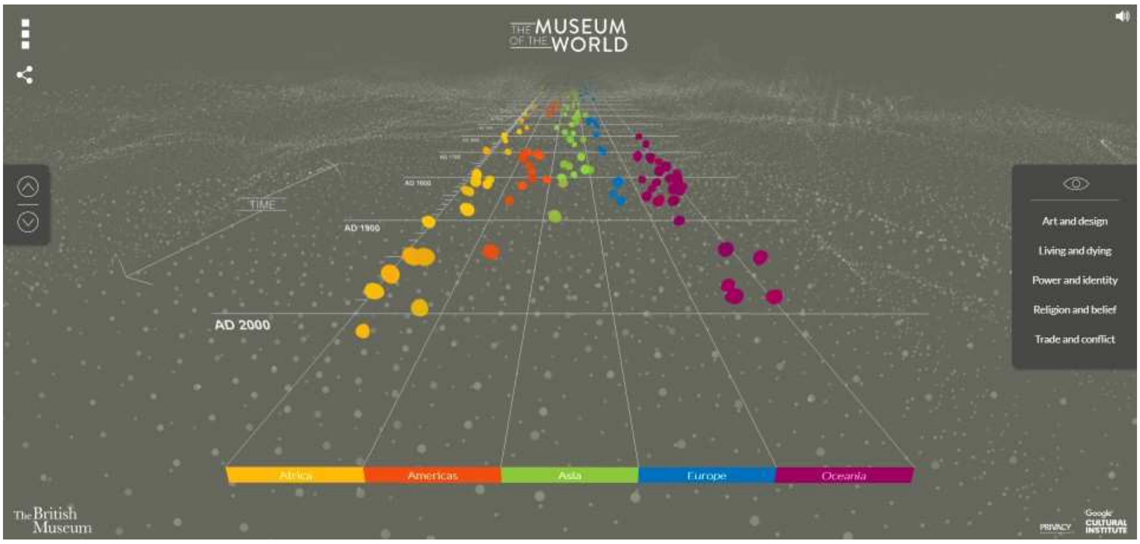


Figure 4.10: The Museum of the World: the British Museum new project in collaboration with Google [186]

Smithsonian National Museum of Natural History

Museum virtual tours

> *[...] allows visitors using a desktop computer (Windows, Mac, Linux) or a mobile device (iPhone, iPad, Android) to take virtual,* ***self-guided***, ***room-by-room***

> *tours of select exhibitions,* ***Figure 4.12****, and other areas within the natural history museum building [. . .]* [188]

that is constantly mapped out to let the explorer know his position inside the museum wing halls as it's possible to see in **Figure 4.11**. Currently there are over a hundred and twenty-six million items in the growing collections that go from the big Tyrannosaurus Rex skeleton bones to the tiny crustaceans, from whale skulls to ancient Chinese shoes, from diamonds to moon rocks and so on [188]. Furthermore, the virtual introduction has definitely provided an helpful documentation tool to give visitors a more careful awareness of the treasures of our world to preserve.

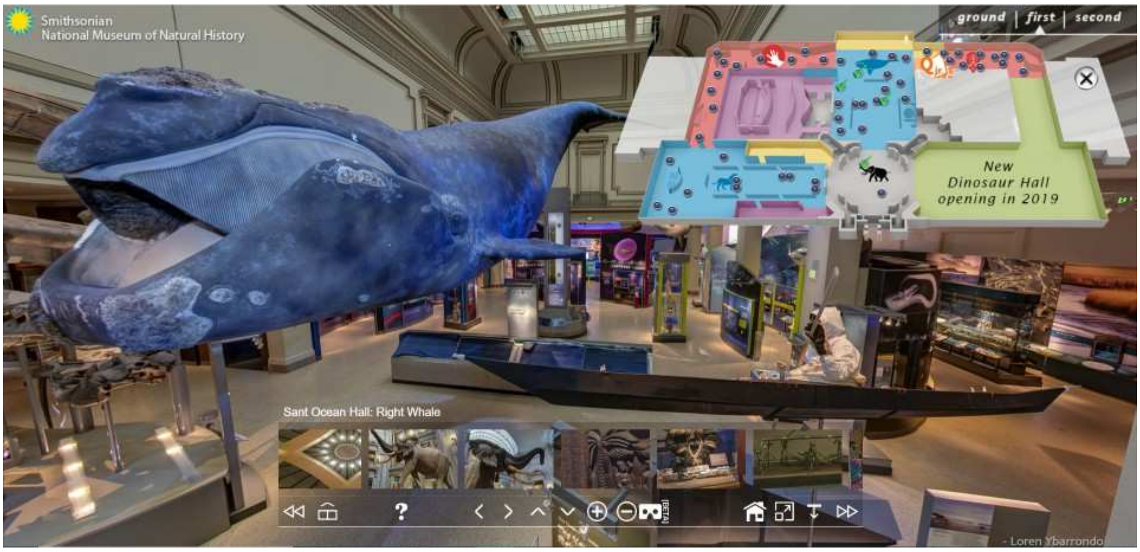
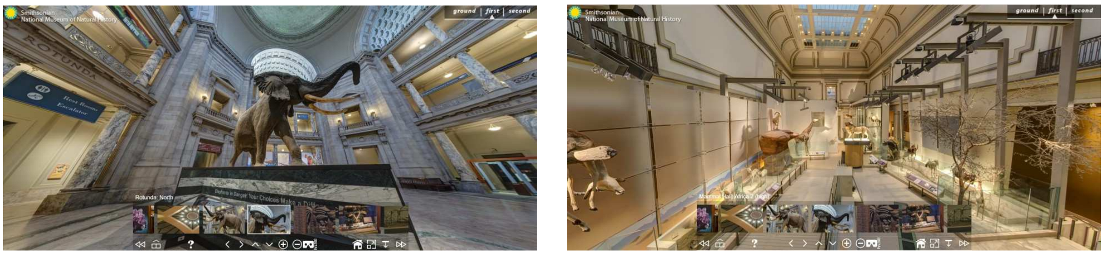


Figure 4.11: The Smithsonian National Museum of Natural History virtual tour of the Ocean Hall [188]



(a) Virtual tour of the Rotunda Hall

(b) Virtual tour of the Mammal Hall

Figure 4.12: The Smithsonian National Museum of Natural History virtual tour [188]

Metropolitan Museum of Art

The 360° virtual experience, shown in **Figures 4.13** and **4.14**, offered by the **Met** in New York, presents a wide access to six rooms of the historical periods of America. Each on line room presentation offers, of course, not only a visual tour, but also contextual information about the collection artworks, about the architectural aspects and about the interior design of the space.

Figure 4.13: The Metropolitan Museum of Art 360° tour experience [187]

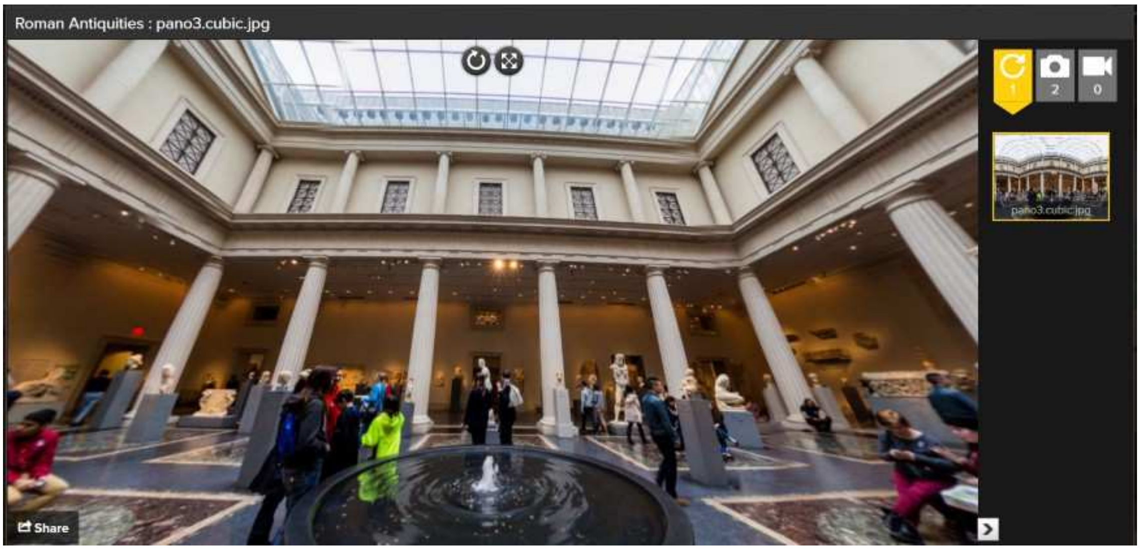


Figure 4.14: The 360° tour experience [187]

Vatican Museums

Also the Italian Museums of Vaticano has joined the big family of virtual tours that offer people the possibility to visit, at a 360° (**Figure 4.16**) at a really high definition quality, not just the famous stunning frescos of Sistine Chapel (**Figure 4.15**) or Raphael's Rooms but also the Gregorian Egyptian Museum, the Ethnological Museum, the Pinacoteca, the Gregorian Etruscan Museum, the new wing and so many others.

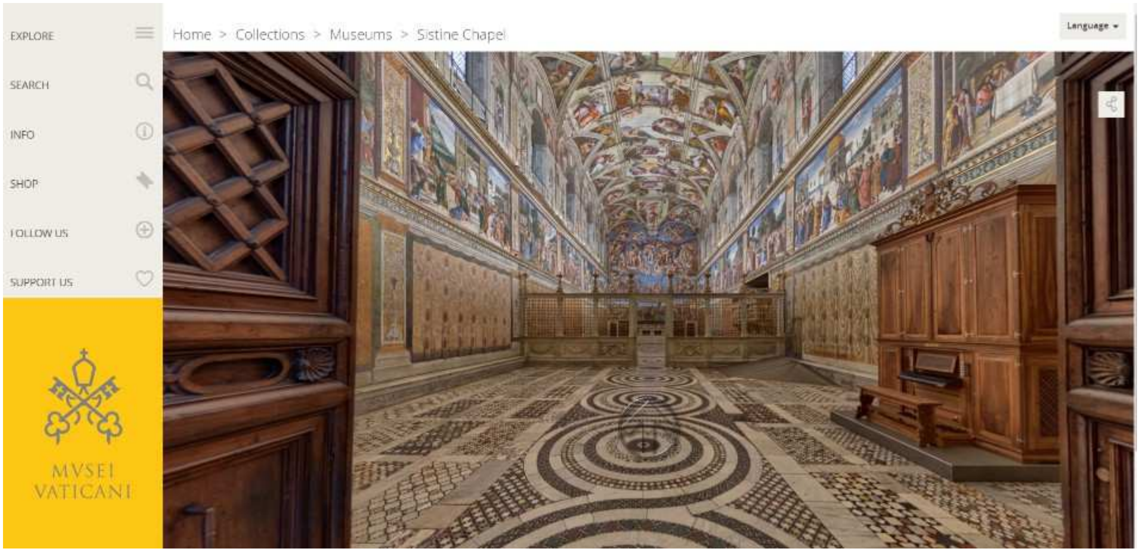


Figure 4.15: The Vatican Museums 360° exploration tour [128]

(a) View towards the entrance door

(b) View towards the Sistine Chapel wall

Figure 4.16: Virtual tour views inside the Sistine Chapel [108]

4.6 VH Learning for Heritage at risk

There's a wide difference between **reconstruction** and **simulation**: apparently they are two terms really similar, in a deep view, they are based on two different purposes.
Reconstruction literally means the process of building again or creating something that has been damaged or destroyed. In the specific archaeology field it means to complete a site or a building, conjecturing the missing parts of the building/site according to the left ones and through the old sources. While simulation, doesn't start from the representative task, but its purpose is to simulate a reality thanks to different languages and not yet linked to the conventional experiences [195].
Virtual Heritage Learning aim is to provide audience an analogical process where the external observer point of view about reality may be the same of a symbolic and synthetic system or, in other words, a **model representing the reality** [195].
Representation can be more or less adherent with reality, reason for what, according to the different data source types of VH projects I've divided three main categories of Virtual Heritage learning models, which are mathematical models, ranging from the modality of **sources gathering** (Documentation), passing through the **modelling processes** (Representation) until arriving to the **displaying way** (Dissemination) which are, for citing Ibrahim, the VH domain (**Figure 4.17**).

- **Reality-based** models, **surface** or dense models hailing from 3D laser scanning operations which is the section that I'll be facing with more careful than the other two;
- **Geometry-based** models, that are 3D reproductions based on two types of modelling:
  - Solid-based modelling, or Construction solid geometry (CSG), a 3D conceptual representation method based on elementary solids;
  - Volume-based modelling, a representation method based on the creation around a geometric point of a volume performed by voxel;
- **Simulation-based** models, or procedural modelling, which are nothing but theoretical reconstructions of models aided by automation software;

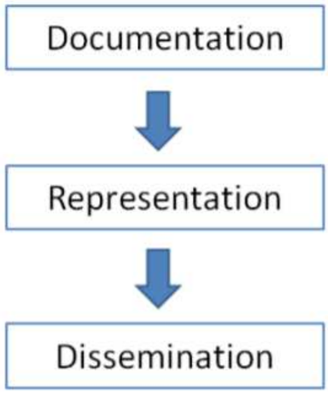


Figure 4.17: Virtual Heritage domain [85]

4.7 Reality-based models

It's undeniable that recent events have *"dramatically highlighted the vulnerability of the world's material cultural heritage"* [107] but it's undeniable at the same time, that much more vulnerable is the object taken in exam and more attention into documentation, protection and enhancement it'll require. As the London charter underlined, the main goals to pursue are defined by a **scientific rigorousness approach** of sources recording, model creation and at last visualisation with large-scales immersion platforms.
The added value of reality-based models [31], despite other kinds of models, lies really in its **metric** and **Geo-referenced** origin based on integration approaches of Geomatics technologies, ICTs and computer graphics that have occurred to document, to safeguard and to enhance "digitally" and "virtually" some of the *"most at-risk heritage objects, sites and places"* [107].
Many 3D metric survey recording methodologies and sensors (*Photogrammetry, 3D Laser scanning, surveying*) are available nowadays to achieve the required **Level of Detail (LOD)** of a 3D model, but the best approach lays on the **integration** (**Figure 4.19**) of the LODs of each *Multi-resolution data* source [158] to pursue a *"more complete and photo-realistic result"* [160].
An increasing method for recording existing architectural spaces, large scale overviews in a scientific approach based on the reality data, nowadays is the already mentioned LIDAR technology whose records called **point clouds** shown in **Figure 4.18** are made up of points in a three-dimensional system of coordinates.

The great qualifying and sometimes underestimated aspect of 3D laser scanning equipments and methods, lies in the richness of interoperability with other 3D survey approaches performing that integration but also the richness of use for the research, the protection and enhancement processes [26].
Point clouds can easily be kept as scans that makes it possible to see through the point surfaces and point walls for a better understanding of the internal architecture spaces complexity, or they can be converted in polygonal meshes in order to apply textures and to render them like any other 3D models.
The potentialities of surface models don't end at this step because the scanning operations and the following processes can flow into video animations, environment and landscape reconstructions for the architectures in exam or, more in line with the modern times required experiences, virtual walk-through immersions [10] and educational **serious games** development for cultural heritage.

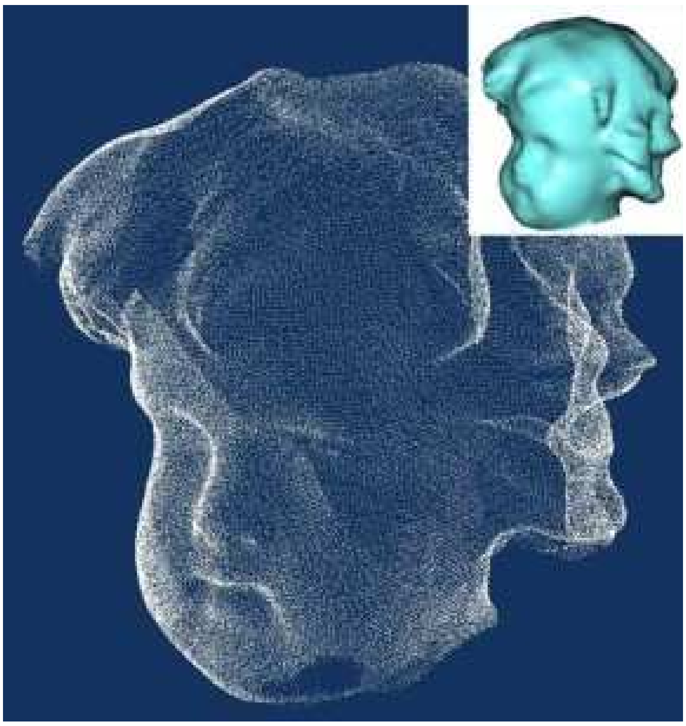


Figure 4.18: Example of a point cloud of an object from a 3D laser scanner [174]

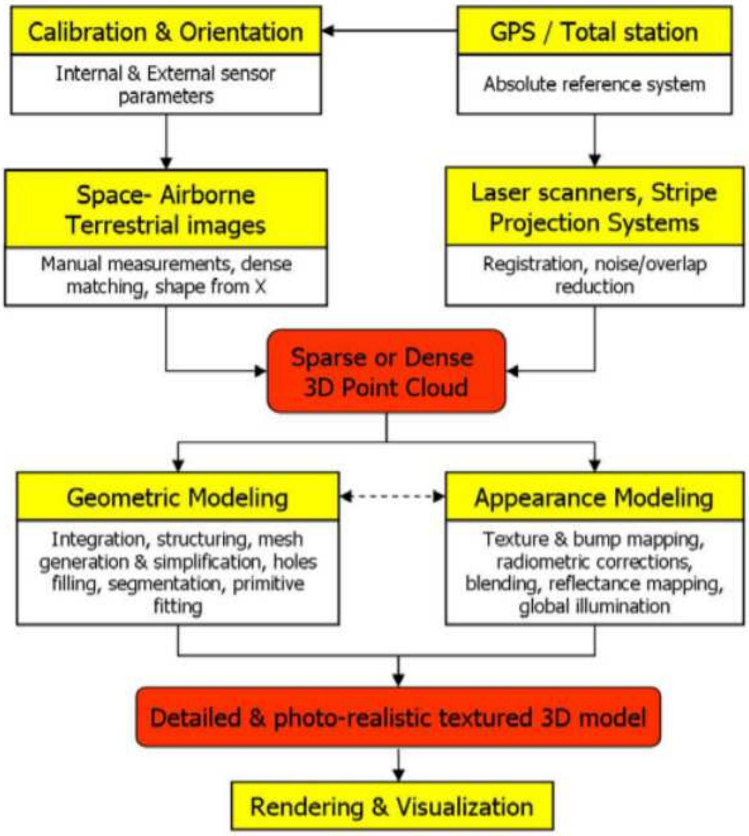


Figure 4.19: Multi-sources integrative pipeline to a photo-realistic 3D result [158]

Digital Segusio

The digital Segusio project is, for using the authors words *"[...] the result of intensive discussion and exchange of data during the urban landscape documentation activities, and due to the technology of virtual model generation, making it possible to recreate the charm of an ancient landscape"* [182].
Segusio was the ancient name for Susa (near Turin, North of Italy) and it's related to Celtic roots since it means "Victory" and a doubtless proof of the Roman invasion is the Augustus Arch showed in **Figure 4.20**. Furthermore the city of Susa has been also the main subject of a didactic project about the 3D reconstruction (**Figure 4.21**)of the whole ancient city [23] that has required a cartographic system approach rather than the others derived from the survey.

(a) Integrated photogrammetric and laser scanning model of the Arch

(b) The 3D model Arch, result of the cooperation between the DIRECT team from Politecnico di Torino and 3D Optical Metrology

Figure 4.20: Models of the Arch of Augustus in Segusio [182]

Figure 4.21: 3D Reconstruction of the city of Segusio [23]

3DP ARCH project

The 3D Digital Preservation of At-Risk Global Cultural Heritage (3DP-ARCH) is an American project in collaboration with other digital heritage projects linking together the UC San Diego, Berkeley, Los Angeles and Merced for studying, monitoring, preserving and curating at risk heritage data with a wide employment of recording technologies based on the integration of UAVs, LIDAR, 3D GIS, digital mapping, augmented and virtual reality. All have active research projects in countries with at-risk cultural heritage, notably in Cyprus, Greece, Egypt, Ethiopia, Israel, Jordan, Morocco, Turkey (**Figure 4.22**). The project:

- *"Takes advantage of PRP (Pacific Research Platform) one of the highest-speed fiber optic networks in the world;*
  - *Melds state-of-the-art 3D scientific visualization with large-scale immersive platforms for museums and public places in addition to serving inexpensive personal virtual reality (VR) devices;*
  - *Confronts the problem of Big Cultural Heritage Data (BCHD);*
  - *Develops citizen-science crowdsourcing programs;*
  - *Provides unique learning opportunities to prepare students to use new information technology tools to enhance their career paths"* [107].

Figure 4.22: Cultural Heritage at-risk map of the project[107]

3D Arch project

The 3D Arch project is an Italian project born in 2005 in partnership with FBK in Trento and NRC in Canada based on recording and modelling completely geometric data of several castles in Trentino province, in the North of Italy. The approach used combined active and passive sensors in order to exploit the advantages of each technique for internal (**Figure 4.23**) and external areas (**Figure 4.24**)[161].

Figure 4.23: Textured model of an interior view of Valer Castle [161]

Figure 4.24: The modeled castles (Beseno and Stenico)of the surrounding landscape and visualized with Autodesk LandXplorer [161]

The Roman forum of Pompeii

The forum of Pompeii was digitally reconstructed (**Figure 4.25**) integrating aerial images, TOF terrestrial laser scanning, close-range images, GPS data for the absolute geo-referencing [162].

Figure 4.25: The integrated model of the forum of Pompeii [162]

4.7.1 Geometry-based models

Geometry-based models show the relationships between the constituent parts of objects or buildings in a mathematical way. They have important roles since they conceive the design in order to solve construction difficulties and to monitor the object anomalies.
These models are based on two kinds of modelling [221]:
Solid-based modelling, also called Construction solid geometry (CSG) is a 3D method of objects construction, commonly used in technical and CAD fields, based on the use of primitive geometric solids (such as parallelepiped, sphere, cone and so on) which are supposed to create complex volumes through boolean operations of them (Union, Subtraction and Intersection), extrusions and smoothing operations. A particular kind of solid-based modelling also used in CAD field and mechanical engineering applications, is the **parametric modelling** based on features where solids are in relationship through mathematical, geometric and physic parameters and they are created with analogous operations to the ones used for the true realization of them.
Volume-based modelling, is a representation method using voxel (which is the 3D volume unit in volumetrical graphic field) that generate a volume around a geometric point in the space that will be displayed and rendered.

4.7.2 Simulation-based models

Procedural modelling is a 3D modelling method aided by software which support the automatic or semi-automatic creation of the wanted geometry. According to the needs of applications, there are lots of software generating or software simulating 3D volumes, mesh or surfaces.

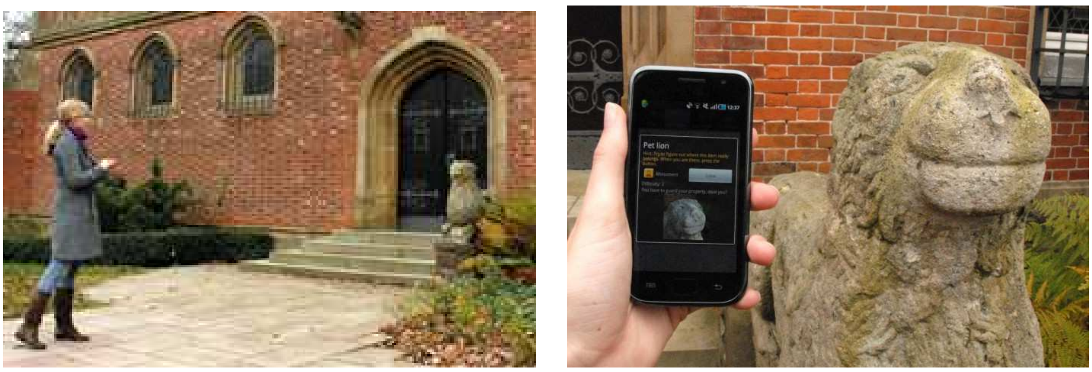
4.8 Serious Games based on CH

The increasing appealing interest of people and teachers about unconventional methods of teaching and learning, is meeting with wide application the development of these SGs that make use, in cultural field, of historic sites or ancient buildings as digital and virtual learning environment for 2D or 3D interactive experiences.

They are not just useful for students because with the web and mobile applications (smartphones, tablets etc) everyone, also the less involved in the field, can get closer to it and benefit them without getting a tour guide or sitting again in a school classroom.
We can divide two main category of SGs based on cultural heritage [126]:

- **Heritage awareness** SGs;
- **Historical reconstructions** SGs;

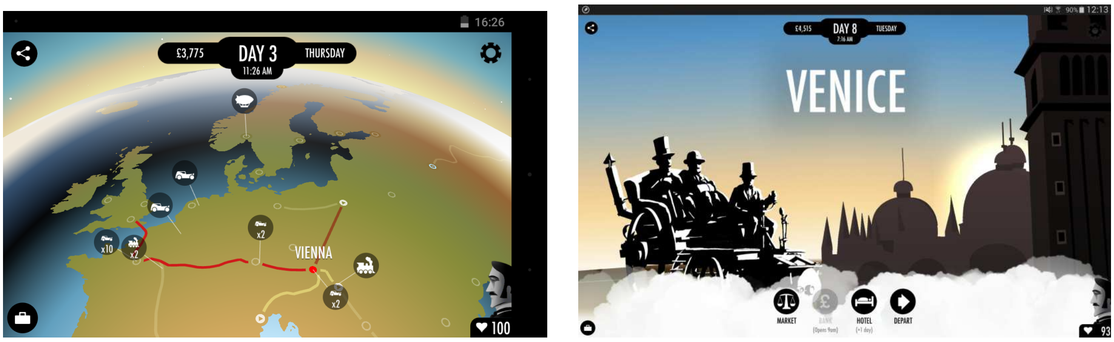
The formers are kinds of educative games that existed in the past just in the 2D dimension, reason for what they were not as engaging as in recent years which they exist mostly offered in a three-dimensional, total immersive or mixed reality experiences for let the audience appreciate architectural, archaeologic and naturalistic values or simply in order to give users a motivation to have the real experience [126].
For citing a couple of examples, ***Tidy City*** [193] is a MR real location-based game so it's played just outdoor, in real time and with mobile platforms. The innovative aspect lies in the purposes for the gamer as it's visible in the **Figure 4.26**, of solving riddles getting to specific places around the city, on foot, by bus, by whatever transport is good for the user, to spot unseen cultural objects or buildings, to explore new places where the unsolved riddles are waiting and to learn about them and about city's CH.



(a) The place-spotting phase **(b)** The riddle-solving phase

Figure 4.26: Tidy City mission [193]

80DAYS [4] is another serious game project developed by the European Commission [61] to support the virtual learning through serious game about geography, architectural and naturalistic world heritage. As the title underlines, it took inspiration from Jules Verne's most famous novel *"Around the world in eighty days"*. In this case, the heritage environment is not real-based but reconstructed and the player has 80 days to reach every city with a initial low amount of money using the several arranged transports for the journey routes before the other players do it (**Figure 4.27**).



(a) The 80 Days Map **(b)** The Venice stop-over

Figure 4.27: 80 Days game [4]

The seconds kinds of games are based on 3D historical reproductions, available also in virtual immersions, of 3D geo-referenced modelling of ancient building, archaeological sites [21].
A clear example was ***"Pompeii: The Legend of Vesuvius"*** released in 2000 (aka TimeScape: a Journey to Pompei), a first-person template (FP) where the main character, Adrian Blake has to save himself and the second female character before the cataclysm occurs. The narrative path, beyond the game, provides the users a **real map** of Pompeii, shown in **Figure 4.28(a)**, with an **in-game encyclopaedia** that is interactive and gives a great insight of the city as it once existed for the user enhancing knowledge. After eighteen years, the CIN technology of the FP perspective (**Figure 4.28(b)**) with 3D 360° imaging rotations is still effective in the latest games and it's a timeless example enhancement and learning of cultural heritage.

(a) FP perspective of Pompeii **(b)** Interactive real Pompeii map

Figure 4.28: Pompeii: The Legend of Vesuvius game [71]

Rome Reborn [166] is an international SG project whose primary aim is the creation of a 3D digital model able to illustrate the ancient Rome (**Figure 4.29(a)**) development: from the late Bronze Age to the Middle Age.
This great VH project has met the collaborative field of several institutions and universities such as the Virtual World Heritage Laboratory of the University of Virginia, the UCLA Experiential Technology Center, the Reverse Engineering Lab at the Politecnico di Milano, the Ausonius Institute of the CNRS and the Bordeaux University. They collaborate about the secondary aim:

> *" [. . .] to create the cyber-infrastructure whereby the model could be updated, corrected, and augmented. Spatialization and presentation involve two related forms of communication: (1) the knowledge we have about the city has been used to reconstruct digitally how its topography, urban infrastructure, shown in **Figure 4.29(b)**, (streets, bridges, aqueducts, walls, etc.), and individual buildings and monuments might have looked; and (2) whenever possible, the sources of archaeological information or speculative reasoning behind the digital reconstructions, as well as valuable online resources for understanding the sites of ancient Rome, have been made available to users."* [166]

(a) Bird-eye view of Rome

(b) Aerial view of Rome cyber-infrastructures along the Tiber river

Figure 4.29: Rome Reborn images [166]

Chapter 5

St. Nicola in Tolentino Case study

Following the time-line of the recently seismic happenings that strongly shook and shake so far the Italian territory, the centre of Italy for the accuracy, it came across to me the volunteer of action somehow among the emergency and the **cultural heritage at risk** field: from the study of the level of criticality of structures in earthquake and post-earthquake phase, to the idea of contributing the documentation actions in order to preserve the cultural buildings in terms of protection and future fruition or availability of them.
These, though, were only few of the pushing motivations since they were contained inside a bigger work-flow where students from all the university formative paths, Engineers and Architects, have the opportunity to work and to study together comparing and sharing knowledges. Indeed, the Politecnico of Turin Team that operates in this field, the **Di**saster **Re**covery **T**eam (**DIRECT**) [51], gave me the *"leit movit"* and the opportunity, since I'm a team member, to face these new situations and experiences.
The Direct, is a student team, coordinated by tutors, that operates in all the phases of the Disaster Management: from the vulnerability analysis to the early impact, passing through the capacity building or in other words the educational process in the field of the emergencies management, the Geomatics and the 3D metric survey. Like the Sofia declaration underlined, the responsibility of the recording and the knowledge building process is entrusted in a compensation of several abilities, skills that help each other, at the same way: my second necessity took inspiration from the **interdisciplinary** matrix having its tangible example in the didactic sharing among the Department of Architecture and Design (DAD) in

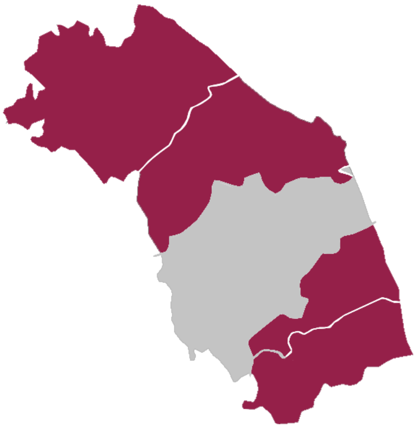
a deeper way the Geomatics for Cultural Heritage Laboratory [143], the Department of Engineering of Environment, Territory and Infrastructures (DIATI) with its Laboratory of Fotogrammetry, Geomatics and GIS [144] and the collaboration of the Department of Structural, Civil, Construction and Geotechnical Engineering (DISEG) [145] of Politecnico of Turin.

Figure 5.1: Polito Direct team logo [51]

5.1 Territorial overview

The church of San Nicola is situated in the municipality of Tolentino (province of Macerata), in the Italian central region of Marche. Tolentino has a surface area of about 95 kmq hosting 19.698 inhabitants [101]: this information is referred until the date 31 March 2017.
Starting from the administrative point of view, its geographical boarders consist of several percipient municipalities such as, Belforte di Chienti to the South-West, Macerata to the North-Est and Pollenza to the North. As already disclosed, Italy and in particular way, the centre Italy, is really affected by seismic events due to its fragile position between two plates and the geological composition of the territory that we'll see in the next sub section of this chapter.

(a) Region of Marche



(b) Province of Macerata

(c) Municipality of Tolentino

Figure 5.2: Territorial overview of Tolentino Municipality, Elaboration: Carla Borriello

5.1.1 Urbanistic aspects

Within the administrative and urbanistic context, the Church of San Nicola is highlighted in red inside the regional digital **Figure 5.3** (1:5000 scale) and it's classified by the **General Regulatory Program** (PRG) for the municipality of Tolentino [40] as an **A1** area showed in **Figure 5.4**, the historic centre of the municipality or rather an area where lays an architectural property, heritage of historic and cultural interest.
Our case study indeed like the entire buildings district (A2) (VP1) are subjects of monitoring and supervising operations from the Superintendence of cultural properties and furthermore, they are vulnerable to restoration and conservative renovation also because of some buildings are susceptible to archaeological protection (SA).

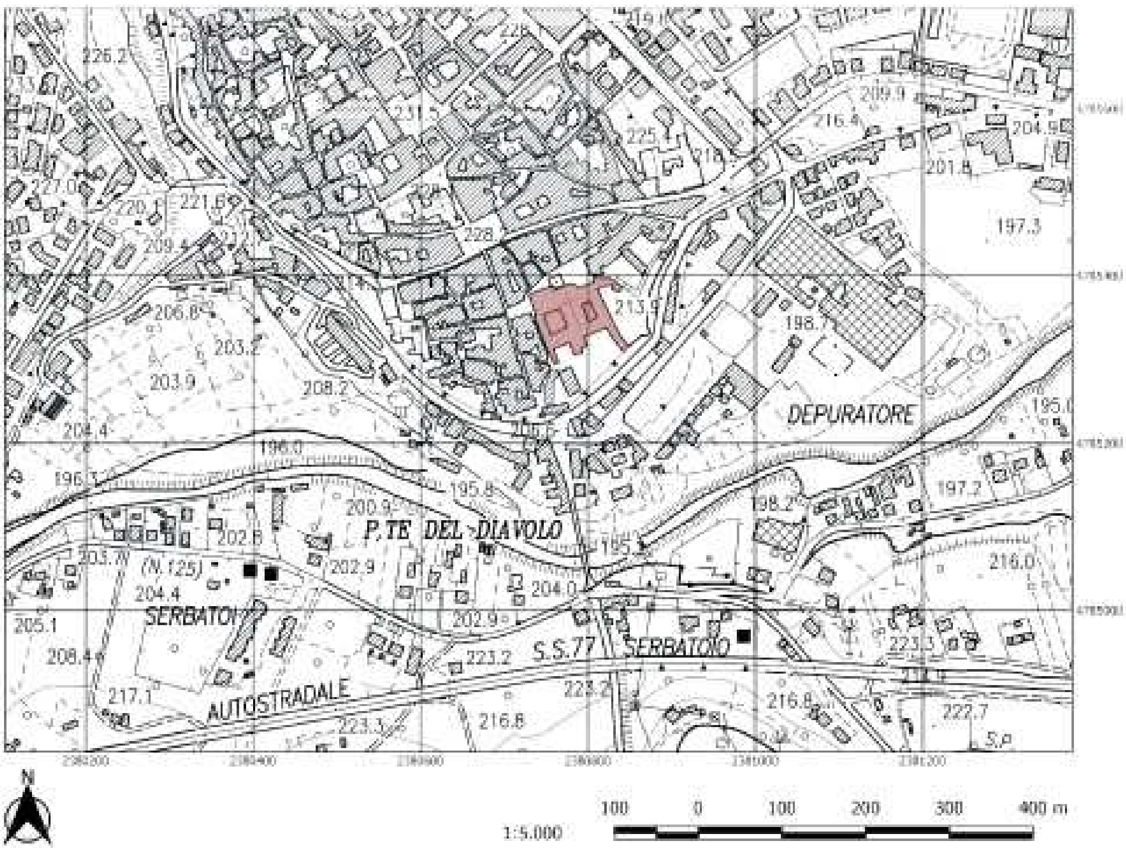


Figure 5.3: Extract of the regional digital map of Tolentino [155], section 302160

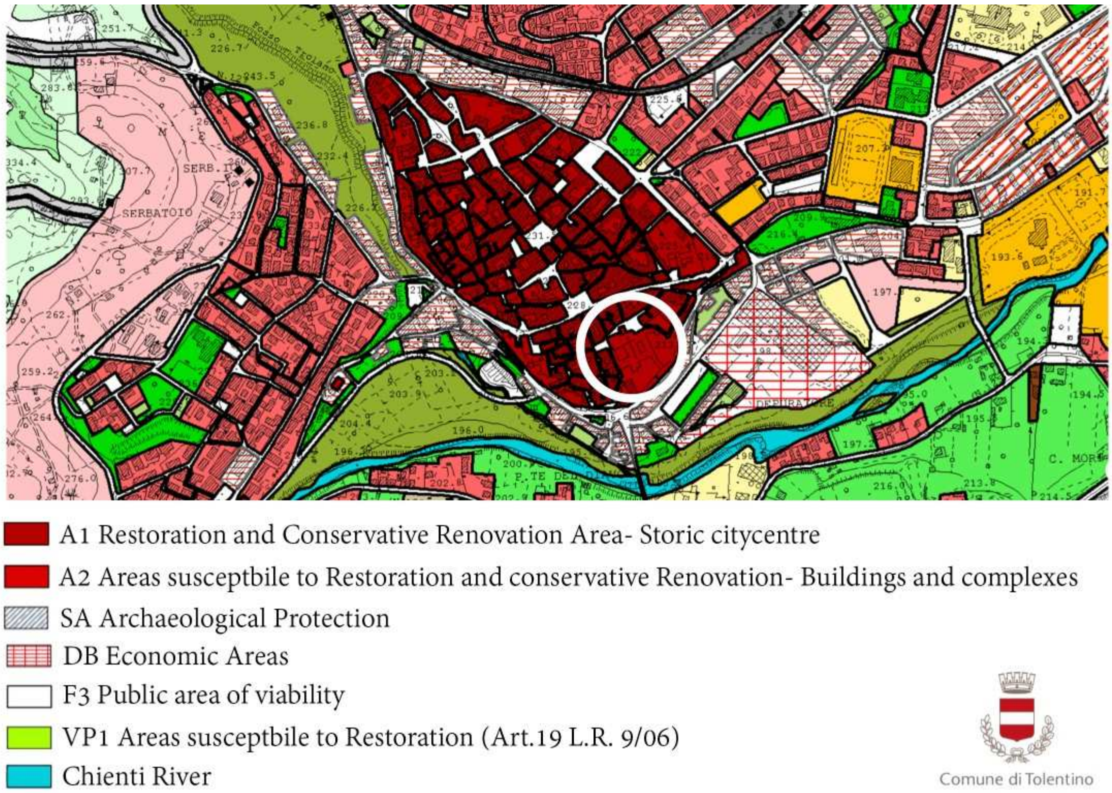


Figure 5.4: General Regulatory Program Map of Tolentino [39]

5.1.2 Geological aspects

Orographically speaking, the territory of Tolentino is considered in the middle-hilly country slot of Marche, with heights included between around 150 m and around 523 m on the sea level. Geologically the territory is characterized by sedimentary rocks, formed by the continuous store of deposit sediments, other rocks from landslides or river floods, organic materials and so on. If we have a look at the Geological map of Italy, by the High Institute for Protection and Ambiental Research (ISPRA) [99], it's possible to understand in **Figure 5.5** the two common kinds of sedimentary rocks complexes:

1. **"Laga rocks"** (LAG_3), it's a rock complex mainly made by sandstones and not for casualty the area is really next to the river.
2. **"Gypsum rocks"** (GES), it's talking about clays, limestones and gypsum stones.

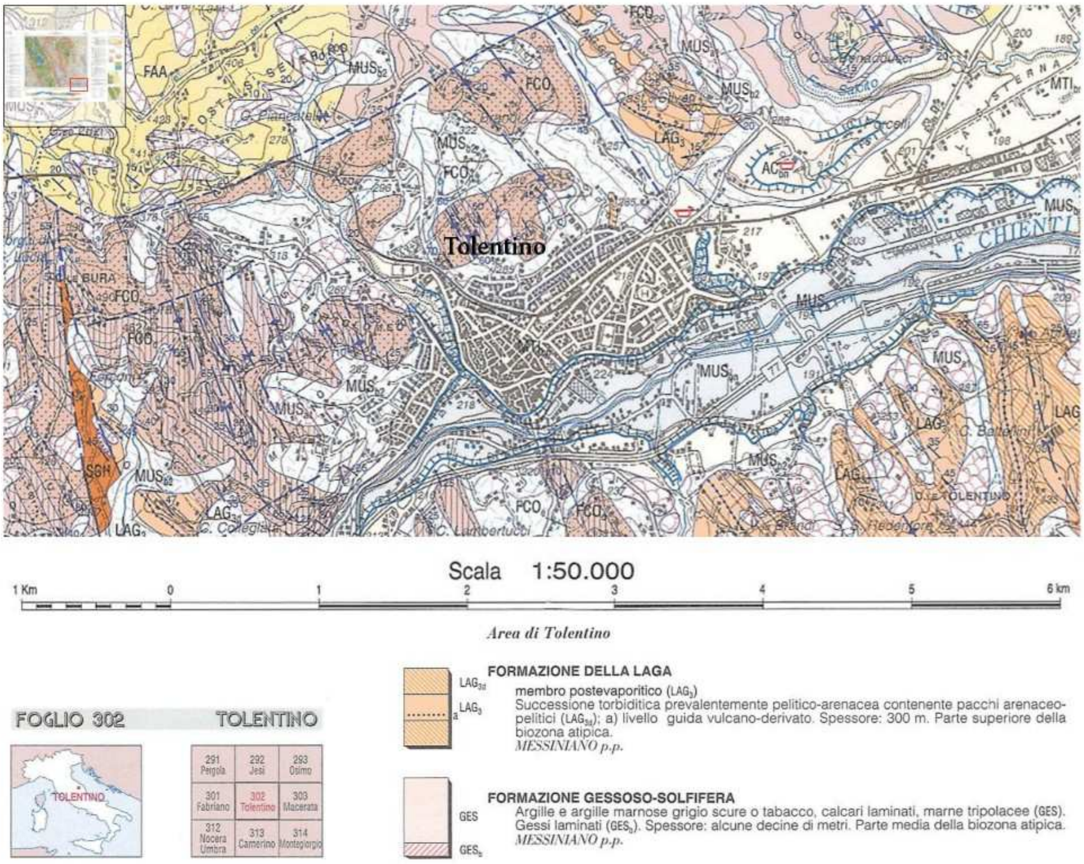


Figure 5.5: Excerpt of the Geological map of Tolentino territory [99] (Topographic base from Italian Geographic Military Institute with authorization IGMI n°4729 of 19/01/98)

Of course, the variation of kinds of rocks, sandstone and clay ones, has territorial consequences dued to the different mechanical characteristics of them. Indeed, the sandstone rocks are characterized by a bigger granulometry rather the clays, and so are more resistant to erosion dynamics.
On the contrary, the clay rocks are really sensible to the atmospheric phenomena and more inclined to hydrological instabilities [157].

5.1.3 Hydrological aspects

For what concerns the hydrological asset, the municipality belongs to the river Chienti hydrografic basin mainly. As seen in the previous section, the presence of rivers was already proved by the geological composition of the terrain made mainly of clay rocks especially above the river proximity where the terrain it's really permeable (Class I and II) like it's shown in **Figure 5.6** and surrounded by debris of landslides.

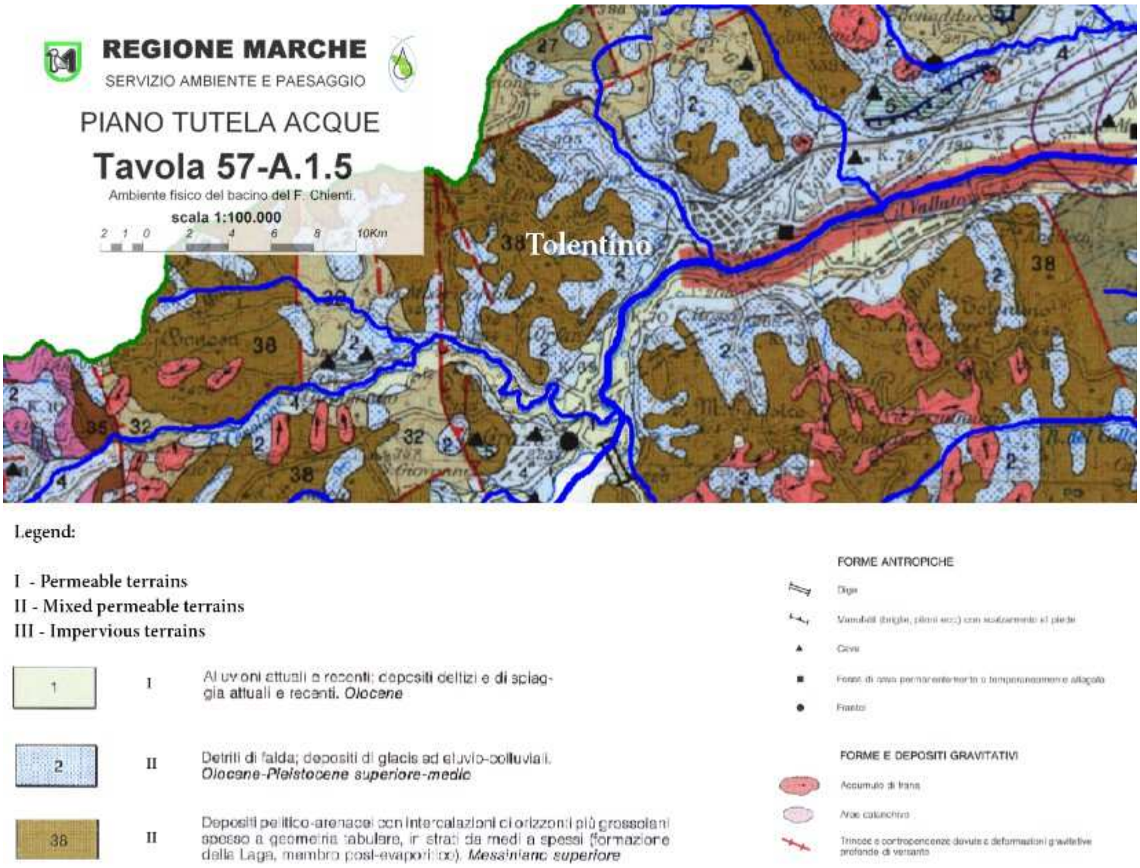


Figure 5.6: Excerpt of the PTA map about the physical environment of the river Chienti: (Tavola 57-A. 1.5) [156]

5.1.4 Seismic aspects

As the seismic risk of Italy it's really high it has been introduced specific technical laws for the construction of buildings, infrastructures and architectures. The seismic risk for Tolentino, presented in zooming **Map 5.7**, is classified in the second area. This is warranted by the presence in the tectonic map extracted from the Geological one [129], of direct faults shown with red lines in the **Map 5.8** below.

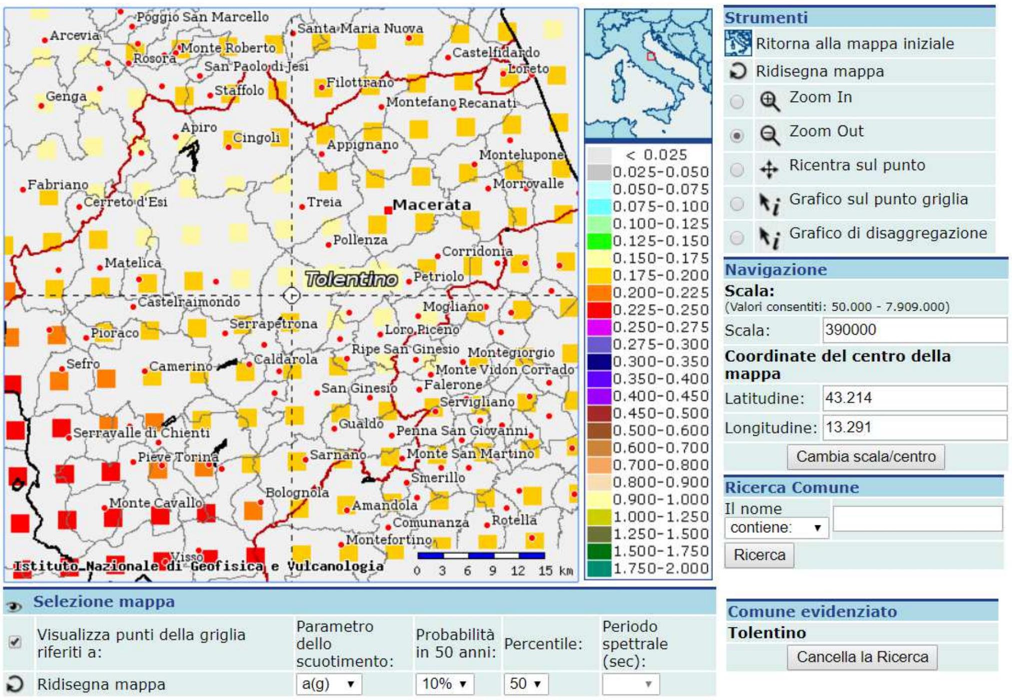


Figure 5.7: Interactive seismic hazard map of Tolentino, INGV [95]

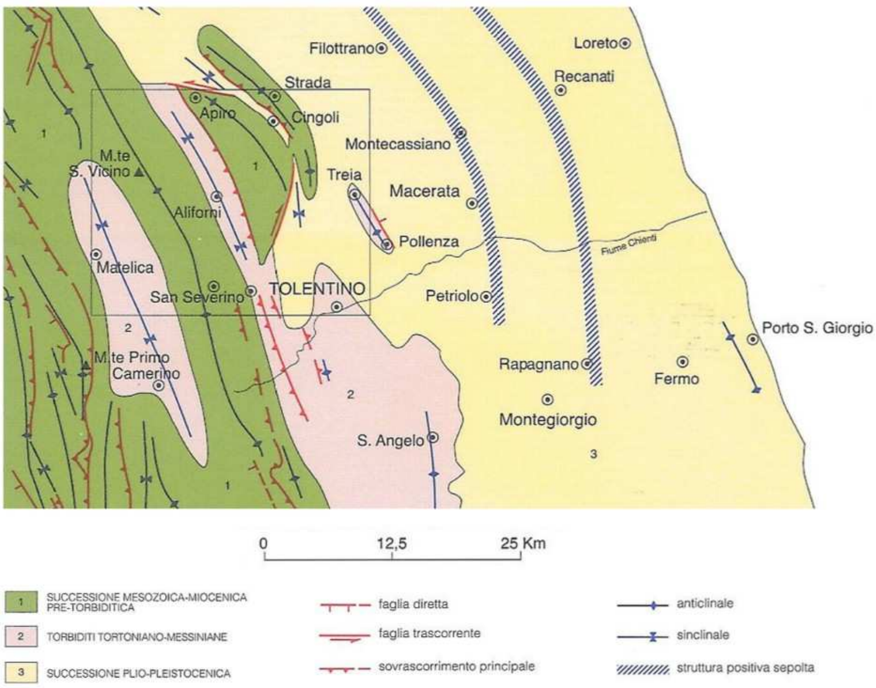


Figure 5.8: Tectonics map of Tolentino territory [99]

5.2 Historical Framework

The Church of San Nicola in Tolentino, belongs to a conventual complex under the Hermit Monks of Saint Agostino Order (OESA) that in the second half of the XIII century was still stabilizing its power. The figure of the Saint of Nicola has established such a great point of reference on the growing path of the religious devotion, that after his death, the building complex had been dedicated to Saint Agostino until 1456, when its name was used together with the name of Saint Nicola, and has been dedicated only to Nicola from 1465 and later.
We have no sources about the very primary settlement of the Agostinian Order in Tolentino, but some historical figures [192] support the theory that this moment can be placed before the first half of the XIII century and the religious nucleus was made up of several monks of Brettino fraternity. Anyway, we have sources about the presence of the Agostinian Hermit Order before 1250, since it's proved in 1256 the so called "Big Union" wanted by the Church in order to unify all the hermit fraternities scattered around the territory.
The original nucleus of the actual conventual complex has been theorized and reconstructed by Pio Francesco Pistilli [139] but as regards the church, the topic is a little more difficult. Indeed, the religious architectures of the Marches territory never have a recurring application of some planimetric schemes, but they have peculiar elements connected to the local constructive reality. This is readable in the way of treating of the constructive techniques, materials and perimeter walls that are so typical of the culture of the Marches.
For making the chronological phases of the history of the conventual complex readable in a easy and efficient way, I created a **timeline**, presented in **Figure 5.10**, to browse year by year every important event documented by accurate bibliographies during the sections. And just because I'm an aspirant architect, I also wanted to give a graphical method correspondence to the planimetry time evolution of the Church and of the conventual complex during the centuries, basing my hypothesis on two sources:

- the current results of the 3D metric survey drawings that helped me to look back in history and make hypothesis from the recent clues to the origin ones;
- the historic-bibliographic sources of the Tolentino library;

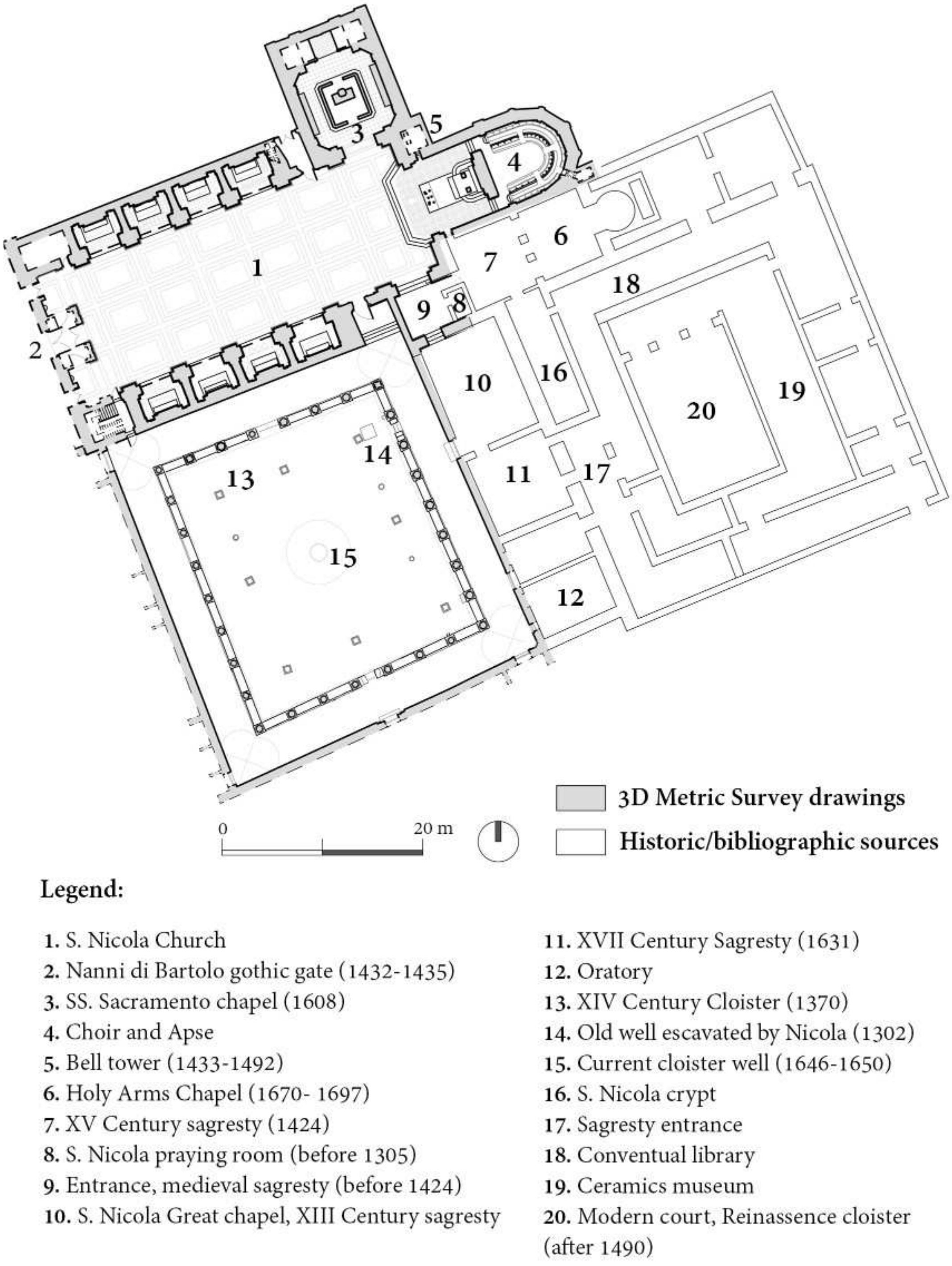


Figure 5.9: The current Church complex, Elaboration: Carla Borriello

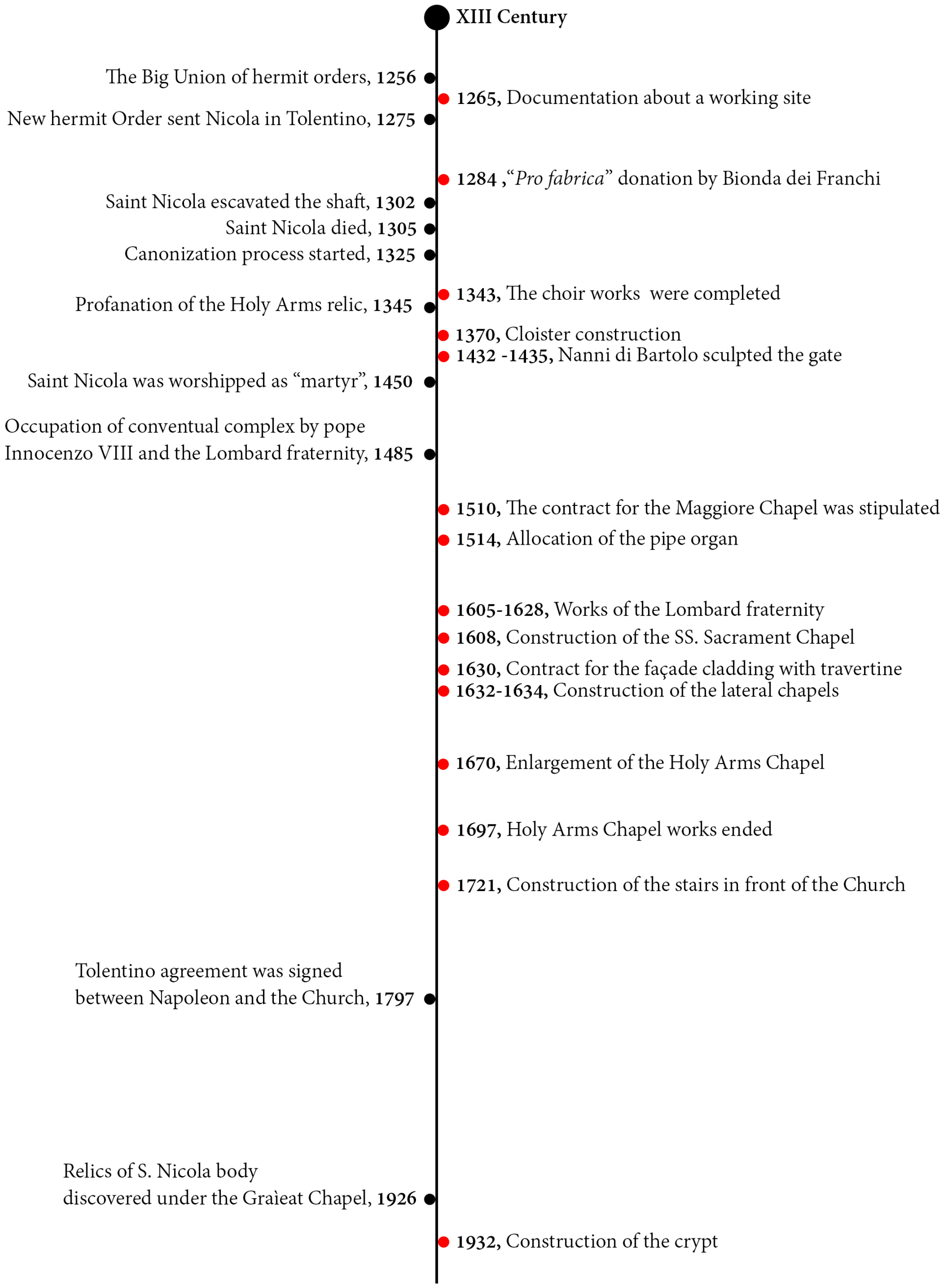


Figure 5.10: Time-line of the religious and constructive phases, Elaboration: Carla Borriello

5.2.1 Thirteenth century

The first source about the church is included inside a parchment which refers to the 20 July of 1284 when Bionda dei Franchi, Saccente di Tommaso ”de Francis” wife, donated half of her dowry:

> *” [...] pro fabrica et hedificio ecclesie S. Agostini de Tolentino [...] pro dicta ecclesia fabricanda”* [123]

There’s no valid document that proves the effective construction after that economic help and this is the reason why, the formula *”pro fabricanda”*, as in many other documents of the same period, could refer not necessarily to an edification, but more to an extension or restoration of the building.
For a better comprehension, I graphically retraced the evolution asset of the church planimetry during the centuries: in the Thirteen century, shown in my **Image 5.12**, the complex typology was probably that one referring to the architectural iconography of the late XIII century: a unique central nave plan with a only straight ending apse and a little choir. A rectangular cross vaulted presbytery, lack of lateral chapels, a wooden truss system roof in view and a simple hut façade [45].
This last one, it’s proved by the recent internal survey of the rooftop façade wall where there are still visible the old trusses and their ”readable” traces on the wall and maybe, a theoretical little cross-shaped opening in the middle of the gable with one or two lateral windows that had been stop up later with different typologies of bricks rather than the old ones.
This combination is also quite seen in churches of the same period and also in the architectures of religious orders such as the XIII century Dominican churches of S. Domenico in Cortona (Tuscany) and the same century one of S.Domenico in Siena (Tuscany) as we can see in **Figure 5.11**.
Indeed the most part of the architectural heritage of the Marches territory had in the first original asset or have so far a romanic matrix: the longitudinal asset, with an undefined transept covered by a wooden truss in view system that rests on the longitudinal walls is the most seen in the regional architectural reality [67].

Figure 5.11: Churches of S. Domenico in Cortona [115] and S. Domenico in Siena [24]

The community devotion about the person of Nicola, that was already on even before its death in 1305, may have caused, architecturally speaking, a sort of untouchability of a little compartment room that was traditionally the penitence ascetics place of Nicola showed as number 8 in **Figure 5.9**.
Indeed, its presence has caused a planimetric anomaly that can be seen in the lack of connection between the church and the conventual wing: this one doesn't attach, according the common rule for the mendicant orders, directly to the choir but it seems to be attached to a squared plan room (that is the entering way to the Great Chapel of Saint Nicola and the Holy Arms Chapel) confining in the east side with the ascetics room and its back wall doesn't align the perimeter wall of the conventual complex [45]. The great unitary of the plan shows that this asset was already clear at the starting works of 1284.

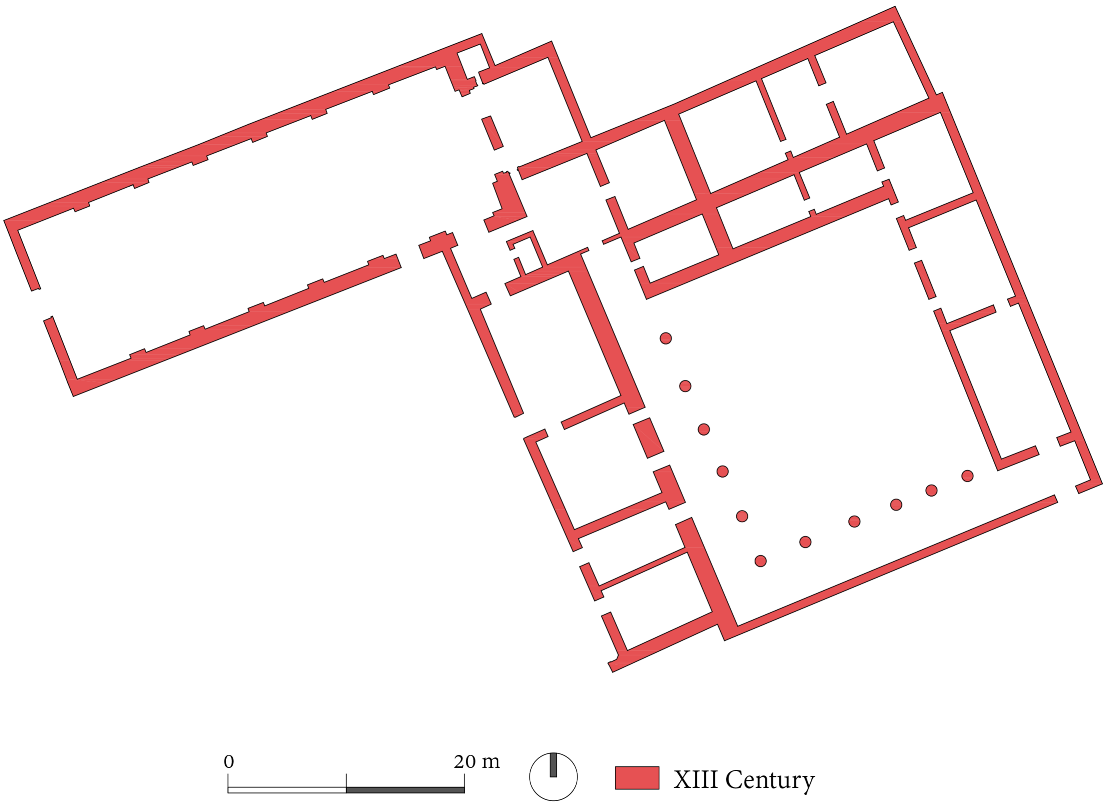


Figure 5.12: Evolution of the Church complex of Thirteenth century, Elaboration: Carla Borriello

5.2.2 Fourteenth century

The visitors devotion for Saint Nicola exploded at his death in 1305 when a big number of worshippers were closer and closer to the saint relics placed in a wooden ark in the Great Chapel of Saint Nicola, but after the sacrilegious act of profanation of the relics that happened in 1345 with the cut of the arms:

"brachia scindit sacroo a corpore divi Nicolai quadragesimo sui obitus anno" [212]

the agostinian monks decided to hide them with the body under the ground of the current Great Chapel but at that time was the late thirteenth century sagresty. So there, it necessarily started the works for the the frescos decorations. In 1309 the choir works were completed even if in 1343 there's a proof of a will left in honour of the *"Eccesiae Sancti Augustini, pro aedifitio"*[45] that would prove a further temporal extension of the works.
The canonization [131] process started in the summer of 1325 and this represented a big push towards the conclusion of the conventual wing interested in the memorial Chapel of Nicola.
In 1370 and following years, started the works for the conclusion of the cloister and the different construction times are proved by the different construction styles used in the portico capitals. Indeed, the attention lays on the disomogenity of style of the east and the west cloister wings due to the reduction of the cloister spans number for the lateral chapels as we will read in the next sections.

5.2.3 Fifteenth century

After a spiritual crisis due to the Church Scisma, the recovery period started with the end of canonization process of Saint Nicola in 1446. Between 1432 nd 1435, the florentine sculptor Nanni di Bartolo [7], called "The Red", designed the floral Gothic gate made of Istria stone in **Figure 5.13**. This gate will remain on an empty brick façade until the following two centuries.

Figure 5.13: Floral Gothic gate by Nanni di Bartolo, Ph:Alinari

In 1433 the bell tower resulted in construction according to some documents, while according to others it declared the tower already existed since 1492. From 1450 on, Saint Nicola is worshipped as a martyr and was proclaimed, with Saint Catervo, co-protector of Tolentino.
In 1459 the agostinian general Alessandro Oliva signed a contract for the construction of the choir and once completed, the church was consecrated by the bishop of Camerino in 1465 with the official title of ”Church of Saint Nicola”.
In the fourteenth of January 1485 the conventual complex was occupied with an administrative order by the pope Innocenzo XIII and the Lombard Agostinian fraternity. The arrival happened during night, but the official reason of the occupation was explained as an order of introduction of the religious reform

observance. The Lombard fraternity stayed in Tolentino until the 1810 repression. This unexpected occupation represented a decisive event for the architectural development of the entire complex: with the help of lots of artisans and other professional figures, the fraternity finally completed the open works and the adorning works of the church. In 1490 there were registered the payments for the construction of a new cloister in addition to the pre-existing one and from November 1497 it started a contract for the construction of the new dining hall.

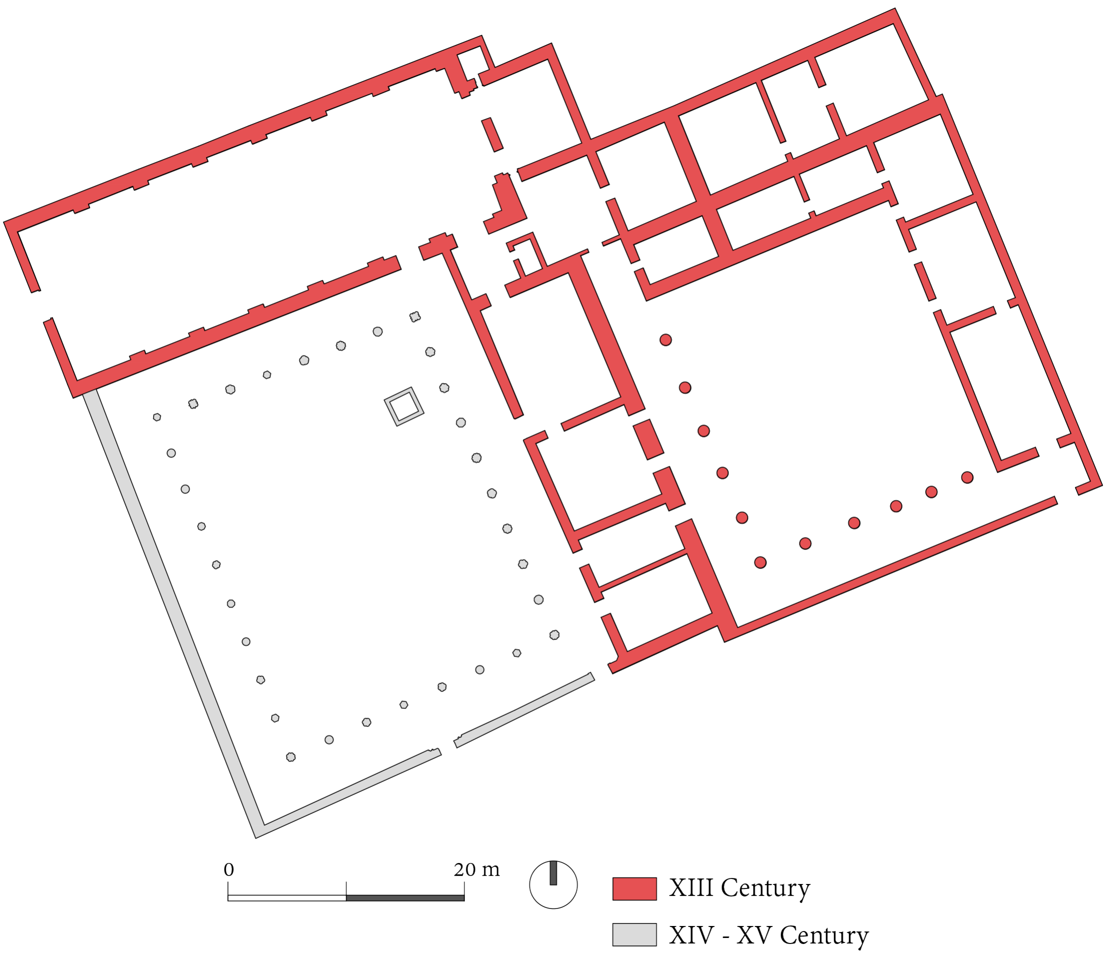


Figure 5.14: Evolution of the complex between Fourteenth and Fifteenth century, Elaboration: Carla Borriello

5.2.4 Sixteenth century

In 1503 the central nave works were completed. It seems really interesting in 1510 that was stipulated a contract for the construction of the Maggiore Chapel by Pietro and Antonio di Bartolomeo. These important figures were also involved in the reconstruction of the apse:

> *"[..] Item debano far uno bello pedocho longo in sino a la quantità et longitudine de la Sagrestia cum sette facciate nel qual quattro siano finestre, de le quali siano tre aperte et una serrata et uno ochio grande al mezzo del dicto pedocho"* [45]

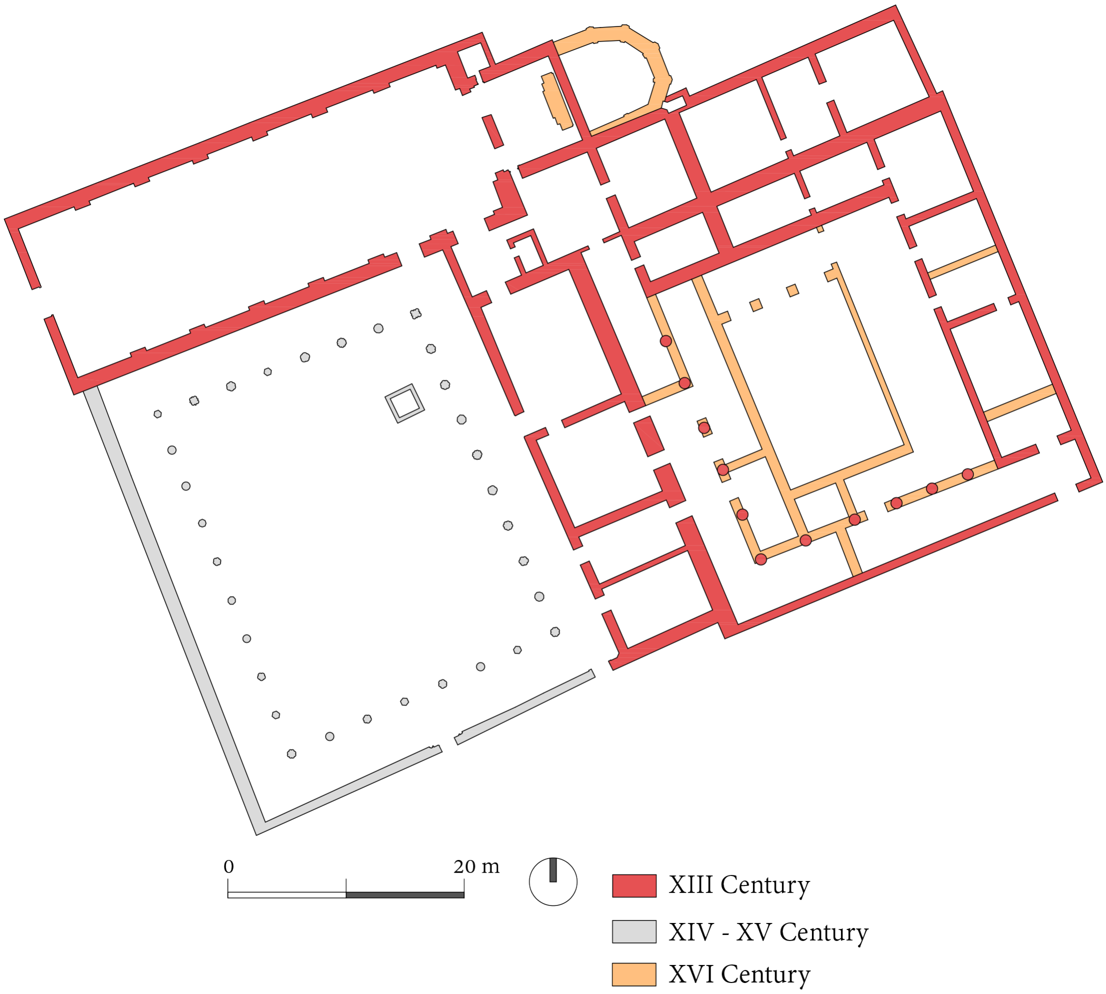


Figure 5.15: Evolution of the Church complex of Sixteenth century, Elaboration: Carla Borriello

The description obviously refers to the polygonal ending apse with seven sides and round arches and the progressive development of the Holy Arms chapel. The fifteenth century sagresty, that is the compartment number 7 of the **Figure 5.9**, situated on the right side of the presbytery was addressed to host the saint relics and due to the peregrines flows, a new dome vaulted compartment with a squared plan on the east side was constructed. We'll see, that in 1670 another compartment will be constructed of east side of the previous one: an octagonal plan room with a new altar. In 1519 the pinnacle was reconstructed and in 1510 it started a contract about a wooden structure for the allocation of the barrel organ, that was placed precisely in 1514 [124].

5.2.5 Seventeenth century

The fraternity works continued for all the XVII century: from the 1605 to 1628. The engraver master Filippo da Firenze, thanks to the volunteer of the agostinian bishop Giambattista Visconti, realized the great golden coffered ceiling of the church and from April 1608 it started the construction in the north side of the transept of the Holy Arms chapel, today dedicated to Holy Sacrament because the agostinian order decided to move the saint relics to the south side of the transept with the enlargement of the fifteenth century sagresty.
About the façade, it was stipulated a contract in the 1630 with the chiseller Florindo Orlandi di Cagli for the travertine façade cladding with the exception of maintaining the original floral Gothic gate made by the master Nanni di Barolo that will be completed only in 1767.
This new image of the church had a monumental and strong impact, infact the agostinian order decided to buy an house placed in front of the church just to demolish it and to have more space for a frontal square.
A drawing by the Conventual Archive dated 1631 (related to the project of the restoration of lateral chapels), showed in the **Figure 5.16** an idea about the transept vault where clearly appeared an evident sign of an hemispheric dome projection, but since it was an ingent economical task, it remained just a project idea.
The same year, it started the works for the new sagresty, that was the compartment number 11 of the **Figure 5.9**, by restoring the squared plan compartment of the conventual wing of the chapter house and by enlarging the way to the church by the entrance passing trough the Chapel of Nicola, compartment number 9 of the

Figure 5.9. From 1632 to 1634 the agostinian monks decided to obtain the space for the lateral chapels of the church by subtracting the space from the two cloister wings (in order not to reduce the central nave space) that reduced the number of the spans from nine to eight.
The Holy Arms chapel was completed in 1697 [122]. In 1698, monks decided to place the Holy Arms relic inside the Great Chapel, but since in the same year the works for the the new Chapel ended, it was called for the reason the Holy Arms Chapel, current compartment number 6 of the **Figure 5.9**.

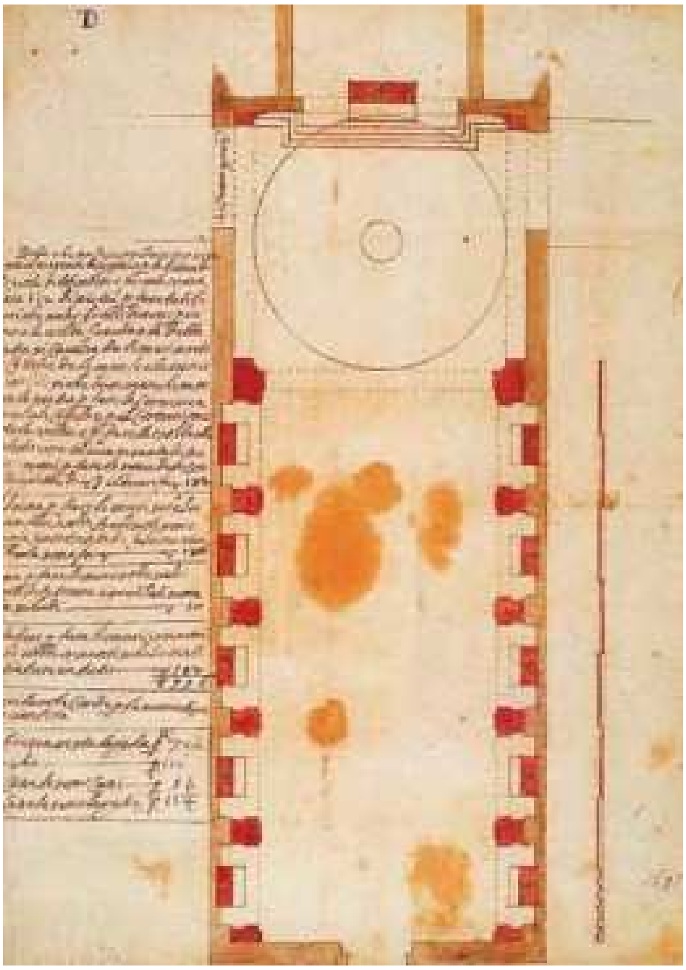


Figure 5.16: Theoretical project of 1631 about the hemispheric dome of the transept [45]

5.2.6 Eighteenth century

The new monumental façade impact was underlined in the following years with the creation in front of the church of stairs in 1721. But for the complete façade we have to wait until 1757 when Giovanni Andrea Ascani da Sant'Ippolito worked on the restoration of the pre existent façade and on the conclusion of the second order left undone. In 1765 it was demolished the mediaeval tympanum that was still on the façade and it was built a new one.

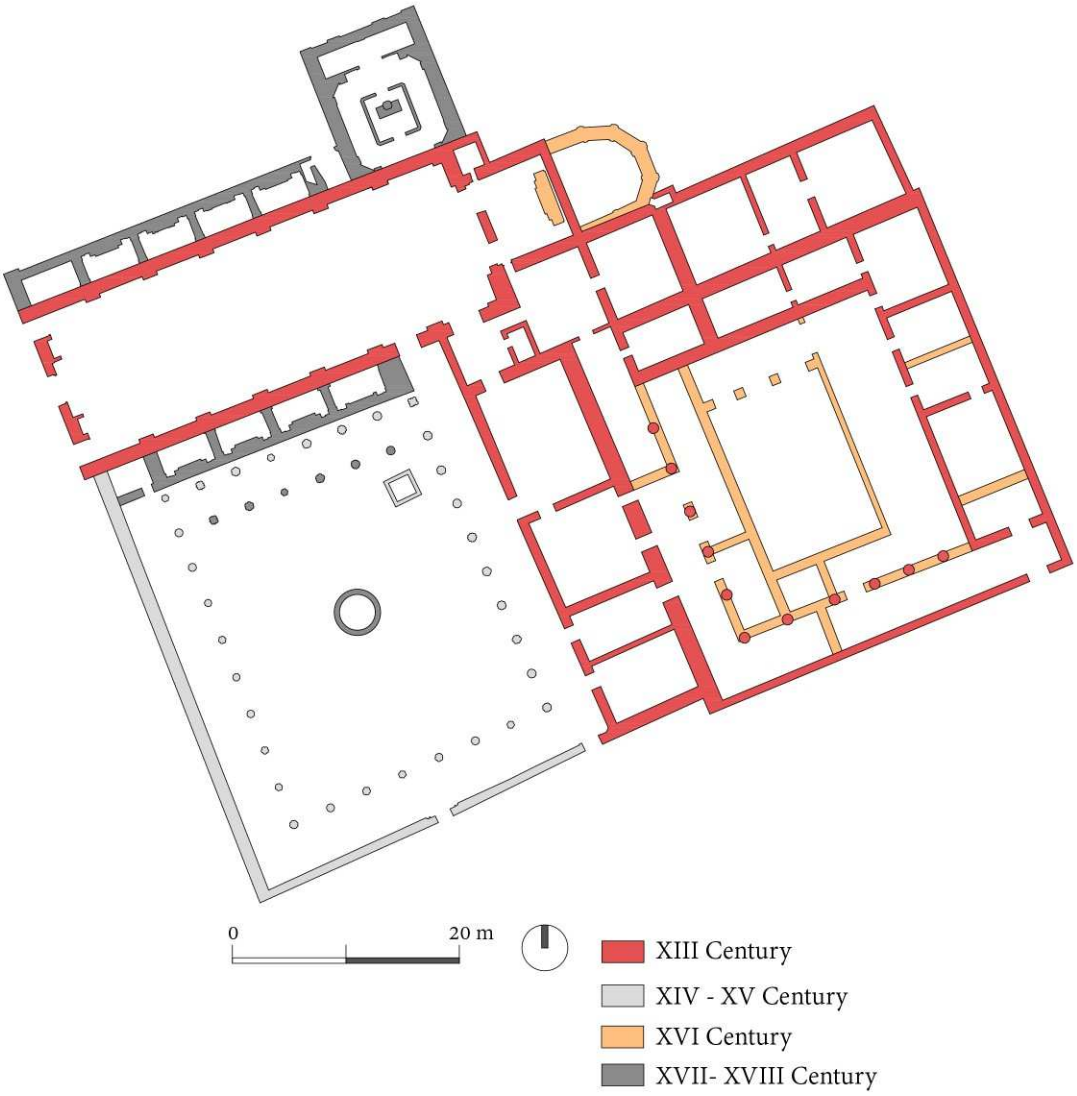


Figure 5.17: Evolution of the Church complex of Seventeenth and Eighteenth century, Elaboration: Carla Borriello

5.2.7 Nineteenth century and following years

The recent image of the church is the result of the reforms and the restoration works by the architect Giambattista Carducci. His operations consisted in the demolition of the original cross vault of the presbytery and the works for the erection of the presbytery dome in 1859. The same year, the dome was decorated with a cycle of frescos by Luigi Fontana that reproduced the famous *"The Vision of Ezechiele"* of Raffaello [45]. The 1856 project for the new pipe organ of the church was less or more as it's right now as it's possible to notice in the **Figure 5.18** drawing from the archive of the convent of Tolentino archive [124]. From that archive has been discovered also the 1900 decorative project of the central nave of the church that showed a leaning towards the marble decoration above the arcs like it's showed in the **Figure 5.19** by Cesare Caroselli.

Figure 5.18: Project of the new pipe organ by Giambattista Carducci [124]

Figure 5.19: Decorative project for the church by Cesare Caroselli [124]

In 1905 the works for the frescos of the spheric dome of the Holy Sacrament ended thanks to Francesco Ferranti, who also designed the altar of the chapel and the marble balustrade that were carried out in 1932 by the Tecchi di Fano brothers. And since a thunderbolt damaged the famous fresco of the presbytery dome by Luigi Fontana, in 1924 it was called again Francesco Ferranti for the painting restoration works. In 1926 after two years of patience searching and excavations starting from archives and old documents proof, it was found the body relic of Saint Nicola just underground the Great Chapel [124]. So, in 1932 it was created, just under the exact point where the relic was discovered, an underground crypt that completed the typological plan for a dedicatory temple in the Saint honour. In 1972 in the conventual archives is dated also the project of the doors of the presbytery by the Reali brothers [210] showed in the **Figure 5.20**.

Figure 5.20: Photograph of the presbytery doors realized by Reali brothers, Ph:M.Santilli

In the last ten years there has been conducted by the Superintendence of Monuments of Ancona lots of architectural recoveries like the museum spaces and of course, all the frescos cycle of the Great Chapel. In 2000 it has been started the restoration works of the cloister frescos while the restoration works of the same are still work in progress.

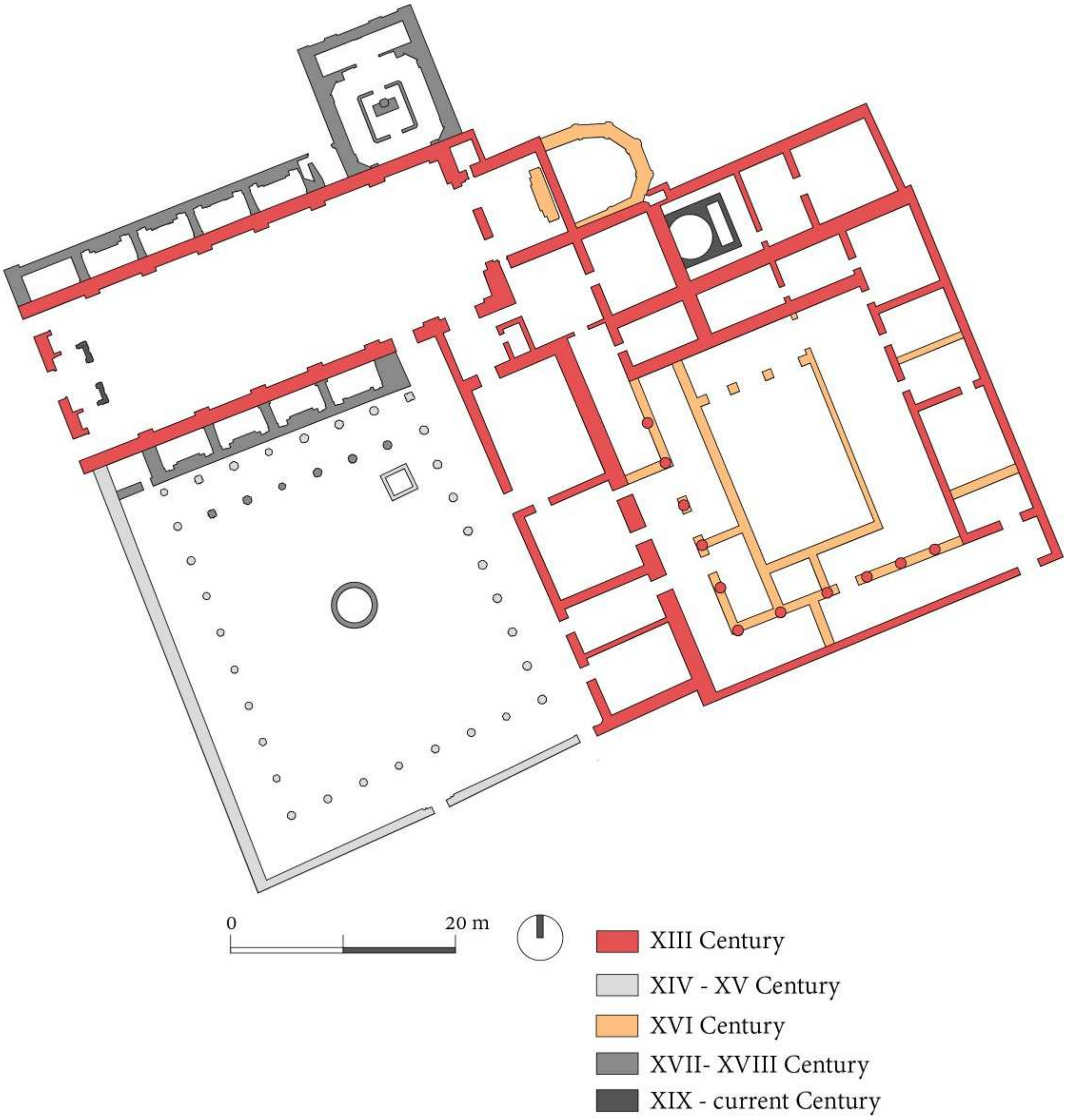


Figure 5.21: Evolution of the Church complex from Nineteenth Century on, Elaboration: Carla Borriello

5.3 Actual conditions

The seismic events that affected the territory of centre Italy from October 2016 has highlighted the vulnerability and the fragility of the historic buildings of these areas [169]. In the specific, the conventual complex of Tolentino has suffered from several damages along its structure and components.

5.3.1 The Church

The current interior space of the church results to be composed by a big central nave that opens the way to the eight lateral minor chapels with two arcades (**Figures 5.23** and **5.24**).
As already seen in the historical section, the original asset of the church was the longitudinal Romanesque one with single nave and not casually it exists a strictly interaction between the structural efficiency with the planimetric typology. The only nave it's indeed a weak structural typology. The bearing walls surfaces (Sp) on the covered surface (S) is a parameter that has been used in many researches to verify the structural efficiency of the churches of the Marches territory [67].
The parameter results of the multi-naves churches have been deeply lower rather than the one nave churches results.This is because a single nave with lack of lateral chapels (that operate like buttresses) needs, to balance the vaults load, bigger sections of pillars. Among the main vulnerability factors we may find:

- Lack of transversal tie bars
- Weakening of the "building box" due to the old trusses and the wooden coffered ceiling resting on perimeter longitudinal walls
- Lack of buttresses in the apsis zone
- Structural interactions between the church and the cloister

The current damages include important chinks located in the organ area, near the arches adjacent the façade wall and in the presbytery area especially in the join points between the dome and the spheric pendentives as it's possible to see in **Figure 5.25(c)** and in other photographical documentations of the building survey inspection in the group of **Figures 5.25** taken during another mission with a group of experts of the DISEG department.
This discloses a possibility of an estrangement of the central nave and the wooden ceiling weighing on it: this is the reason why the DISEG team mission had with

main aim the installation of a monitoring system made up of twenty accelerometers. Seventeen of them were settled on the bearing walls of the structure along the main axis of the Church, while the other three at the bottom of the bell tower in order to have a triple accelerometer reference on the ground (**Figure 5.22**).

The installation was also completed with three specific systems for the temperature rate detection [169]. The purpose is the acquisition of global dynamic behaviour of the macro-elements belonging to the central part of the Church that were damaged by the seismic events in order to evaluate the evolution of damage mechanisms [169].

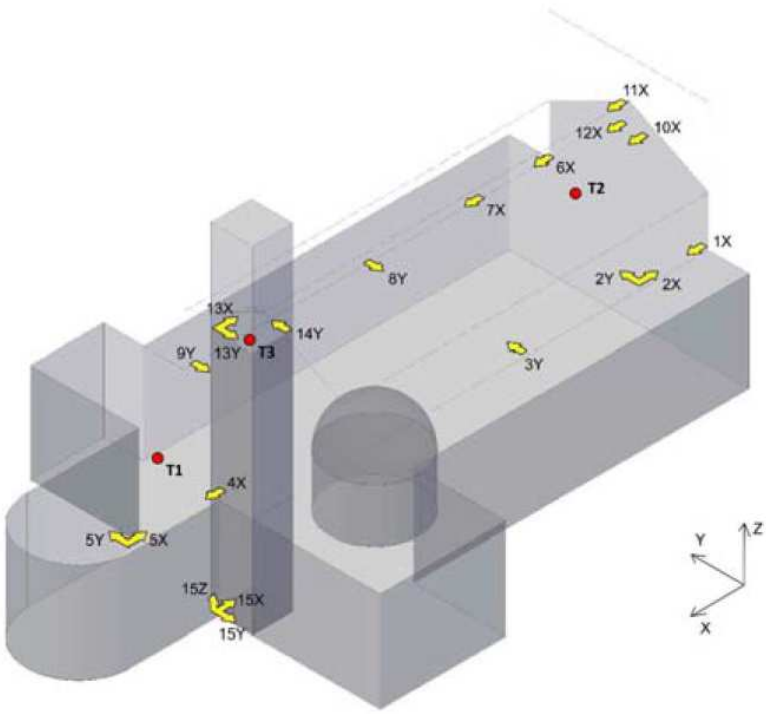


Figure 5.22: Monitoring system: Accelerometers location in yellow, Temperature detection systems in red [169]

Figure 5.23: Drone view towards the apsis zone, Ph: Team Direct Polito

Figure 5.24: Drone view towards the pipe organ zone, Ph: Team Direct Polito

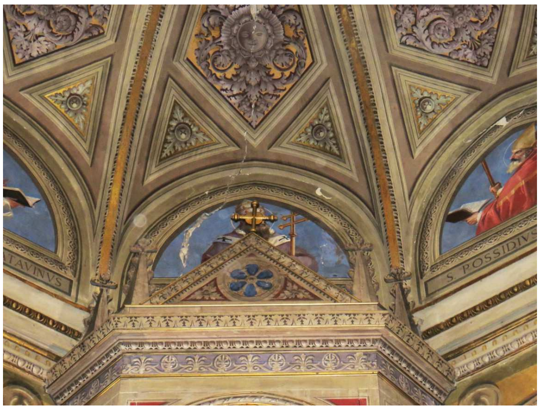
(a) Current chinks in the pipe organ area

(b) Stairs adjacent the pipe organ zone

(c) Joint between the dome and pendentives

(d) Presbitery area chinks

(e) Arches chinks in the presbitery area



(f) Chinks over the apsis area

Figure 5.25: Earthquake effects on the Organ and the Presbytery area, Ph: DISEG Team

5.3.2 The Façade

The church façade appears scanned in the lower part in five spans from four Tuscan pilasters that stand on high pedestals. They, on their turn, support the decorative moulding while, the central span hosts the over-cited floral Gothic gate. The lateral spans host the two secondary gates with a broken gables on top and above them there are two big windows with ribs on top. As regard the upper part of the façade, above the windows are placed two hemispheric recesses. Currently the façade appears covered for the restoration and the structural reinforcement works due to the seismic events that shook the centre Italy. In **Figure 5.26** there's a comparison where in the second image it's possible to notice the two buttresses against the façade in order to oppose the mechanisms of detachment of the façade itself from the lateral walls and from the roof: the resulted cracking framework show mainly vertical directed chinks as in **Figure 5.25(a)** above the pipe organ window. Indeed, this is a common structural behaviour, especially when it's assisted by the presence, as in this case, of weighting elements such as the coffered ceiling, vaults and big windows all along the lateral walls [146].

Figure 5.26: Façade before [103] and during works [43]

5.3.3 The Nanni di Bartolo Gate

The main entrance of the church is adorned with this great Gothic gate surrounded by a floral frame and a rich sculpture additions. Indeed, in the two opposite pilasters is possible to see the sculptures of six saints, among them we can recognize Saint Pietro and Saint Giovanni Battista. As we can see in **Figure 5.27** in a central position inside the lunette there's the statue of the Virgin Mary with Baby Jesus followed trough on the right by Saint Agostino of course, the founder of the agostinian order and on the left by Saint Nicola of Tolentino even if his canonization process would happened more than ten years after the creation of the gate by Nanni di Bartolo [45]. Above this lunette, there's the statue of Saint Giorgio fighting the dragon.

Figure 5.27: Nanni di Bartolo Gate [213]

5.3.4 The coffered ceiling roof

The coffered ceiling is a beautiful masterpiece of baroque cabinet-making, it was carved by Filippo da Firenze and his father. Its length is about more than 38 metres of 21 coffers distributed in three rows and defined by perimeter trabeation rich of decorations with dentil bands and other geometric shapes. On the coffers bases stand out clearly the episcopal coat of arms (**Figure 5.28**) and eighteen statues of saints and the two main statues located in a central position of the roof coffers of the Virgin Mary and the Jesus Christ. All the surfaces are pure golden except for the surfaces of the skin saints statues.
This beautiful masterpiece is the cover of the recent truss systems of the crawl space: we can also see in the photographical documentation of the DISEG mission, the first order of trusses has supporting structure for the wooden ceiling, while the second one supports the real hut rooftop. As already disclosed, the wooden ceiling is considered a weighting element that assisted the detachment mechanism of the façade from the lateral walls of the case study.

Figure 5.28: Detail of the episcopal coat of arms of the coffered ceiling, Ph: Carla Borriello

5.3.5 Lateral chapels

The church presents eight lateral minor chapels, four for side [45]:

- Chapel of S. Anna
- Chapel of the Holy Heart
- Chapel of the Virgin of the Buon Consiglio
- Chapel of the Virgin of Peace
- Chapel of Virgin of Miracles
- Chapel of S. Rita
- Chapel of Virgin of Consolation
- Chapel of S. Tommaso da Villanova

Chapel of S. Anna

This chapel was a property of the noble family of Benaducci and in the altar background we can see one of ht emost important artworks of the entire church: *"The vision of Saint Anna"* by Giovanni Francesco Barbieri, called "Il Guercino". The exact information about the painting commission is showed inside a book of accounts of the brother painter that registered in it the earnings of a certain amount of money for a painting to exhibit in the Tolentino church:

> *"Dal Sign. Benaducci Uditore del Torrone di Bologna si è ricevuto scudi di paoli 170 per il quadro della Sant'Anna da porre nella Chiesa di San Nicola da Tolentino di della città . . . "* [110].

In the lateral walls of the chapel we can find to the left side a canvas that shows the *"Glory of Saint Lucia"* by Marcantonio Romoli (1754) and on to the right side a canvas with the *"Oration in the garden"*.

Chapel of the Holy Heart

This chapel contains the beautiful altarpiece by Virgilio Monti ad shows *"Jesus Christ shows the Holy Heart to Saint Margherita Maria Alacoque"*. The left wall is pretty important because, according to the tradition Sain Nicola used to worship a wooden crucifix that's there represented inside a XVII century canvas by Guercino.

Chapel of the Virgin of the Buon Consiglio

At the altar centre is showed a canvas of the *"Virgin of the Buon Consiglio"* and the lateral walls are all decorated with late IX century canvas that tells the story of the holy image.

Chapel of the Virgin of Peace

On the altar there's the important canvas that represents the Virgin of the peace or also called *"Virgin of the olive tree"* by Giuseppe Locatelli in 1810, since the olive tree was considered a peace symbol from the Christian tradition. In this chapel was preserved the group of wooden altarpiece of the *"Nativity"* of the XIV century and now is located at the Shrine museum of the conventual complex.

Chapel of Virgin of Miracles

Here it's quite important the altarpiece about *"Saint Giovanni da San Facondo that brings a girl back to life"* created in 1691 by Giovanni Anastasi who is also the painter of the frescos cycle of the cloister.

Chapel of S. Rita

The altarpiece dated in 1912 representing the Saint is a masterpiece of the painter Girolamo Capoferri who was commissioned by a canonic figure called Emiliano Pucciarelli.

Chapel of Virgin of Consolation

The wooden altarpiece, *"Madonna della Cintura tra Sant'Agostino e Santa Monica"*, was created in 1858 by Luigi Fontana (that is also the painter of the frescos of the presbytery dome) and it's a derivation of the canvas of Giovanni Gottardi in Rome [45].

Chapel of S. Tommaso da Villanova

According to an accounts book discovered in the conventual archive, the altarpiece represents *"The charity of Saint Tommaso da Villanova"*. The author was undefined, but recently it has been accredited with Giuseppe Ghezzi. In the first asset, this chapel was followed by the Saint Lucia one and then destroyed to create space for the pipe organ tribune [45].

5.3.6 Chapel of the Holy Sacrament

Initially this chapel, located to the north side of the trasept, was addressed to host the holy arms relic but then it was dedicated to the holy sacrament. It was realized with a spheric dome resting on a octagonal lantern as we can see in figure. On the lateral wall are placed two headstones in honour of Francesco Filelfo and Niccolò Maurizi, two important figures both born in Tolentino.

Figure 5.29: Chapel of the Holy Sacrament, Ph: Carla Borriello

5.4 The 3D metric survey on-field mission

The survey mission took by the Direct team of the Politecnico of Turin lasted three full days of acquisitions that were carefully planned in advanced according to the the Geomatics tools and to the quality of information of the case study we wanted to highlight. For having a complete documentation of the internal and the external areas of the case study and for guaranteeing the geo-referencing of all the elaborations (orthophotos, 3D models) it has been necessary to face a mixed approach [42].
The on-site mission started from different steps:

Topographic Network of external vertexes measured by **GPS/GNSS** receivers system with static acquisitions.

Traverses Network that is a supportive network to the first one, made up of vertexes measured with **total stations** and the traverses method in the interior areas of the case study.

Ground Control Points Survey (GCPs) that includes:

- **UAV GCPs** in the external areas around the case study measured by UAV acquisitions in **Real Time Kinematic (RTK)** mode for the photogrammetric process. Some markers have been placed in natural points already existing and easily recognizable on the terrain and others have been placed in artificial points: for each one has been created a documentation. *"The main role of the control network is to establish a unique and stable coordinate system able to satisfy all the accuracy requirements for a complete architectural 3D survey"* [33].
- **LIDAR Markers and Close-Range Photogrammetry** The points to survey, called **targets** have been placed on the Church walls highlighted with chess-boarded papers and measured by **total stations**.

UAV photogrammetric flights performed with a commercial UAV drone.

LiDAR acquisitions performed with twenty-five scans to cover the whole internal area of the Church and two scans to cover the crawl space façade wall that will be our investigation topic of study on structural analysis and damages.

Mobile TLS acquisitions performed thanks to Zeb REVO by walking and choosing time by time the acquisition areas.

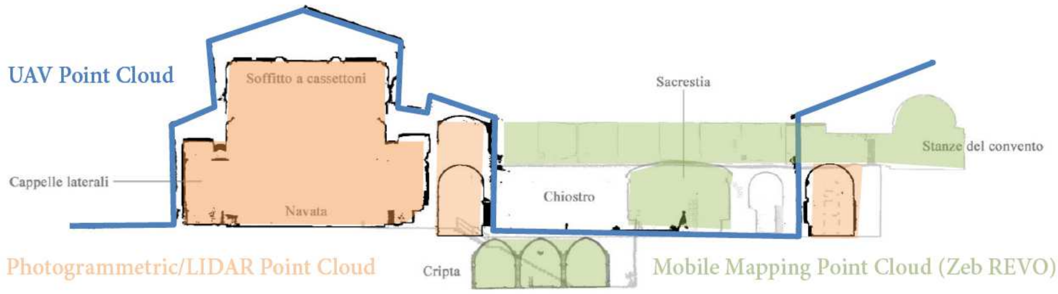


Figure 5.30: Scheme of approaches of aerial and terrestrial survey methods [42]

5.4.1 Topographic and Traverses Network

The very first step for the entire project processing consists in the creation of a **Topographic Network**: this phase is such of a great importance for the entire data collection mission because from this operation derives the interoperability among all the reference systems of other measurement sensors. There were chosen six vertexes on the ground whose coordinates were measured and calculated by a double frequency GPS/GNSS receiver with static acquisition (**Figure5.31**). The coordinates indeed were calculated for *"[...] geo-referencing all the acquisitions from different sensors in the same coordinate system"* [37] in order to link together the LIDAR acquisitions, the UAV flights and photographical documentations.
A supporting network connected to the first one was planned: the **Traverses Network**. The five vertexes located in the interior areas of the Church and near the cloister as we can see in **Figure 5.32**, were measured with the traditional topographic technique of the total station: this helped for the geo-referencing phases of the following products in a unique reference system.

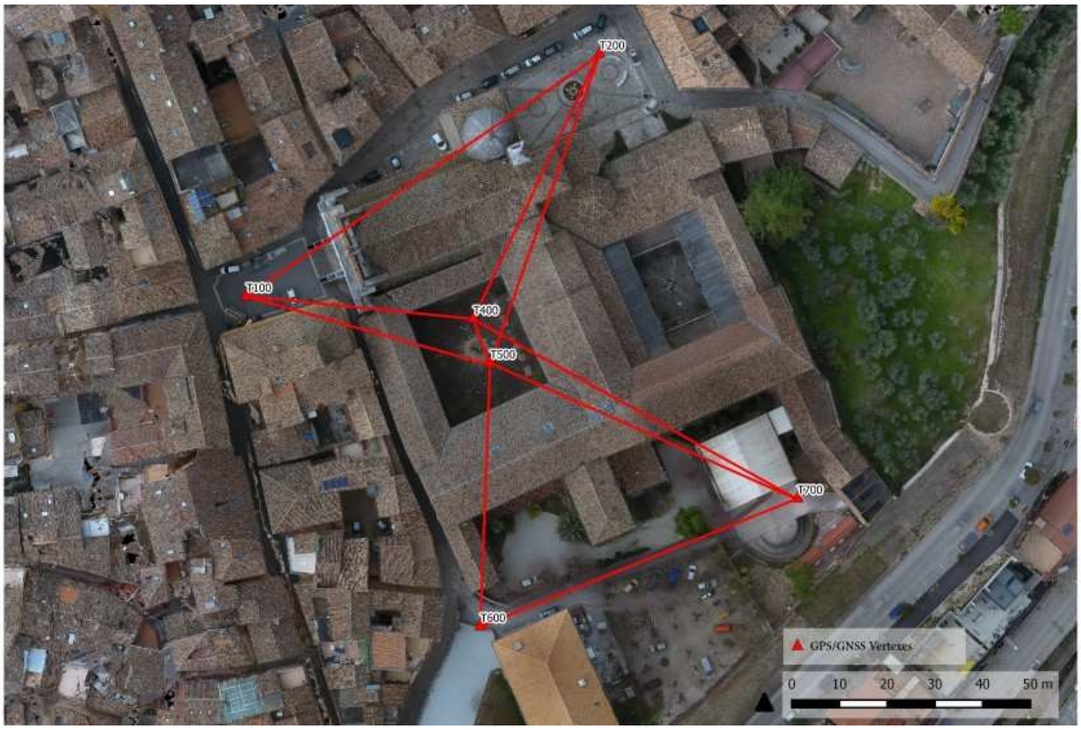


Figure 5.31: Topographic Network, Direct team Polito

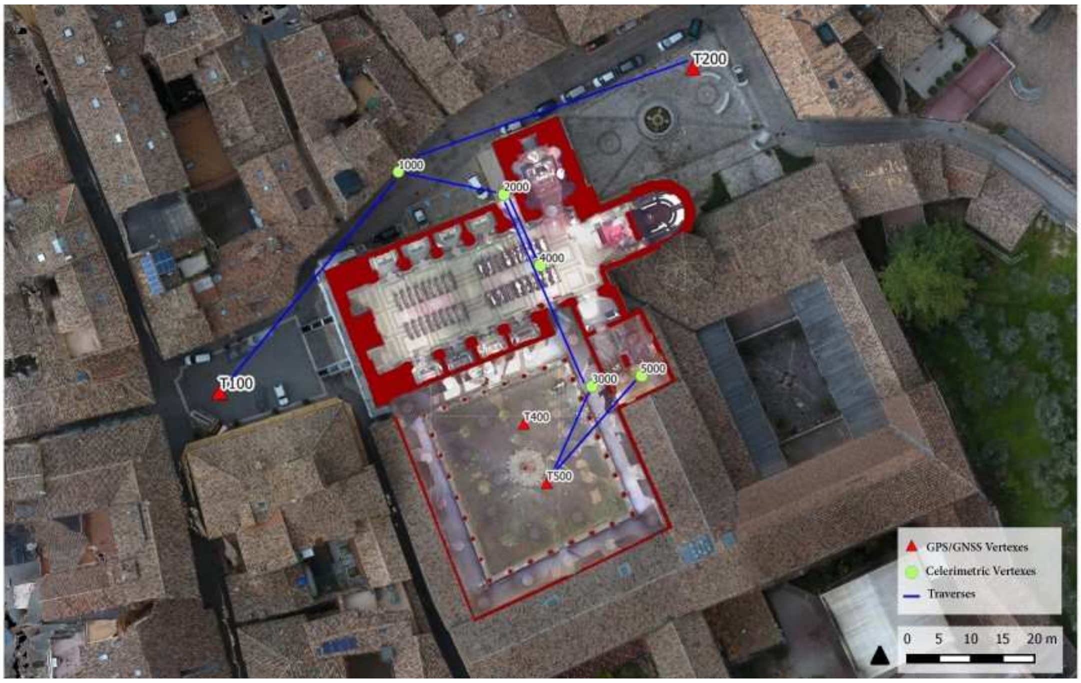


Figure 5.32: Traverses Network, Direct team Polito

5.4.2 UAV photogrammetric flights

The aerial photogrammetric flight, shown in **Figure 5.34**, was performed using a **DJI Drone Phantom 4 PRO** in two sessions of photographical acquisitions with longitudinal and side overlapping level. The flight height, about 63 [m], was prearranged as the flight planning itself with a nadiral camera flight session (camera axis orthogonal in regard to the ground) and an oblique (camera axis at 45°) one: in a total of 440 acquisitions, 256 were nadiral and 184 were inclined.
The planned overlap rate, about 80%, was really high for the employment of the SfM process *Structure from Motion*. Several ground control points (twenty-three GCPs and two check points), shown in **Figure 5.33**, were measured with the Real Time Kinematic (RTK) method and then calculated for the geo-referencing operation thanks to the topographic reference system.

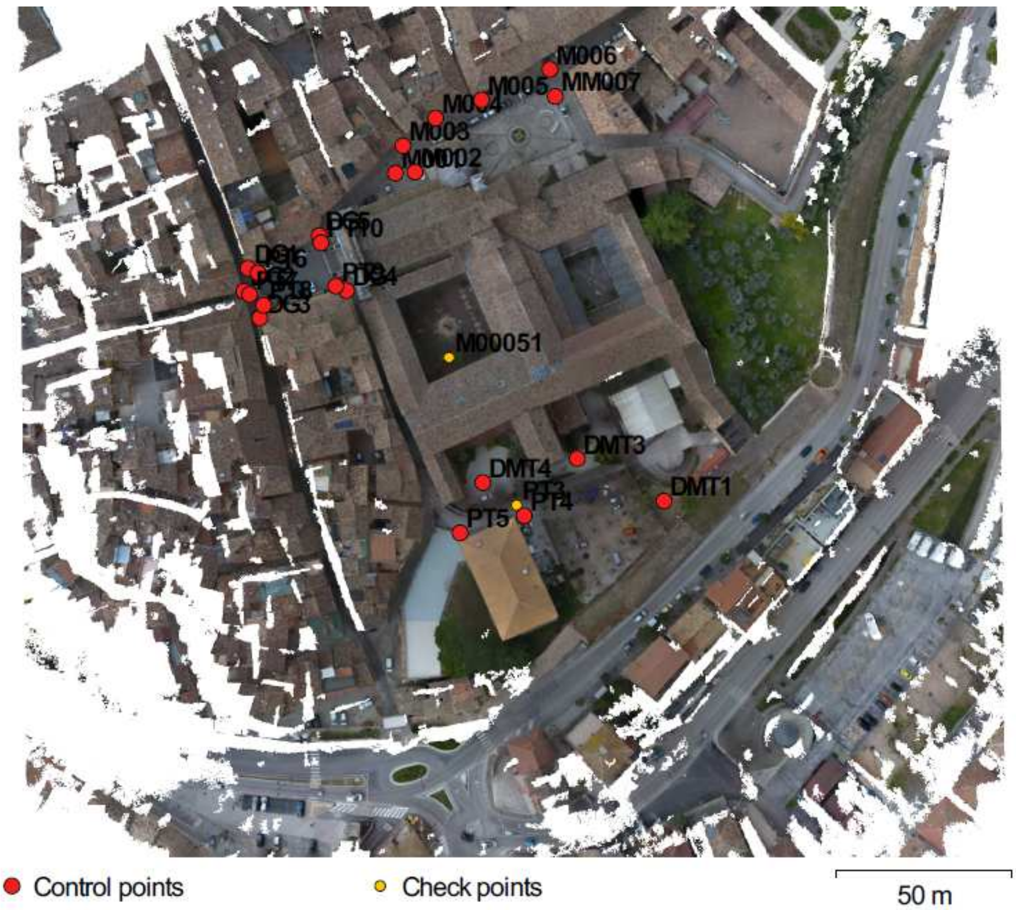


Figure 5.33: UAV Ground control points locations, Direct Team Polito

Figure 5.34: UAV Flight Plan, Direct Team Polito

5.4.3 LiDAR Scans

The LiDAR Survey was performed using the **Focus 3D** laser scanner by FARO instruments and as it's written in the previous section, all the locations points of acquisition were planned in advance in order to avoid the loss of scan information as reported in red in the **Sketch 5.37**.
The covered area of the inside Church area counted twenty-five scans organized in the most specular possible way. The difference of the recording positions for each scan brings the necessity of their registration and geo-referencing phase. And since it's necessary to have at least three common points for each scan also called **control points** or **homologous points**, several targets have been placed on the Church walls with their accurate sketches describing the exact location, highlighted with target papers and measured with traditional total stations to get the 3D coordinates (**Figure 5.38**). *"The Focus 3D has an integrated camera that allows the acquisition of the images needed to assign RGB values to every single point of the cloud"* [37] so each scan (**Figure 5.35**) has the colour feature as shown in **Figure 5.36**.

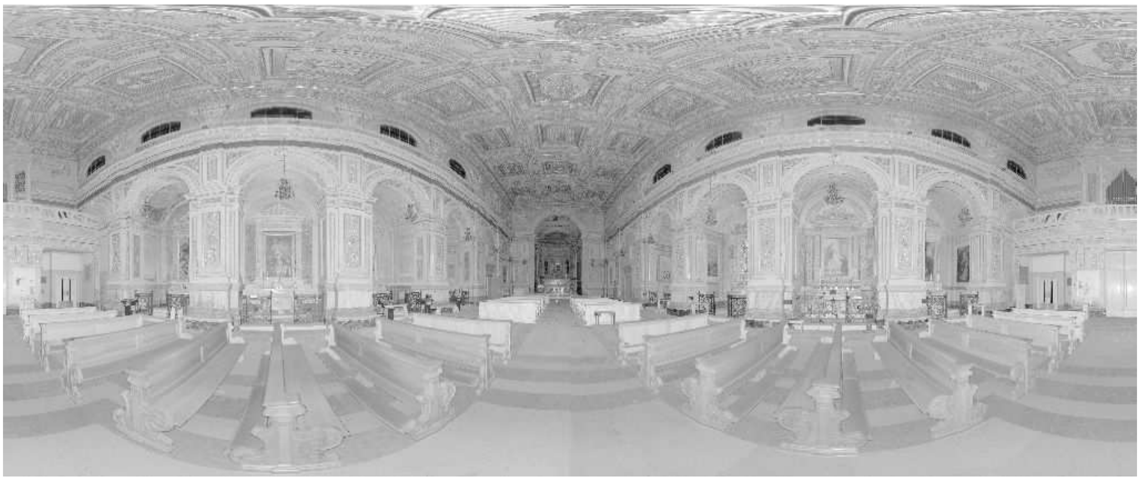


Figure 5.35: Grey scan, Direct team Polito

Figure 5.36: Coloured scan, Direct team Polito

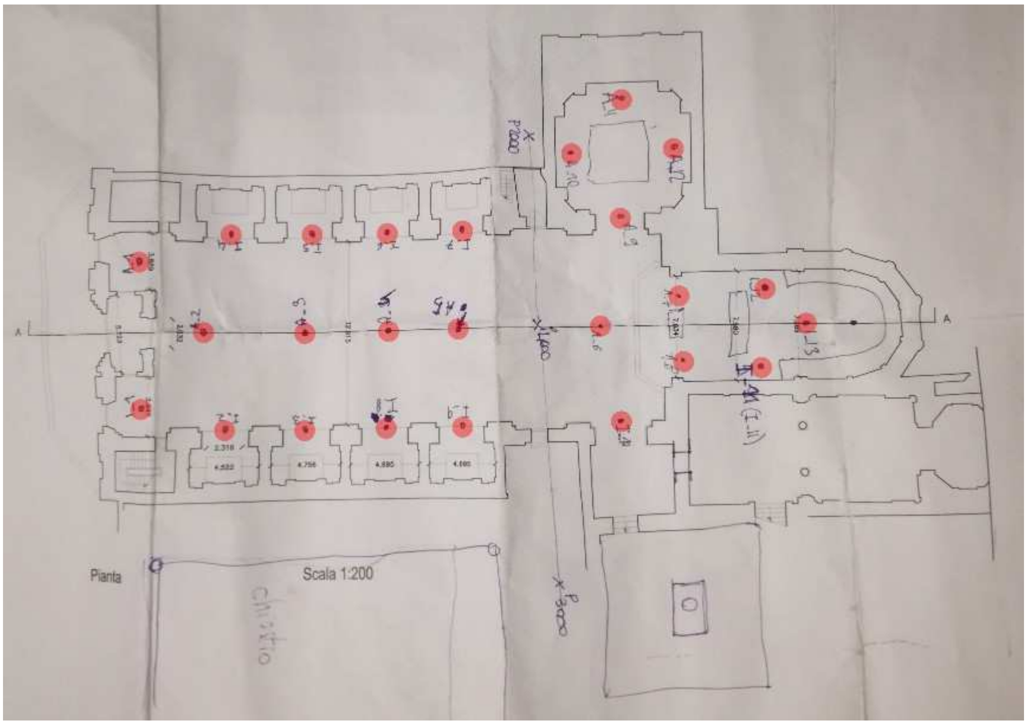


Figure 5.37: Sketch of the LiDAR scan positions inside the Church of S. Nicola, Direct team Polito

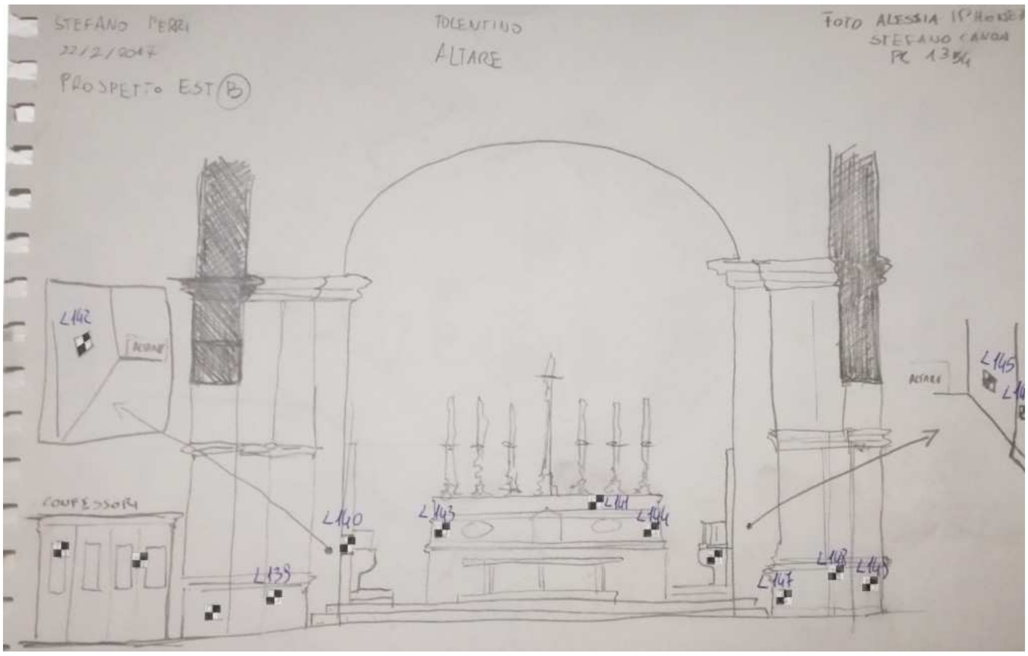


Figure 5.38: Sketch of the targets location in the altar area, Direct team Polito

5.5 Data processing

For the data processing phase were employed many different software according to the survey source. In particular they take into account the managing path that goes from the creation of point clouds (from TLS and UAV) to the creation of a textured/meshed surface model:

- **Pix4D Mapper** for processing aerial photogrammetry acquisitions;
- **FARO SCENE** for the LIDAR point clouds registration;
- **3D Reshaper** for checking the correct alignment of the scans;
- **PointCAB** for the architectural sections extractions from LIDAR point clouds and digital plotting;
- **Agisoft Photoscan** for the Close-range Photogrammetry of the coffered ceiling;
- **3D Reshaper** for structural investigations and the creation of a meshed and texturized 3D model;

Figure 5.39: Data processing summary, Elaboration: Carla Borriello

5.5.1 UAV photogrammetry processing

The software used for processing the UAV aerial acquisition is **Pix4D Mapper** [140], based on a *"Structure from Motion"* [165] approach and dedicated to the products of photogrammetrical drones acquisitions for the creation of models. The process is made up of four steps (**Figure 5.40**):

1. *" initial processing*
2. *point cloud densification (**Figures 5.43** and **5.44**)*
3. *3D model realization*
4. *DSM and orthomosaic generation" [34]*

Figure 5.40: Pix4D processing steps [140]

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
FC330 (3.61 mm)	4000 x 3000	3.61 mm	1.56 x 1.56 μm	No

Figure 5.41: DJI Phantom 4 [52] and camera parameters, Elaboration: Direct Team Polito

As already disclosed, it has been used a DJI Phantom 4, whose camera parameters are shown in the **Figure 5.41**. After the initial processing was completed, it was important to check the quality report in **Figure 5.42** that shows the successful calibration of 440 images out of 440 on the coverage area of 0.061 [kmq]. The *Bundle Block Adjustment* process has been performed through seventeen 3D GCPs with a Root mean square (RMS) error of 0.017 [m].
The result of the processing provides a DSM, a density surface model and the generation of an orthopohoto visible in **Figure 5.45** and its DEM digital elevation model, **Figure 5.46**, whose parameters go from 198 m on the sea level to 261 [m] reached by the bell tower of the conventual complex of the Church of our case study.

Images	median of 54311 keypoints per image	✓
Dataset	440 out of 440 images calibrated (100%), all images enabled	✓
Camera Optimization	1.79% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 23192.1 matches per calibrated image	✓
Georeferencing	yes, 17 GCPs (17 3D), mean RMS error = 0.017 m	✓

Figure 5.42: Quality report data, Elaboration: Carla Borriello

Figure 5.43: Point cloud densification, Elaboration: Carla Borriello

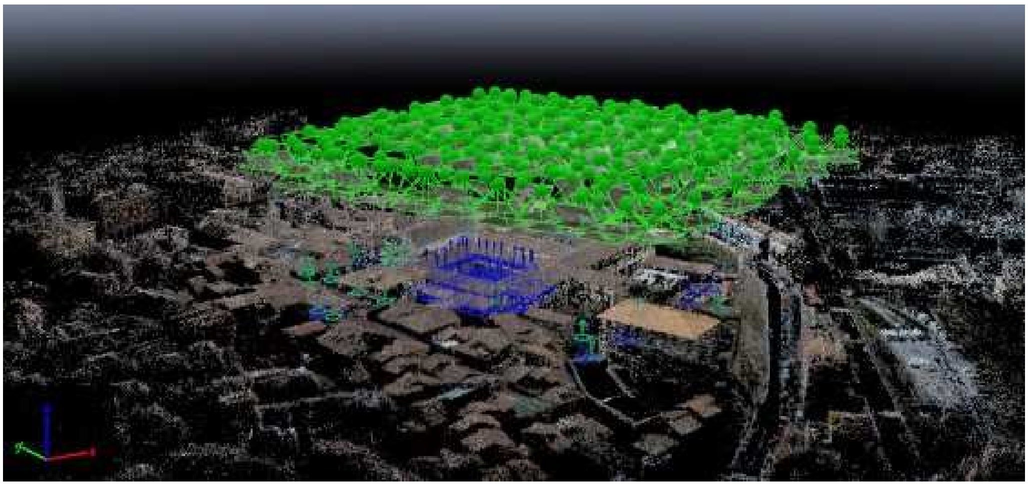


Figure 5.44: Camera locations, Elaboration: Carla Borriello

Figure 5.45: Orthophoto, Elaboration: Carla Borriello

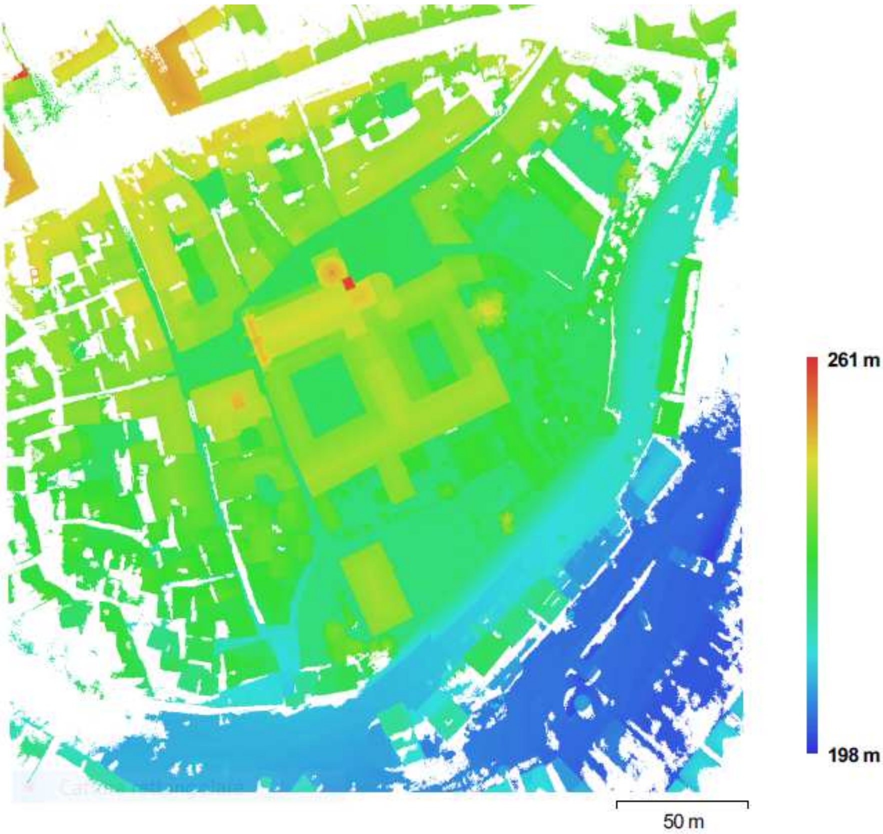


Figure 5.46: Digital Elevation Model, Elaboration: Direct Team Polito

Figure 5.47: UAV point cloud, Elaboration: Direct Team Polito

5.5.2 LiDAR scans registration

For this phase **Faro SCENE** [65] was used, one of the most reliable software companies for the measurement, imaging and 3D modelling technology operating in several fields such as BIM, industrial applications, construction industry, 3D facilities and realities, public safety and Cultural Heritage monitoring. The first step towards the scans registration process was the *scan shape/manual alignment* as shown in **Figure 5.48**.
Gradually, Ii has been identified and named every target above the surface for each scan (**Figure 5.49**) in order to operate a *scan target alignment* for the geo-referencing process. At the end of the scans registration phase, the software provided a quality report about the distance error of registration (4,57 [mm]) as we can see in **Figure 5.50**. In **Figures 5.51** and **5.52** it's possible to see the result of the scans registration phase, 3D views of the aligned scans: it's important to notice from now on, how the whole point cloud turns to be noisy and surrounded by white parts that represents the gaps of acquisitions of the instrument that we'll see more easily in the next chapter that will focus the relevant phase of cleaning all the anomalies and the noise reduction directed to the creation of a surface model.

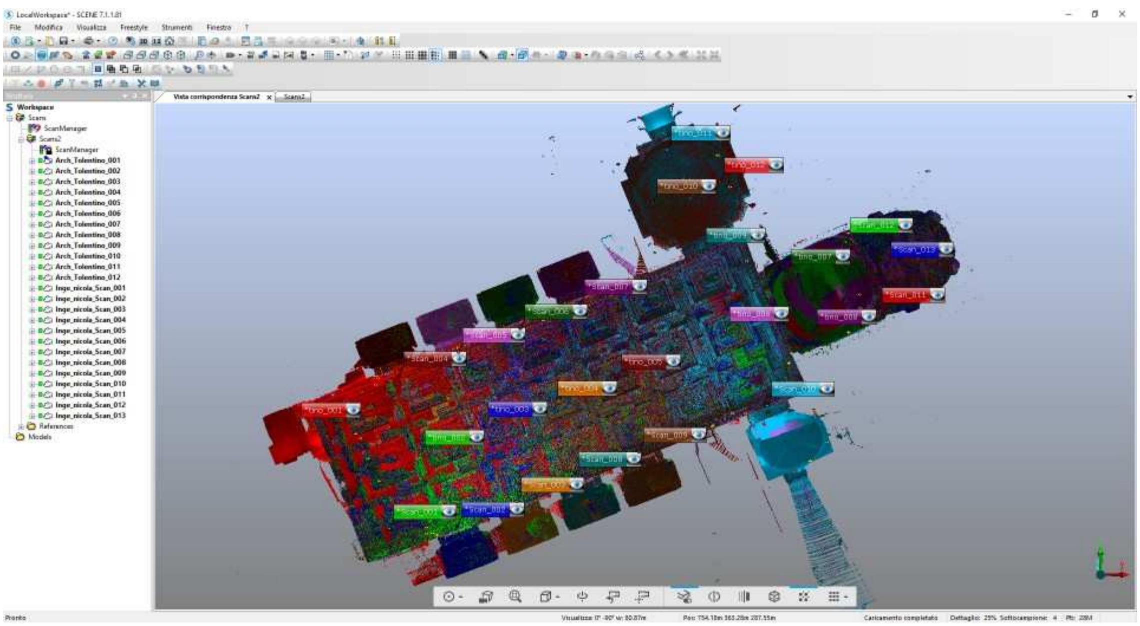


Figure 5.48: The 25 scans, Elaboration: Carla Borriello

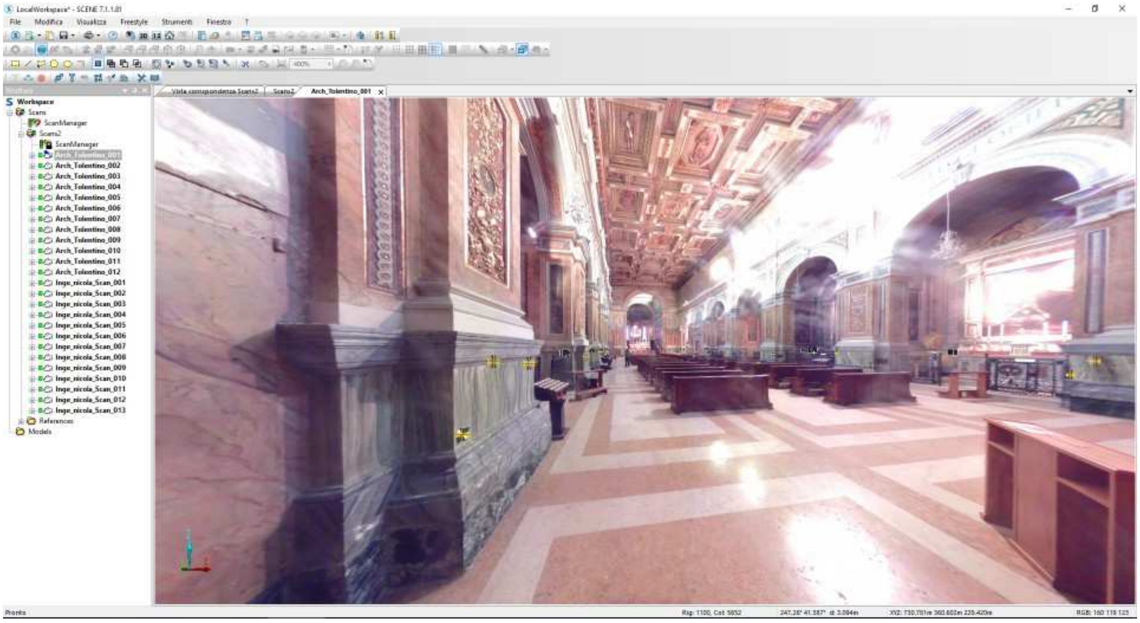


Figure 5.49: Rapid view of a scan, Elaboration: Carla Borriello

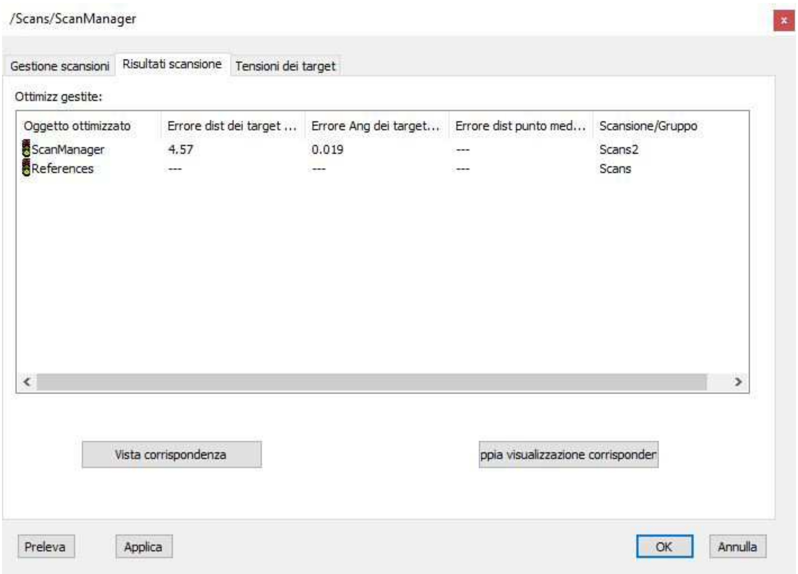


Figure 5.50: The distance error of scans registration, Elaboration: Carla Borriello

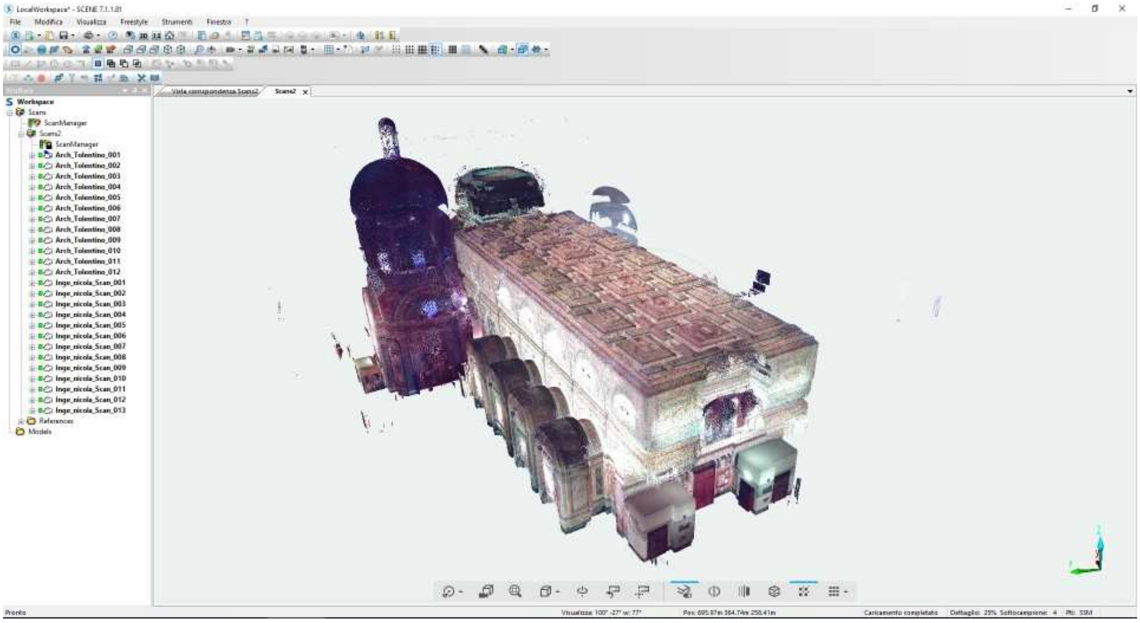


Figure 5.51: Perspective view of the point cloud, Elaboration: Carla Borriello

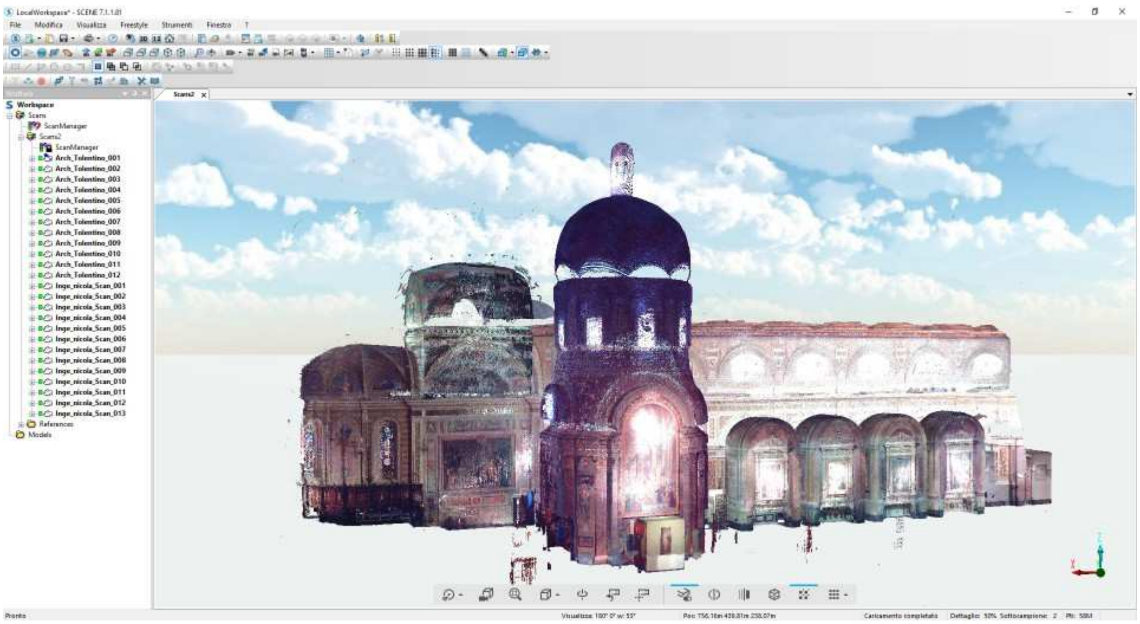


Figure 5.52: Another view, Elaboration: Carla Borriello

5.5.3 Scans alignment accuracy check

After the scans registration, it was necessary to check the correct alignment for the scans in order to have a correct documentation without any kind of displacement that could corrupt the final accuracy of the following products. So, thanks to the software **3D Reshaper** [3], it has been possible to manipulate the whole point cloud and to make simple profile sections just to verify the wall continuity in plan **Figure 5.53** and in a longitudinal section as **Figures 5.55** shows below.
The accuracy test has been quite positive about the alignment: there are no relevant or visible displacements between the scans, we're just talking about displacements in the dimension order of millimetres [mm] in both profile sections: in plan for example there's a soft displacement of scans localized in the entrance door of the church of about 3 [mm] (**Figure 5.54**), while in the longitudinal section (**Figure 5.56**) in the wooden ceiling there's a displacement even lower, about 2,2 [mm] between the scans.

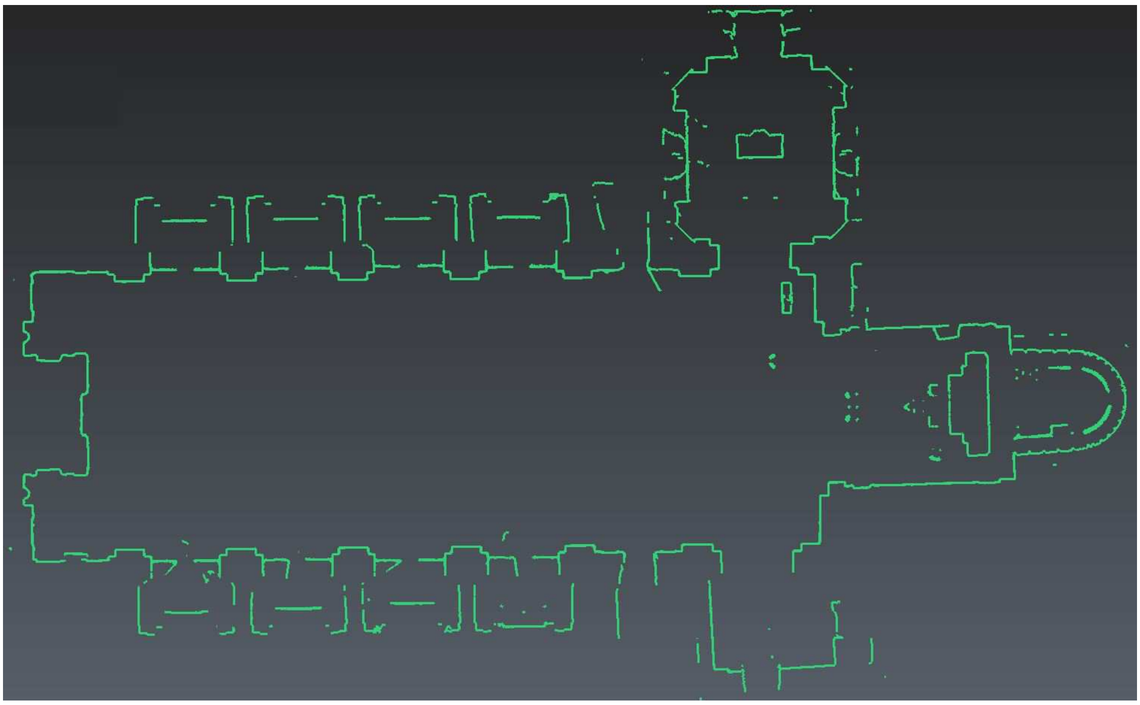


Figure 5.53: Profile section, Elaboration: Alessandra Spreafico

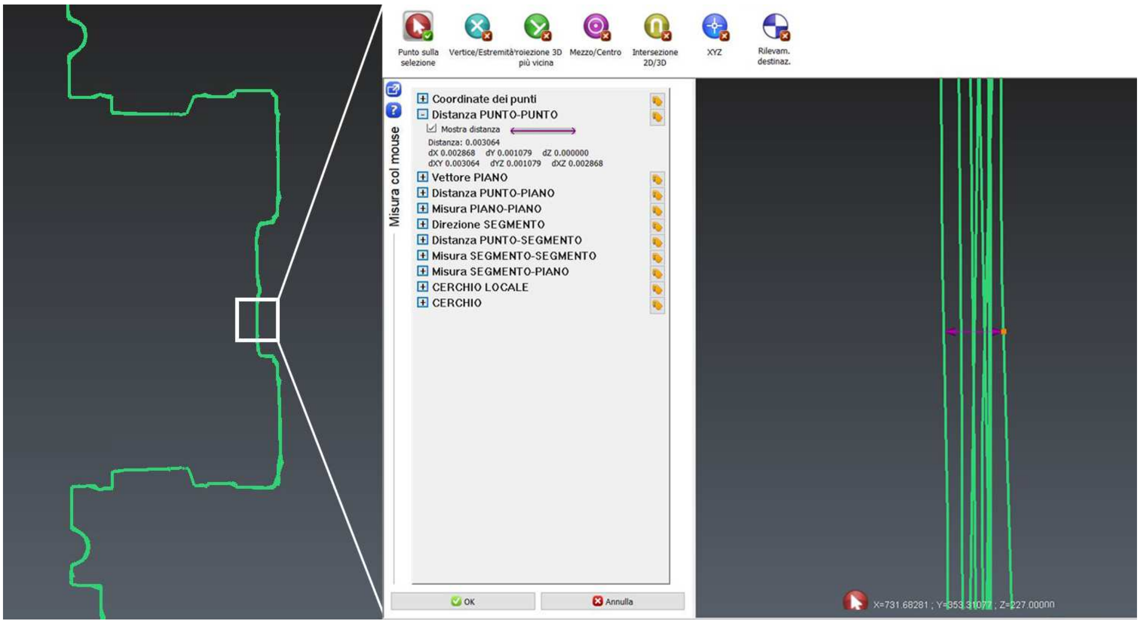


Figure 5.54: Zoom profile plan near entrance door, Elaboration: Carla Borriello

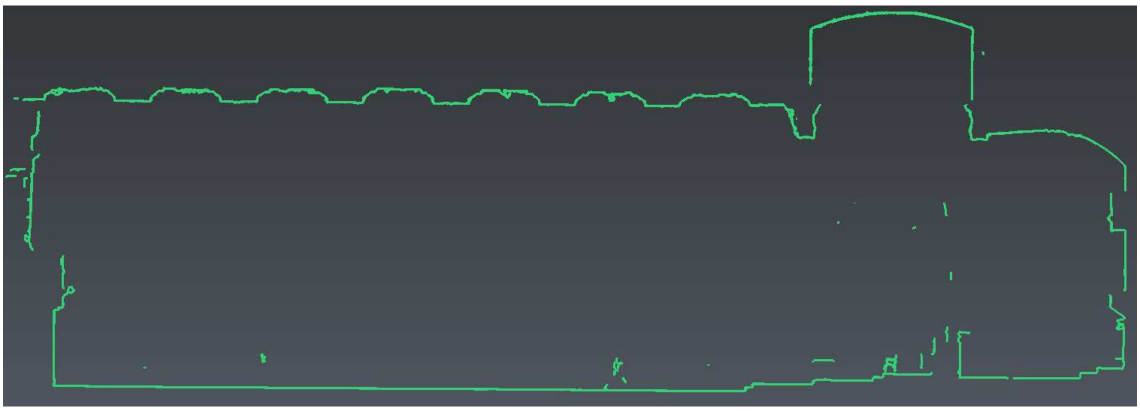


Figure 5.55: Profile sections, Elaboration: Alessandra Spreafico

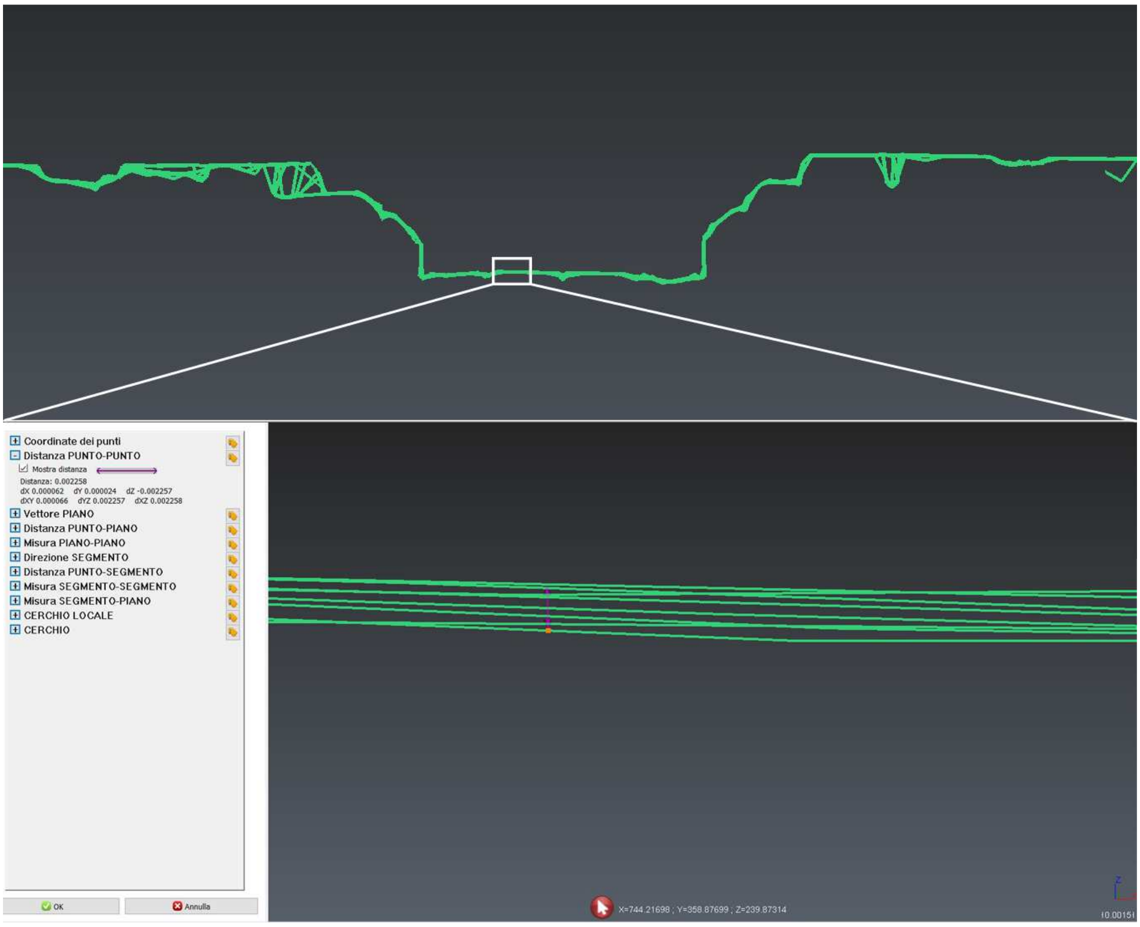


Figure 5.56: Zoom profile section on the ceiling, Elaboration: Carla Borriello

This step represents a first test to understand if the manual alignment of the scans inside SCENE has given a good final result.
This definitely help to generate an accurate point cloud that will be the starting point for the extraction of all the 2D final architectural sections and products. So, once it has been checked that alignment has no relevant displacement of registration, in the order of millimeters in this case, the

5.5.4 Digital Plotting

The digital plotting phase has been driven thanks to **PointCAB** [142], a point clouds high-resolution processing software [142]. It's really intuitive, indeed it can create automatically from point clouds views, sections and floor plans.
Thanks to its big export interface, it's compatible with all the CAD systems, and for this reason, easy for the plotting phase of all the 2D architectural products extraction. After the exportation of the SCENE point clouds in the ***e57 format**, these were uploaded and registered in PointCAB as shown in **Figure 5.57**.
The easy graphical software interface let the user have in the tile menu all the views of the church model without modifying it. Of course, the use of just the internal Lidar point cloud could have generated incomplete 2D products without any clue about the external dimensions of the perimeter structure walls. So, thanks to the UAV external point cloud extracted by the Pix4D software as previously disclosed, it has been possible to integrate the two geo-referenced point clouds.
This integration, shown in **Figure 5.58**, has allowed not only, to fill the gaps of information of both clouds in a single point cloud that will be the starting point cloud of the following 2D products such as plan, sections, fronts and others but also, it has allowed to detect all the empty spaces of the distributive plan and get some clues about the functions.

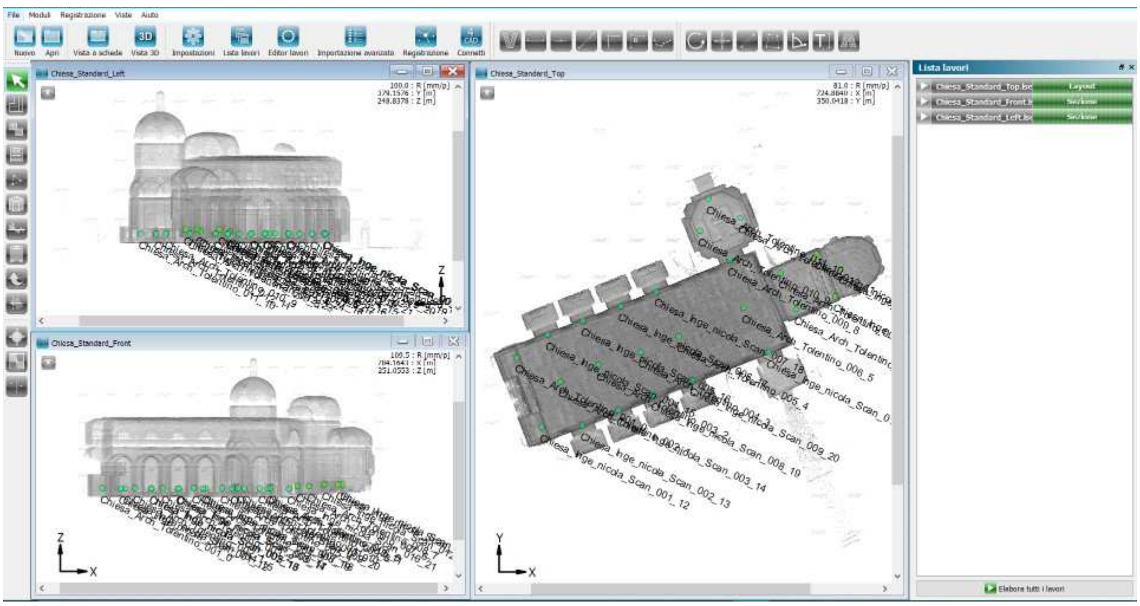


Figure 5.57: PointCAB tile view of the point clouds, Elaboration: Carla Borriello

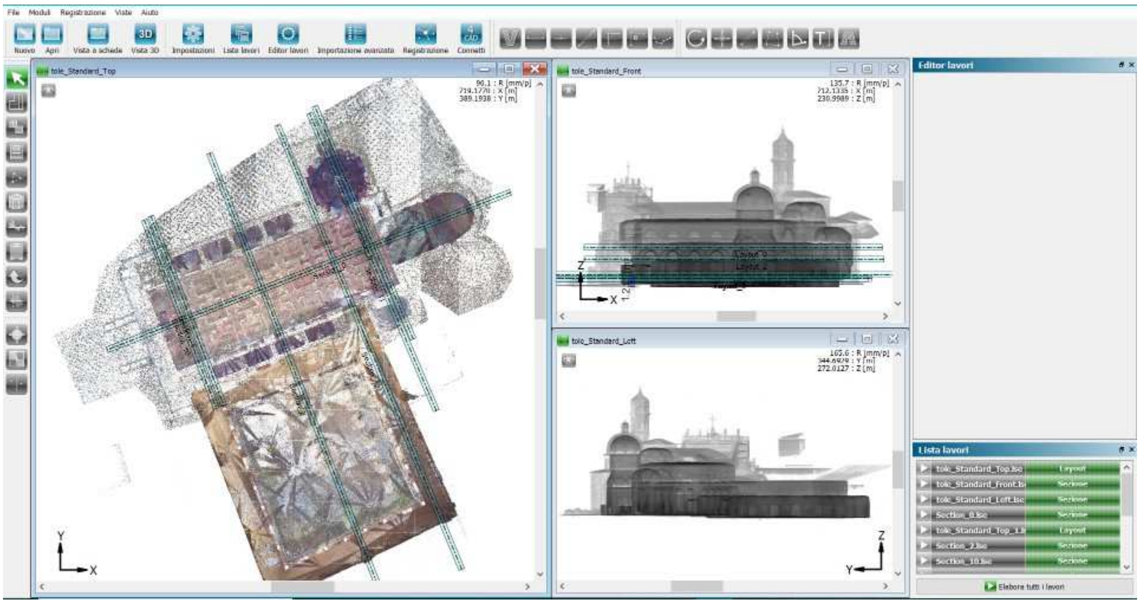


Figure 5.58: Integration of TLS and UAV data, Elaboration: Carla Borriello

With the command *"Layout and Section"* indeed, It has been set a section plan in order to create a section (**Figure 5.59**) on the wanted tile view, the plan in this case, by drawing down a line and by choosing the proper elaboration data settings regarding the image resolution, the scan distance ray, the colour rate and the reflectivity of the generated orthophoto.
The result has showed 3D sectioned orthophotos where all the details were flattered at the same geometric plane: as a consequence indeed it's been difficult to recognize the sectioned elements from the background ones without a good analysis. The ***dwg** format exportation returned a 2D ortho-mosaic (**Figure 5.60**) ready for the digital plotting phase (**Figure 5.61**) that has generated accurate architectural surveys which results are presented in the A3 attachments at the end of the thesis.
For the digital plotting process and consequently for the creation of 2D architectural drawings, there have been extracted an horizontal section (**Figure 5.62**) for the **plan** at the height of 1.20 [m] and three sections:

- **Longitudinal** section shown in **Figure 5.64**;
- **Transversal** section on transept towards the apsis in **Figure 5.66**;
- **Transversal** section towards the pipe organ in **Figure 5.68**;

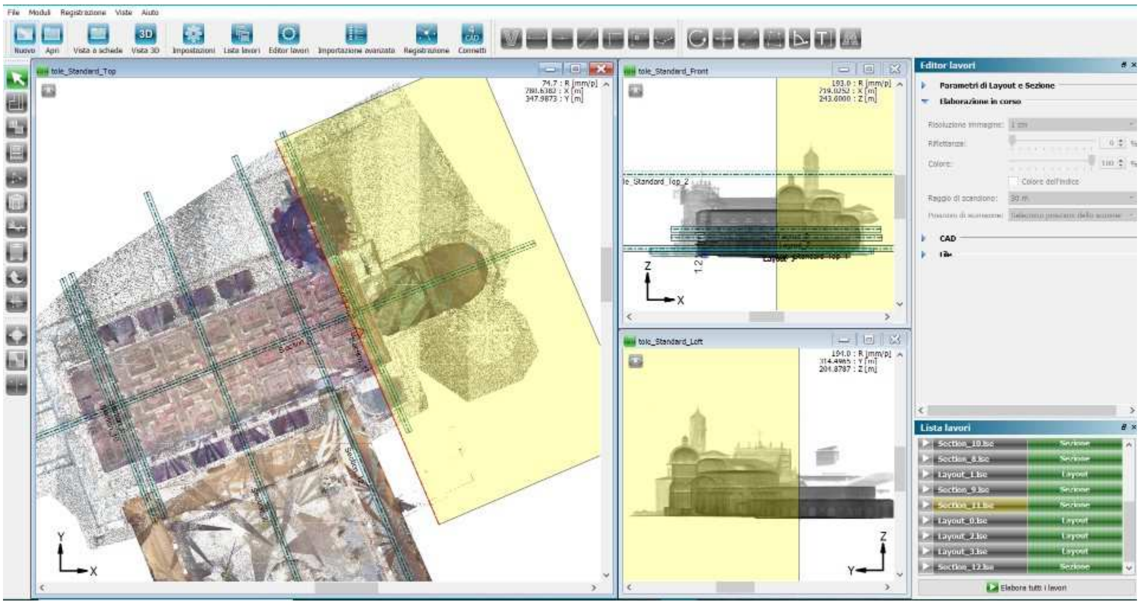


Figure 5.59: PointCAB Section, Elaboration: Carla Borriello

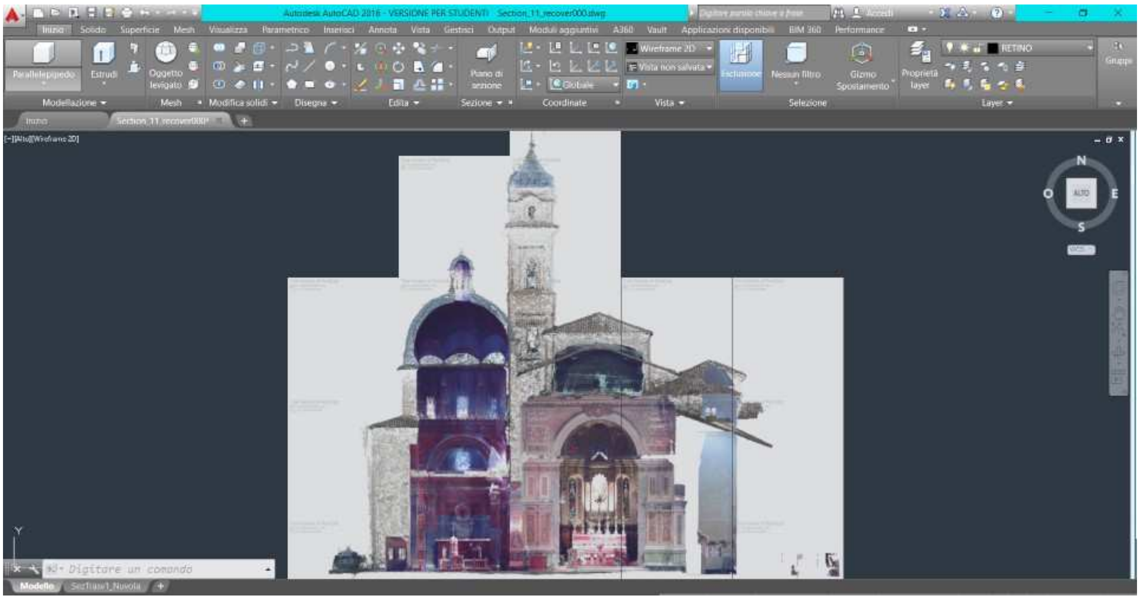


Figure 5.60: Ortho-mosaic section, Elaboration: Carla Borriello

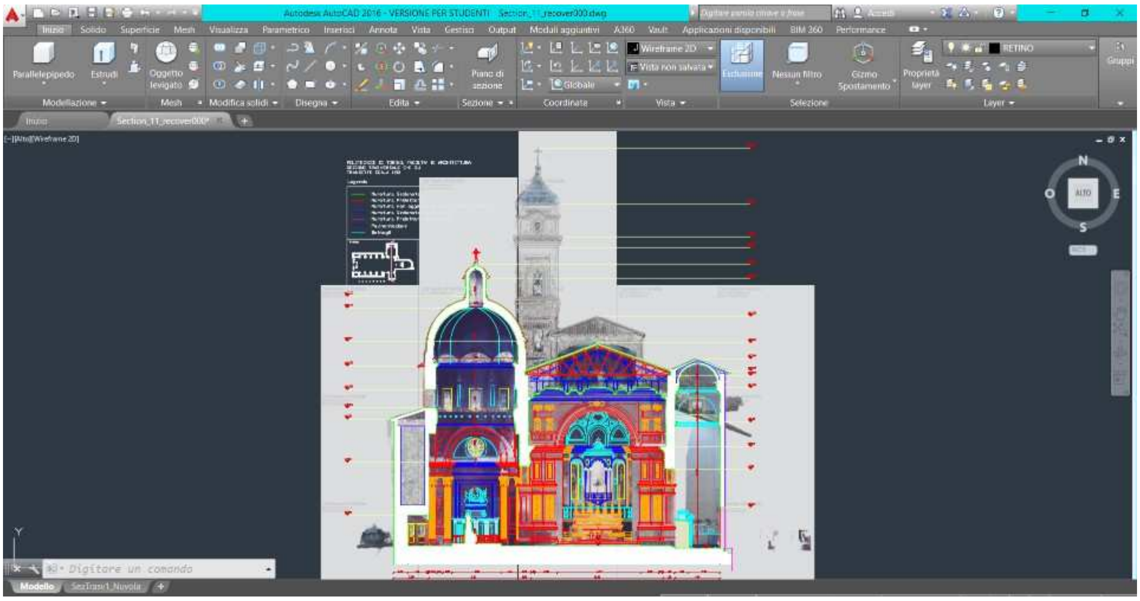


Figure 5.61: Digital plotting phase, Elaboration: Carla Borriello

In the following pages it's possible to find, presented in a scaled version, the final results of the digital plottings with attached their point clouds orthophotos (let's have in mind that A3 attachments are presented at the end of the thesis in a more clearly way). As, we can see in the plan drawing in **Figure 5.63**, the frontal façade of the church results to be drawn with a different line style (dotted line) and colour in comparison to the rest of the plan itself: this is because of the lack of acquisition of those information by the laser scanner. The reason is to attribute to the presence, during the 3D survey mission, of restoration works in the construction site of the façade. So, everything related to that portion is hypothesized on the base of photographical documentations of the church façade before the works. Other areas that are presented with the same dotted lines for accuracy reasons, such as the tower bell, are treated with the same logic: they're just hypothesized even though there are effective photographs that show the presence of them.
While in the sections drawings in **Figure 5.67** and in **Figure 5.69** it's possible to notice the sectioned current truss structures of the roof that have been generated and integrated by the digital plotting phase of the crawl space LiDAR point clouds that, as we'll se in the next section of this chapter, it'll be the main interest area for the structural analysis.

Figure 5.62: Point cloud plan, Elaboration: Carla Borriello

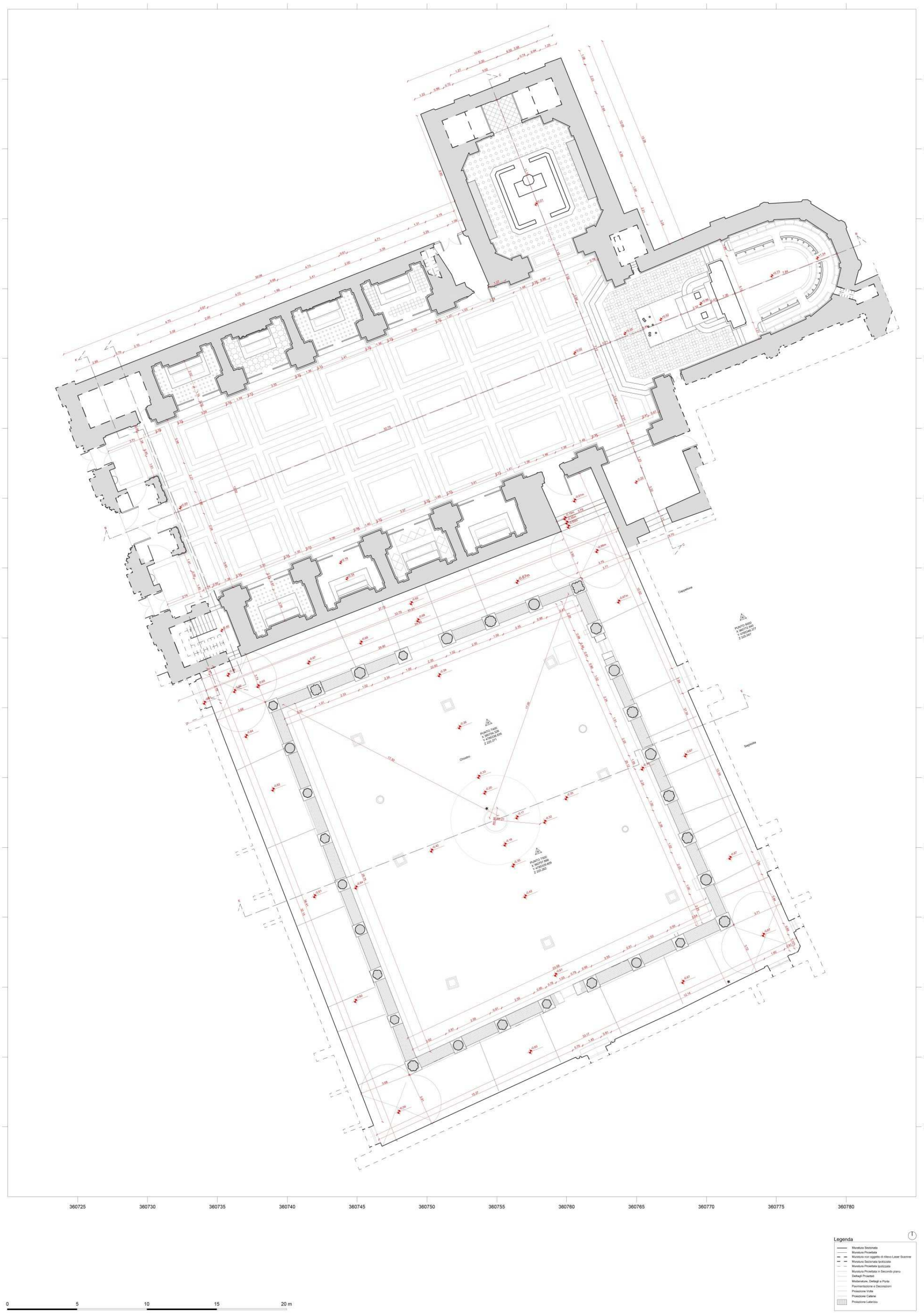


Figure 5.63: Plan of the Church, Elaboration: Carla Borriello

Figure 5.64: Point Cloud longitudinal section, Elaboration: Carla Borriello

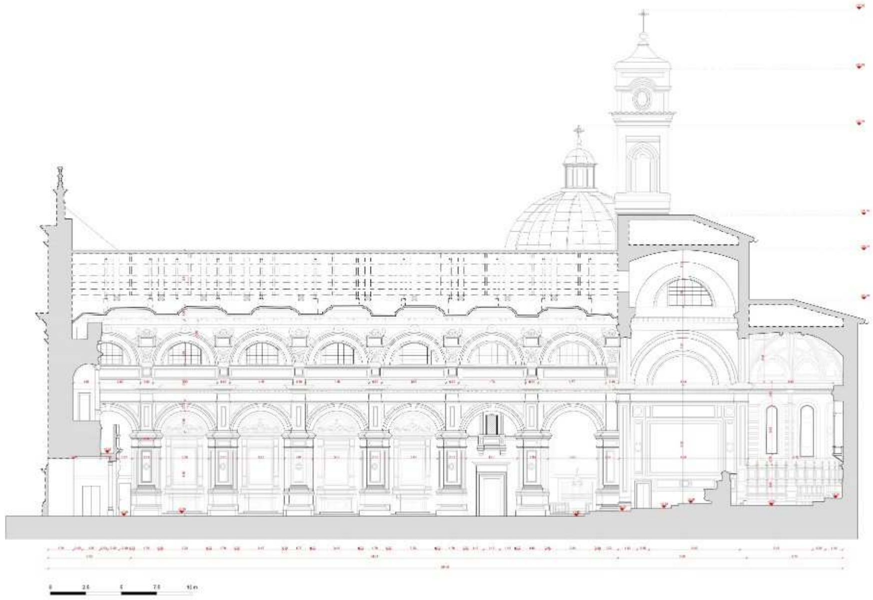


Figure 5.65: Longitudinal section, Elaboration: Carla Borriello

Figure 5.66: Point Cloud transversal section on the transept, Elaboration: Carla Borriello

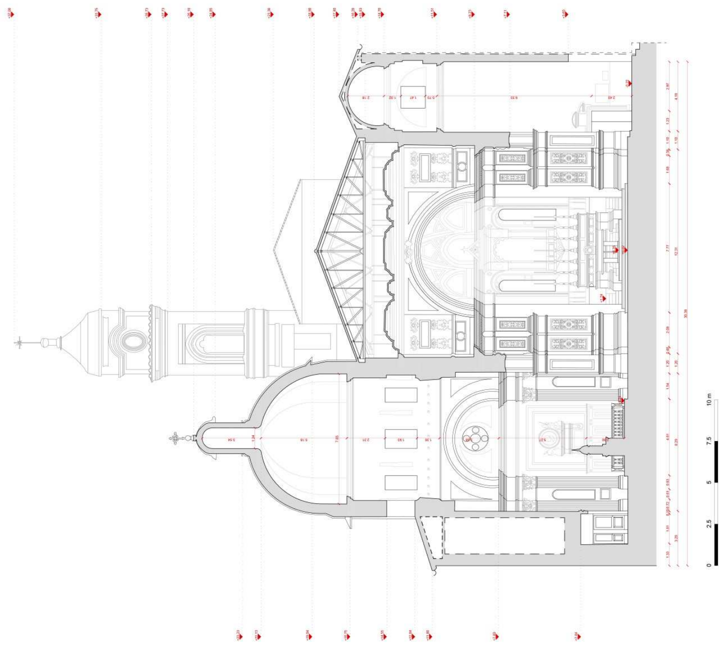


Figure 5.67: Transversal section on the transept, Elaboration: Carla Borriello

Figure 5.68: Point Cloud transversal section towards the pipe organ, Elaboration: Carla Borriello

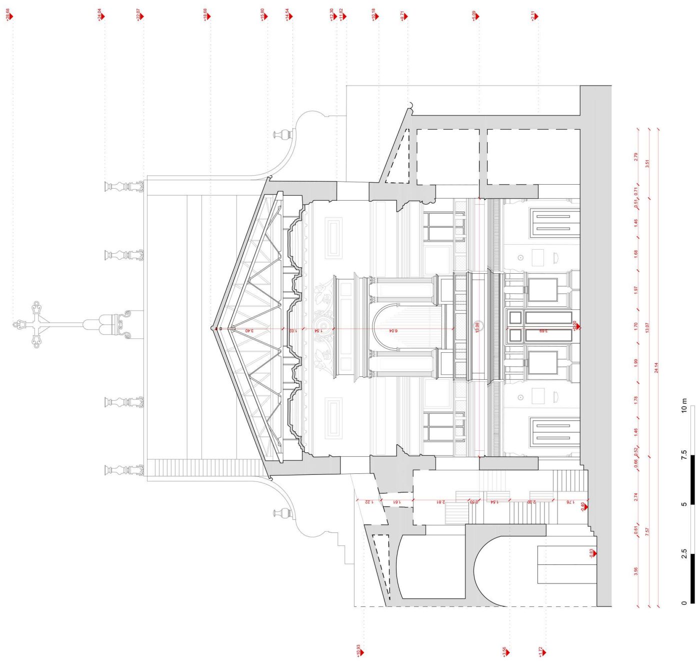


Figure 5.69: Transversal section toward the pipe organ, Elaboration: Carla Borriello

5.6 Structural analysis

It's remarkable

"[...] the effective contribution of 3D high detailed products derived from innovation and integration of Geomatics technologies, allowing a development in descriptive metric capabilities, supporting and improving the material recording, representation, analysis and characterization about alteration of the constructive systems" [170].

The problem of Cultural Heritage at risk field documentation and monitoring during time finds its applicative answer into the technological integration with Geomatics which gives the possibility also to extract from 3D models some vulnerability investigations, structural diagnosis in order to aim to a better and to a more sustainable restoration and protection process in terms of time, costs and personal safety.

From the applicative point of view, there are a lot of commercial software, such as the afore **3D Reshaper**, that are able to offer tools and settings to evaluate anomalies in the geometry of surfaces [170].
The investigations about the wall constructions techniques of my case study, have taken into account divergent approaches that change not only, according to the final aim of the methodological path but also according to the didactic field source of the surveyor team.
Certainly, seeing as how nowadays, and maybe fortunately, it does not exist an unequivocal and codified methodological itinerary since every case study must be approached individually, it has been necessary to extract an objective investigation based on comparison of the current approaches about quantitative and qualitative data.
The *"knowledge path"* opened the line for a reliable evaluation of the Cultural Heritage building based on different levels: an inductive study from the identification of the case study portion to analyse, its geometric features, the description of the past structural systems and the current ones, passing through structural investigations about the plumbing direction or about the possibility of damages on the façade wall to the study of the wall weaving of the materials with the constructive techniques that could be great clues for trying to give some chronological datings.

5.6.1 Crawl space façade wall

The area of main interest in this structural analysis is the one of the crawl space close to the façade wall shown in **Figures 5.70 5.71** and **5.72**: the DISEG on-site mission has improved the photographical documentations of the first survey mission on that area where the visibility rate resulted to be extremely low due to the darkness and due to the dense twist sequence of truss systems as it's possible to see in **Figures 5.75** of the following pages.

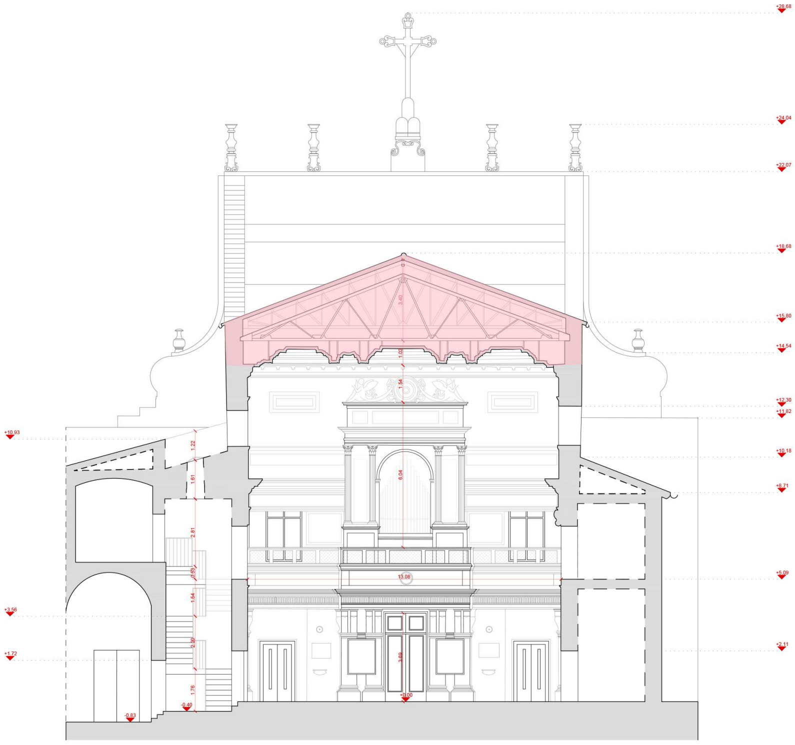


Figure 5.70: Crawl space façade wall in red, Elaboration: Carla Borriello

The crawl space, as disclosed previously, is made up of a recurring sequence of two orders of metallic trusses of recent age having different purposes:

- The first order shown in **Section 5.73(a)** is the lower one and it has the purpose to hold up the wooden boards that make up the coffered ceiling, thanks to structures (shown in **Figures 5.75**) that run horizontally above the whole area of the ceiling;
- The second order shown in **Section 5.73(b)** is the higher one and it has the purpose to bear the weight of the hut rooftop made up of blocks;

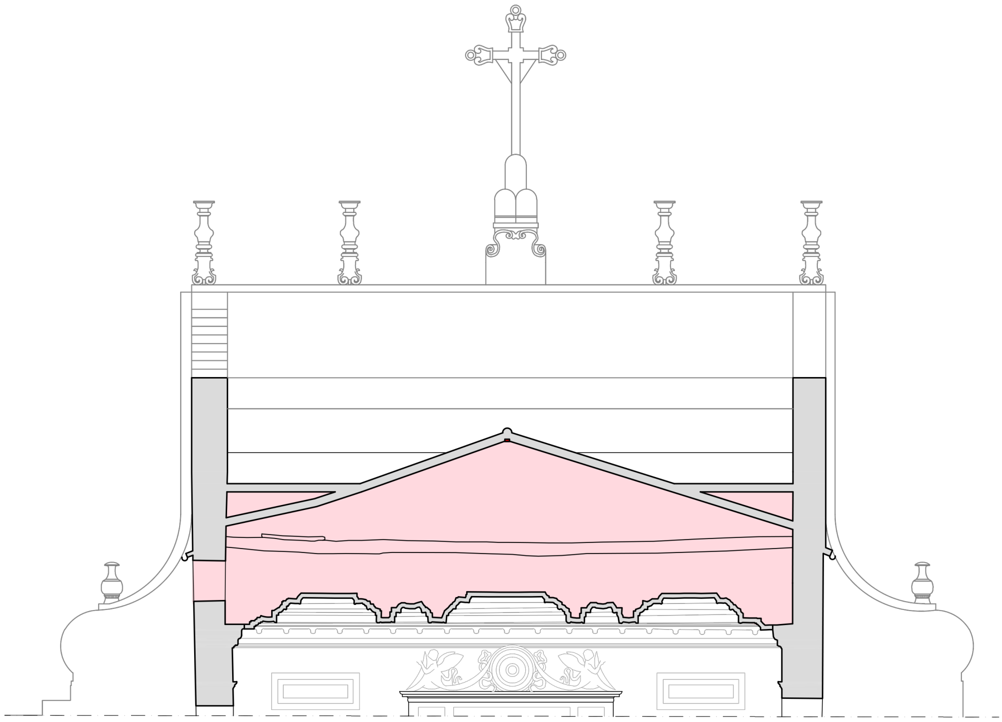
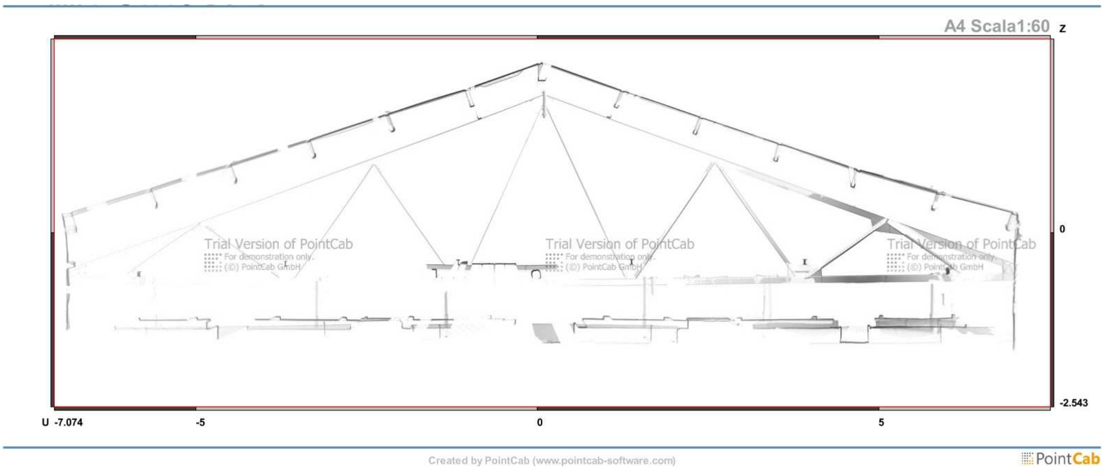
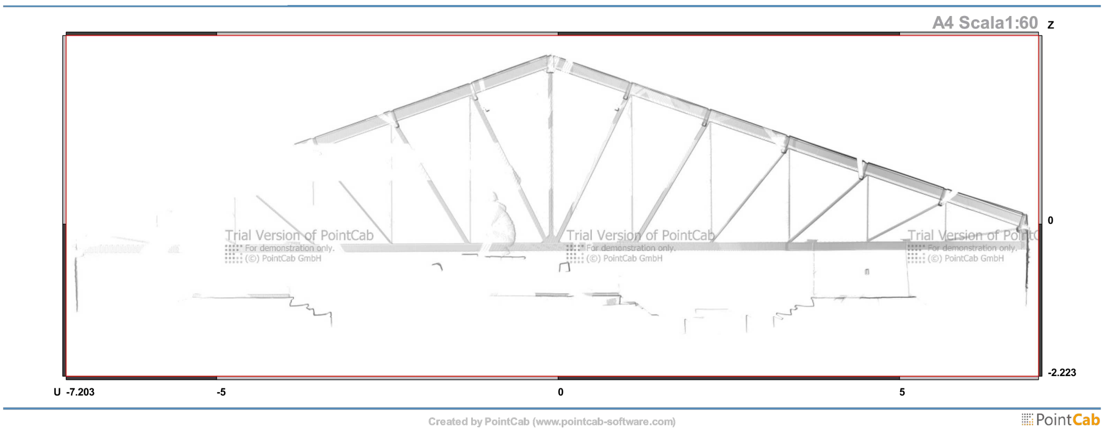


Figure 5.71: Crawl space zooming, Elaboration: Carla Borriello

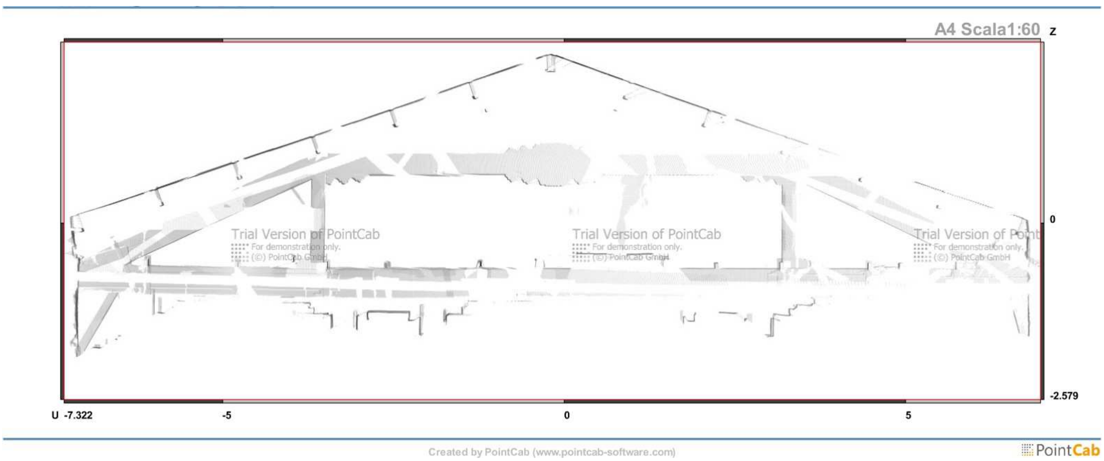
Figure 5.72: External view of the crawl space window, Direct Team Polito



(a) Section of the I order truss system



(b) Section of the II order truss system



(c) Section of the original truss system

Figure 5.73: PointCAB sections of the crawl space system, Elaboration: Carla Borriello

The old sequence of wooden trusses are visible in the **Section 5.73(c)** : they have been cut off and for this reason they have no more structural value. In the **Figures 5.75** it's possible to see the joint part of interaction between the metallic new truss, the wooden one and the perimeter wall.
Another interesting part shown in the last image of the **Figure 5.75**, is the presence in front of the central beam, of a little wooden header, maybe, to prove the possibility in ancient years of windows in the main façade. This could also be testified by the different kind of materials compared to the other ones of the wall: of course there's no certainty about the truthfulness of this hypothesis but in the next sections I will face this topic in a deeper way.

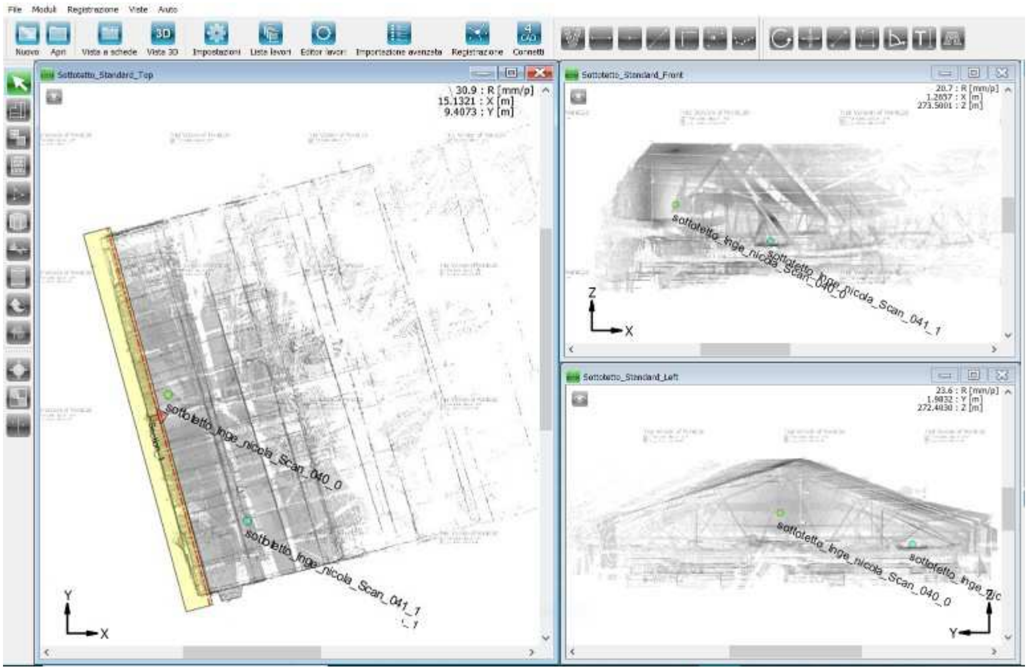


Figure 5.74: PointCAB tile views of the crawl space scan, Elaboration: Direct Team Polito

First of all, it has been fundamental to extract , thanks to PointCAB software, some views and sections from the point clouds, acquired inside the crawl space shown in the laser scans **Figures 5.76** and **5.77**.
I set a section plane tangent to the wall outline, visible in the **Figure 5.74**, in order to have a front view of the wall gable which is shown in the coloured version in the **Figure 5.78**, without colours in the **Figure 5.79** and the resulted mesh in **Figure 5.80**.

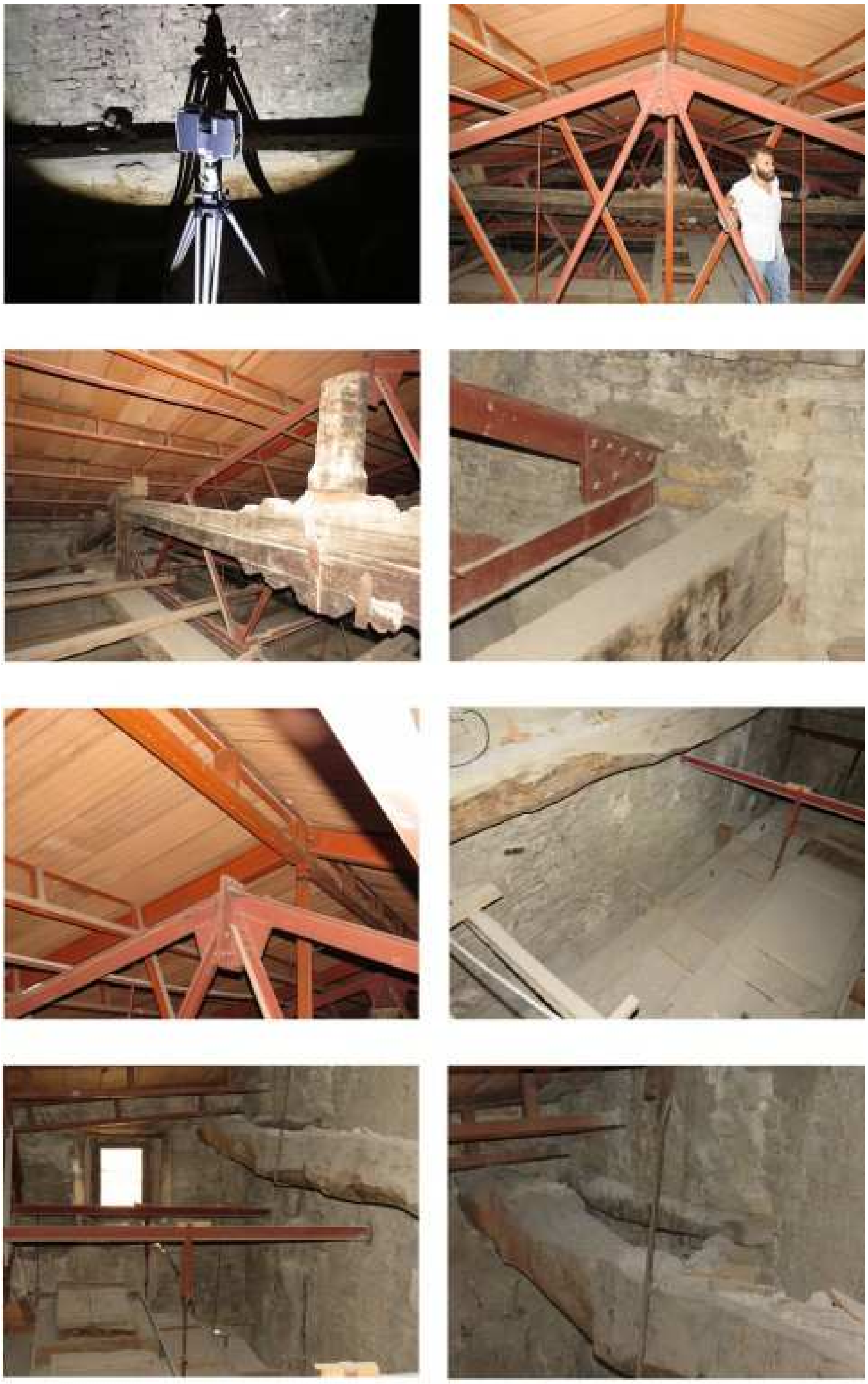


Figure 5.75: Photographical documentation, DISEG mission

Figure 5.76: First laser scan of the crawl space, Elaboration: Direct Team Polito

Figure 5.77: Second laser scan of the crawl space, Elaboration: Direct Team Polito

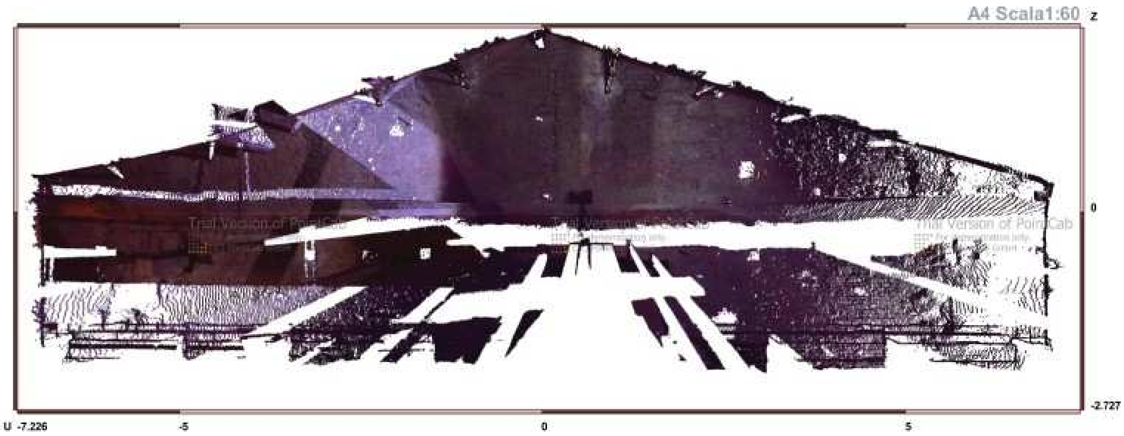


Figure 5.78: Coloured front view of the wall gable of the façade, Elaboration: Carla Borriello

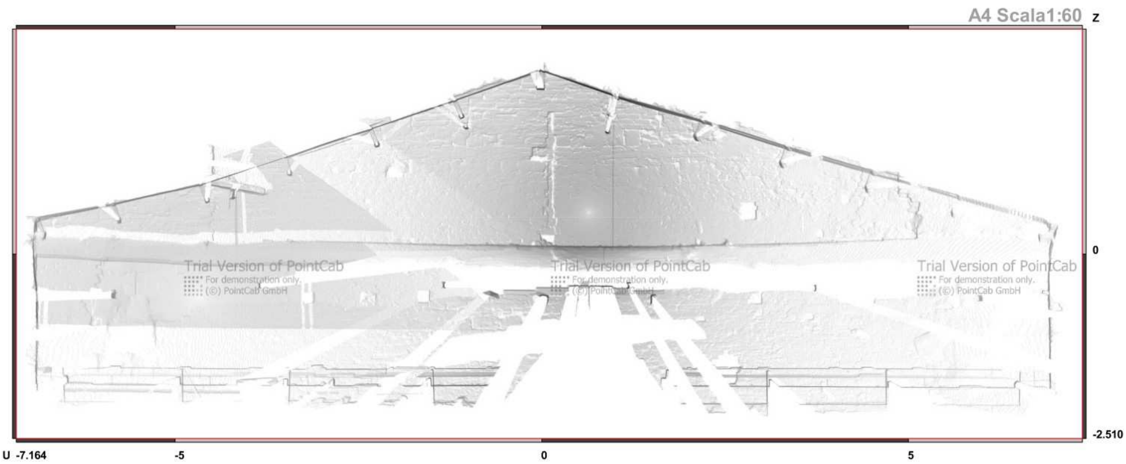


Figure 5.79: Colourless front view of the wall gable of the façade, Elaboration:Carla Borriello

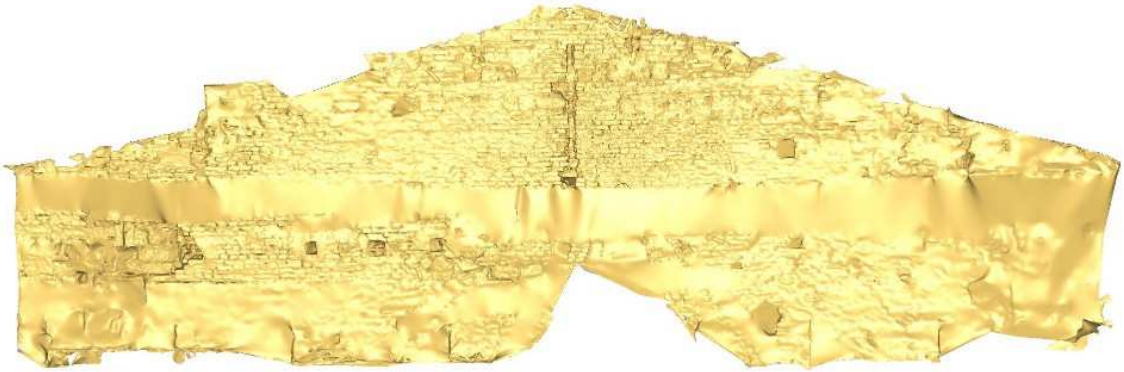


Figure 5.80: Mesh of the wall gable of the façade, Elaboration:Carla Borriello

It's important to have in mind that the smoothest parts of the mesh are those with no information starting from the previous point cloud because the meshing process tries to cover the whole area somehow with not accurate references or with interpolation of new points: the central beam on the façade that has been clean off the point cloud for the following structural investigations and the lower parts under the beam itself. The most detailed zones of the mesh instead, shown in **Figure 5.81** and in **Figure 5.82**, underline two wall weaving discontinuities due to hypothetical and different constructive times that it will be faced more carefully in the homonym section of this chapter.

Figure 5.81: Central area detail, Elaboration:Carla Borriello

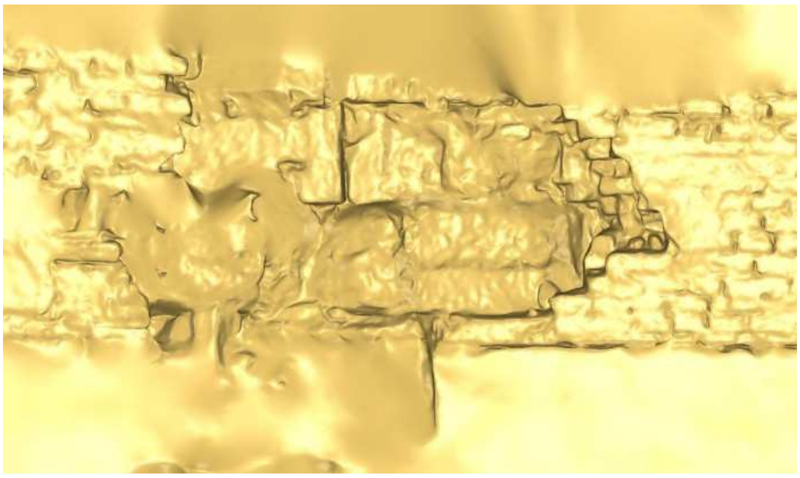


Figure 5.82: Gable detail, Elaboration:Carla Borriello

5.6.2 Plumbing line investigation

It has been directed a glance on the study of the plumbing direction of the façade wall in order to detect and evaluate damages eventually coming from hazards or maybe coming from wrong or incomplete constructive techniques.
Due to the lack of adequately light sources, the reduced dimensions of the space completely twisted by the truss systems, the point cloud data, recorded by the 3D laser scanner, result to be a little bit noisy and full of holes of information.
It followed the structural investigation on that point cloud surface to capture some clues about the wall estrangement in accordance with the lateral walls of the Church. In a deeper way, it has been analysed the plumb direction of the portion of the crawl space close to the main façade wall choosing as a basis for comparison a vertical plane located in tangential way to the main central part of the façade wall point cloud visible in **Figure 5.84**, since the lateral extremities of it result to be, for constructive reasons, intentionally planned in advanced profile positions in comparison with the interior profile of the rest of the wall as the **Figures 5.83**, **5.85** and **5.86** show below.

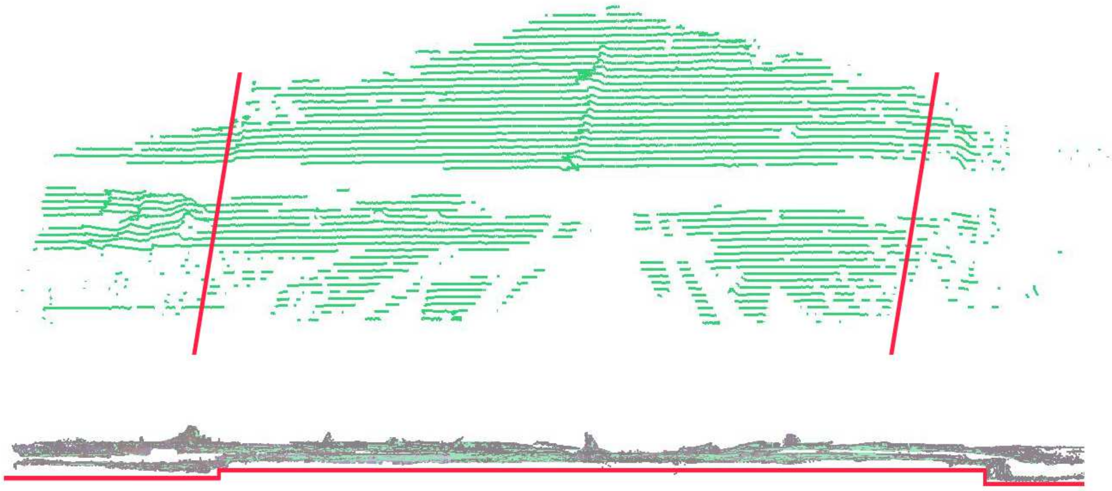


Figure 5.83: View of the profile wall, Elaboration: Carla Borriello

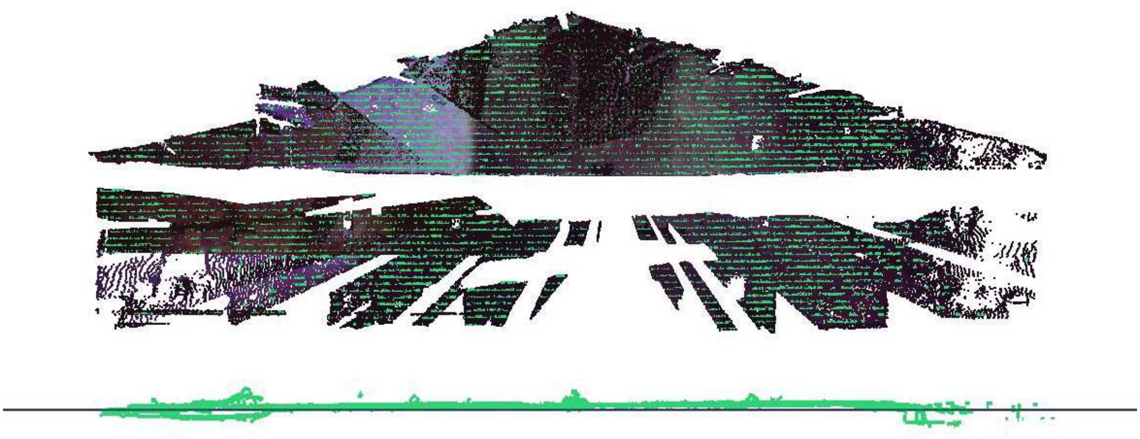


Figure 5.84: Tangential plane profile, Elaboration: Carla Borriello

Figure 5.85: Comparing plane with sections, Elaboration: Carla Borriello

Figure 5.86: Comparing plane with point cloud, Elaboration: Carla Borriello

Then, it seemed logic to choose a single class of investigation with no negative values in order to have a map with only the positive ones that go from +0 [m] to + 0,28 [m] as it's possible to analyse with the point cloud in **Figure 5.87** and with the mesh model in **Figure 5.88**: it means that only the wall portions that aren't estranged from the reference plane of course belong to it.
Colours change in reference to the values scale that are more accurate with no negative values. There's an evident out of plumb line, visible in **Figure 5.87**, of the wall near the left lower part of the wall, where the value reaches + 0,28 [m] of depth.

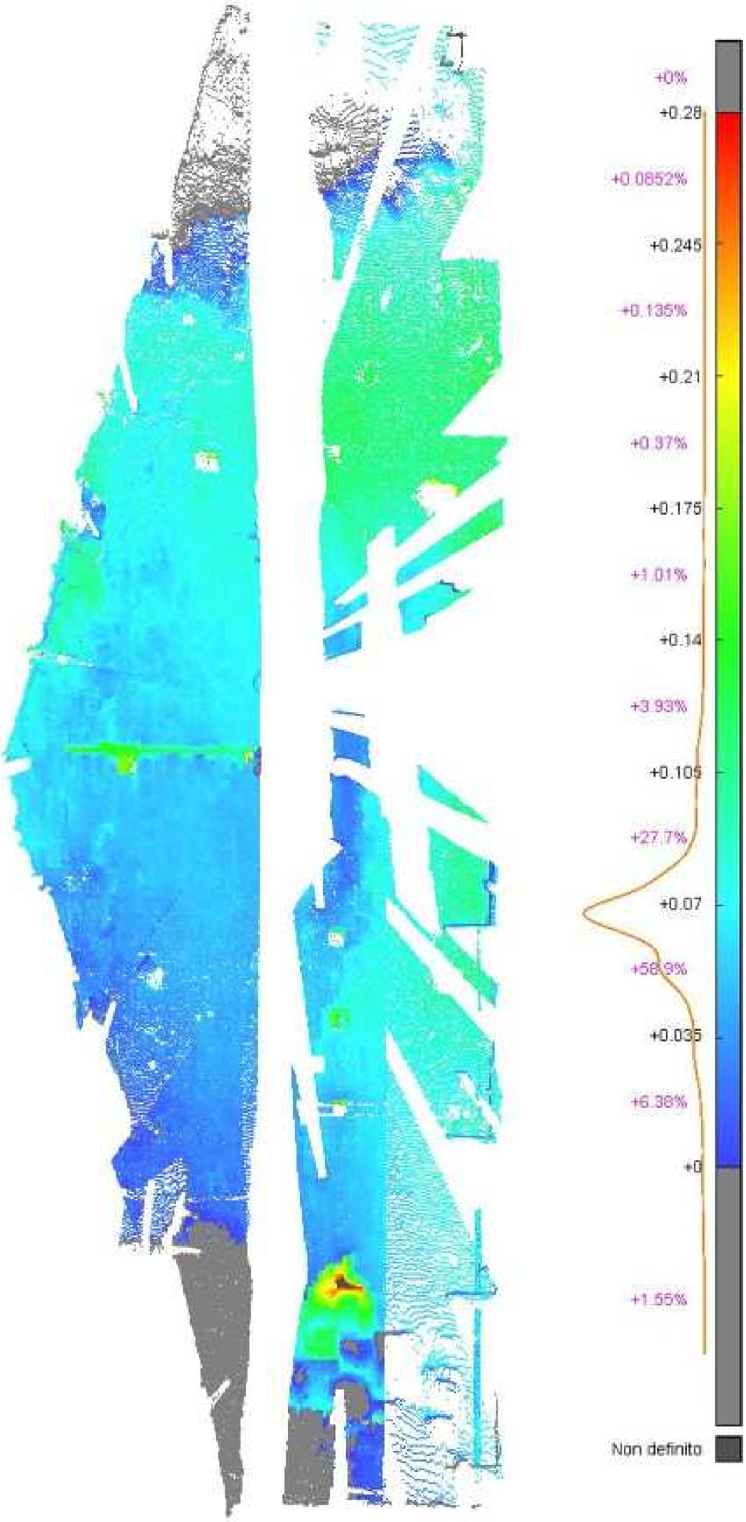


Figure 5.87: Plumbing line evaluation on the point cloud, Elaboration: Carla Borriello

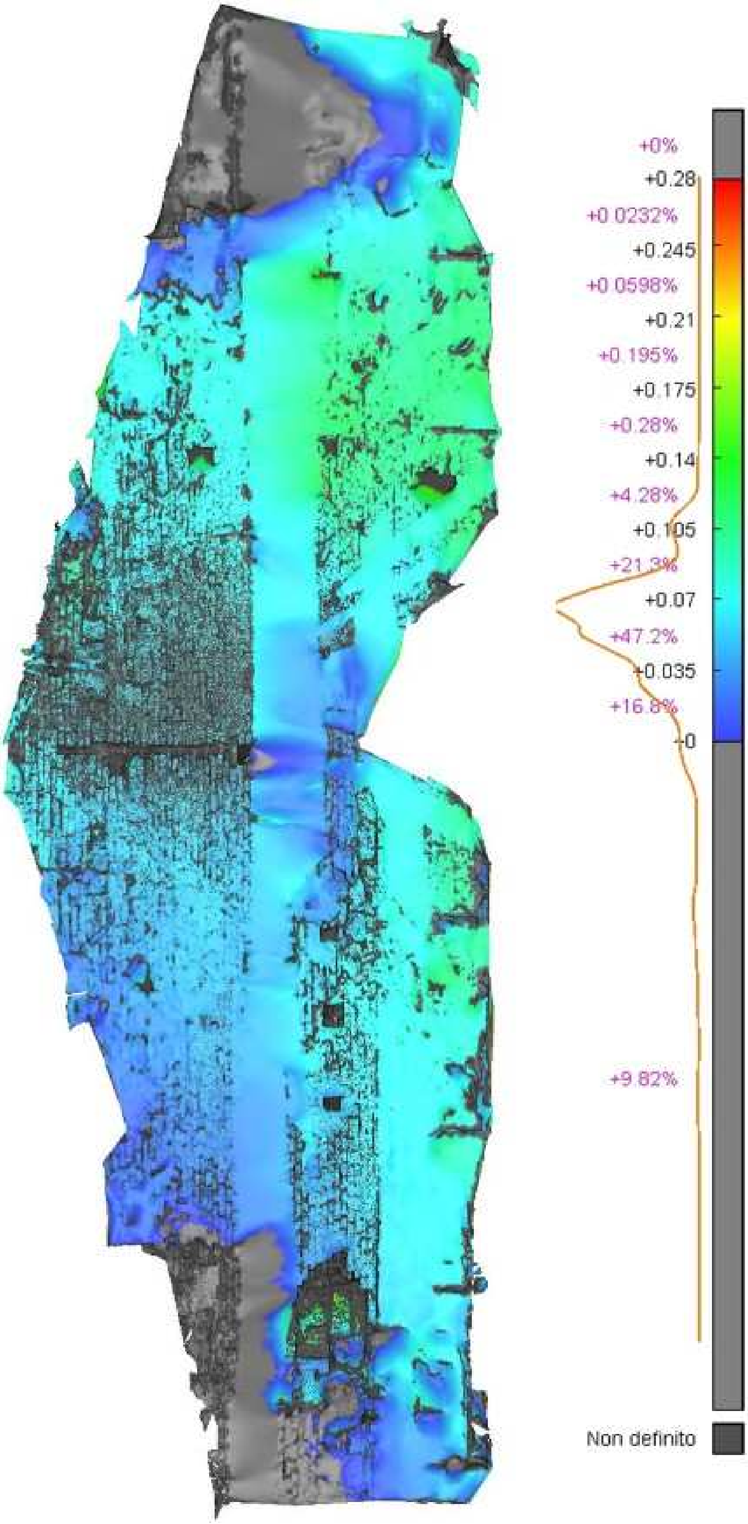


Figure 5.88: Plumbing line evaluation on the mesh, Elaboration: Carla Borriello

5.6.3 Wall weaving investigation

Generally, when it comes to talk about existing structures another important step to make is the evaluation of the wall quality and the eventual experimental investigations of the mechanical features of it, that have as final aim the possibility of understanding if the structure taken into account is able to perform an adequate behaviour to sustain the active and passive actions on the building taking also in mind the geological categories of the ground as the Italian regulation **NTC 02/02/2009 n. 617- *"Istruzioni per l'applicazione delle "Nuove norme tecniche per le costruzioni"* di cui al D.M. 14 gennaio 2008** [73] had highlighted.
For the afore regulation, the structure characteristics to analyse for all the brick-made buildings can be summarized in the **Figure 5.89** below. Furthermore, the regulation takes into account the correspondence for a plan of investigations, *in-situ*, destructive and medium high destructive, according to the level of information (LC: Livello di Conoscenza) about the structure.
My analysis will focus essentially on the evaluation of the wall weaving quality and on the decoding step of the materials rather than the mechanical investigations since our level of information is LC1 and so pretty limited for deeper studies.

NTC 2008 (Circolare 02.02.09 n. 617): FATTORI CONDIZIONANTI IL COMPORTAMENTO MECCANICO DELLE MURATURE	
	tipologia muratura
x	materiali costituenti il paramento (*pietrame, conci sbozzati, pietre a spacco, conci pietra tenera, blocchi lapidei, laterizi, etc.*)
	caratteristiche del giunto
x	malta: qualificazione
x	malta: grado di coesione
x	spessore del giunto
x	presenza di ricorsi o listature
	caratteristiche del paramento (*accostato, ammorsato*)
x	presenza del nucleo
x	caratteristiche del nucleo
x	presenza di connessioni trasversali
	interventi pregressi di consolidamento
x	iniezioni con malta
x	intonaco armato

Figure 5.89: Table of brick structures parameters for the mechanical evaluation [86]

I proceeded with the study of the façade wall weaving: so I started to plot digitally every brick or block of the wall as **Figure 5.92** shows, extracted from the previous sections, in order to highlight its laying lines, to detect the presence of correspondence with the plumbing line investigation results, to extract some geometrical measurements and to try to understand the façade chronological phases from materials.

Thanks also to the dense photographical documentations of the DISEG mission on **Figure 5.91**, it has been possible to have a visual panorama of the materials decay for the main parts of the gable and the constructive techniques that are different for materials, laying processes and kinds of cements.

First of all the materials used such as also the ancient laying methods, **Figure 5.90**, are a big *"chronological indicator"* about the structure in exam, because they may give a correspondence, if there's any, of the century.

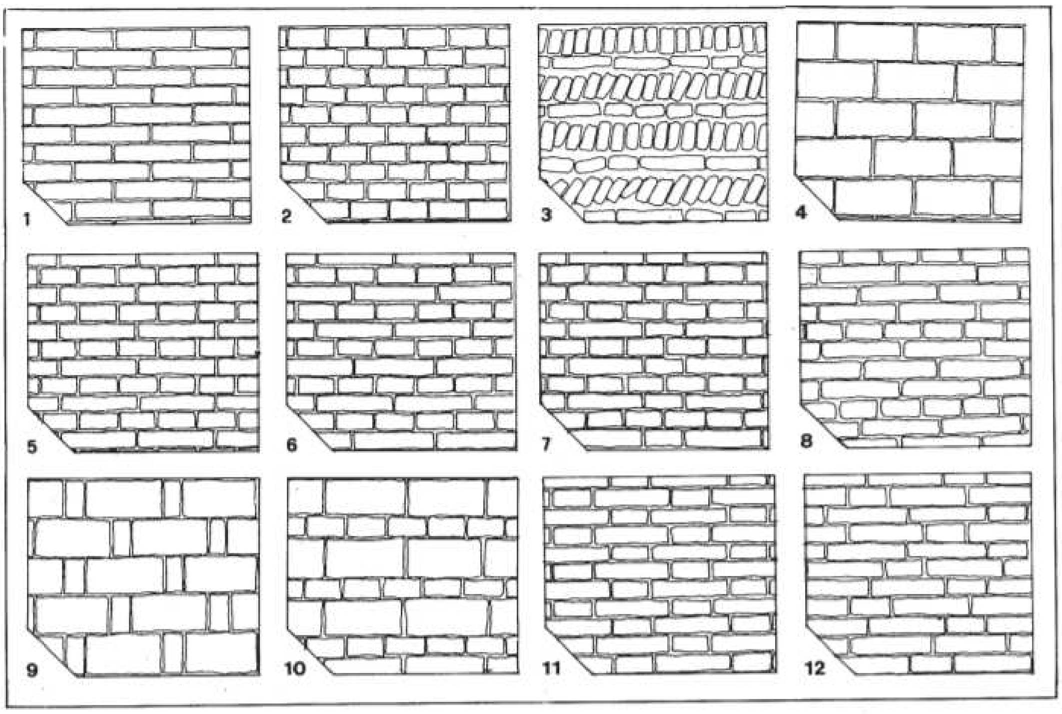


Fig. 6 — Tipologia delle apparecchiature murarie. Materiali laterizi: 1. per fascia; 2. per testa; 3. per coltello; 4. per costa (in foglio); 5. inglese a blocco; 6. inglese a croce; 7. olandese; 8. inglese per giardino; 9. "Rat trap"; 10. "Dearne"; 11. gotica o fiamminga, con due varianti; 12. "senese" o "Monk", con varianti.

Figure 5.90: Laying typologies for bricks made walls [70]

Figure 5.91: Photographical documentation about the wall weaving, DISEG mission

Figure 5.92: Digital plotting: scan of the crawl space façade, Elaboration: Carla Borriello

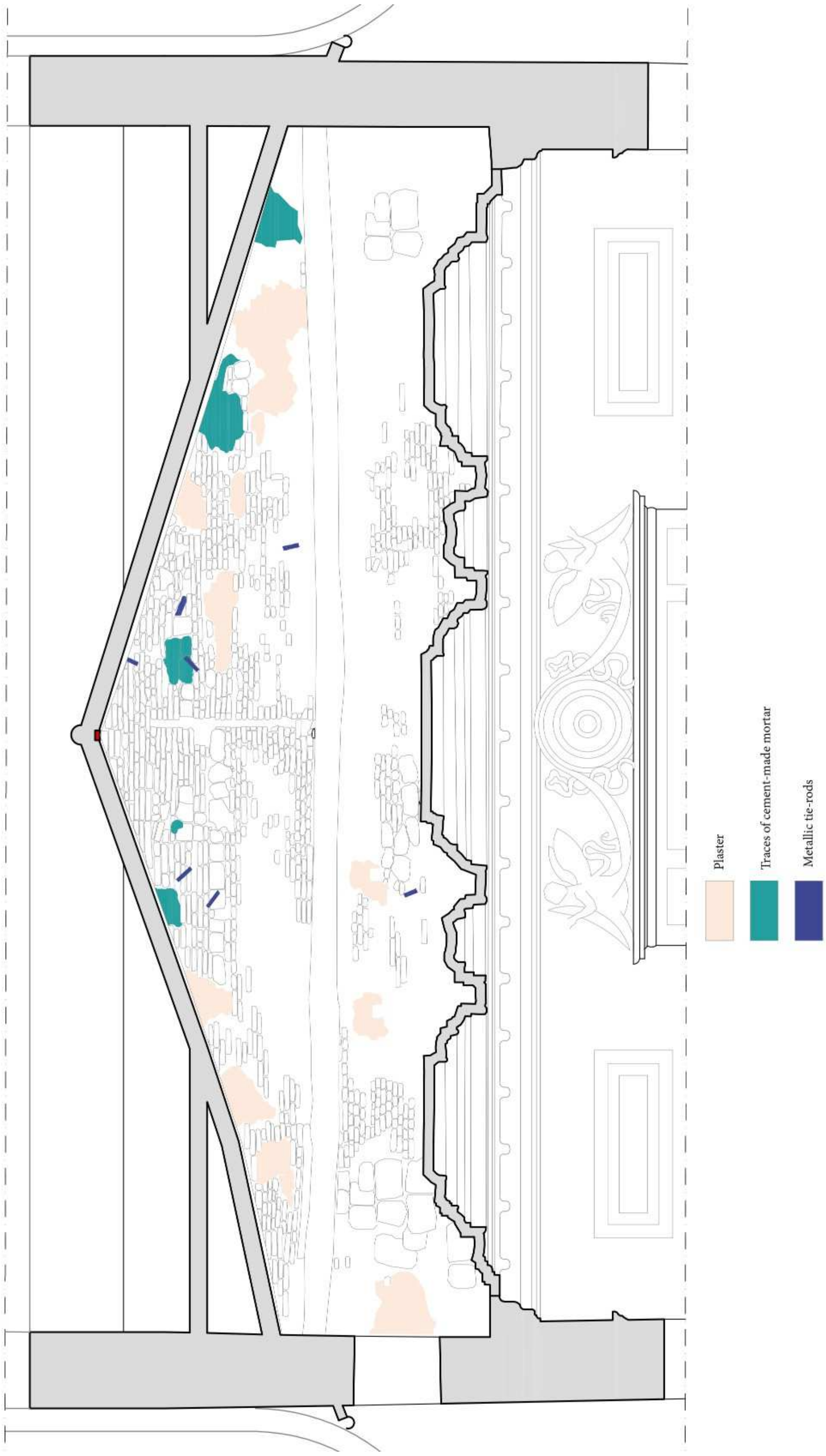


Figure 5.93: Digital plotting: Crawl space wall section, Elaboration: Carla Borriello

The **GNDT group** [76] or National group for the earthquakes defence, has drawn up several abacus for the walls evaluation. One of them, is the weaving divided into two categories:

- **I**: Irregular and low quality weaving;
- **II**: Regular and high quality weaving;

From the comparison between photographical documentation and digital plotting analysis, it arose the presence of a recurring sequence of bricks although some of them results to be cracked or missing.
As regards the weaving, the wall is strongly irregular, apparently has no always a logical laying method for the bricks since some of them are laid alternating a course of headers (laid with the brick width exposed) and one of stretchers (laid with the long narrow side exposed), other lines are made up of just stretchers and some parts are laid with medium blocks of stone.
Although the wall unreadability since the materials quality isn't really preserved and so the mortar consistency's deteriorated, it seems that the mixing method with stones it has been intentionally done in the past during some works.
The difference is clearly visible in some extracted samples, visible in **Figure 5.95** which I will face more carefully in the next pages, of the digital plotting drawing of the wall where the central weaving seems to be more regular with several brick courses of stretchers than the lateral ones that appear to be laid with brick courses of headers.
Another important evaluation to make, as we can see in **Figure 5.93**, is the presence on the wall surface of irregular plaster tracks, maybe dating back to the first centuries of construction of the Church when the roof system was made up just of wooden trusses visible from the interior spaces and it needed for this reason an appropriate finishing touch suitable with the rest of the Church surfaces.
The central wooden beam that cross the wall gable, in my hypothesis couldn't be the rest of an old wooden truss that ended to be cut off just for one reason: in **Figure 5.94** is shown that the height between the old trusses and the wood board of the coffered ceiling in its highest point it's in the order of magnitude of few centimetres, while the distance between the beam and the same highest point it's in the order of magnitude of almost a meter. This important difference could prove in theory the different purpose of the beam, despite the trusses, to be a brace element for reinforcing the façade structure.

The presence, instead, of cement tracks let me think about more recent interventions on the wall surface due to the addition of the new two orders of metallic trusses that needed to be anchored to the walls.

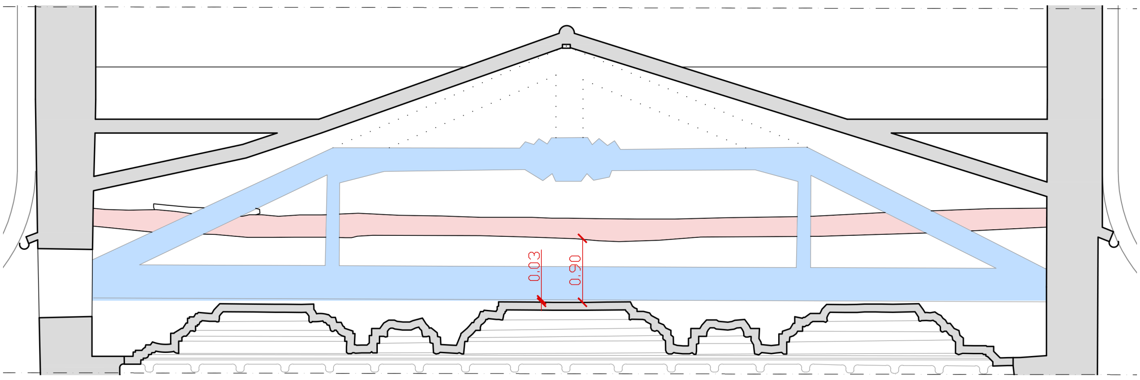


Figure 5.94: Diagram of heights of the brace beam in red and the old truss in blue, Elaboration: Carla Borriello

As far as the laying quality of materials are concerned, in the **Map 5.95** I chose four wall samples to analyse for their distinctive traits to be located in different portions of the wall and because in my point of view some of them can give important clues about age, constructive phases and hypothetical vision of the ancient Church façade of the XIII century.
As I've said before in the introduction, these represent just some hypothesis based on observations, quantitative data and objective investigations which give qualitative explanations about purposes, ages or assets that can't be really proved.

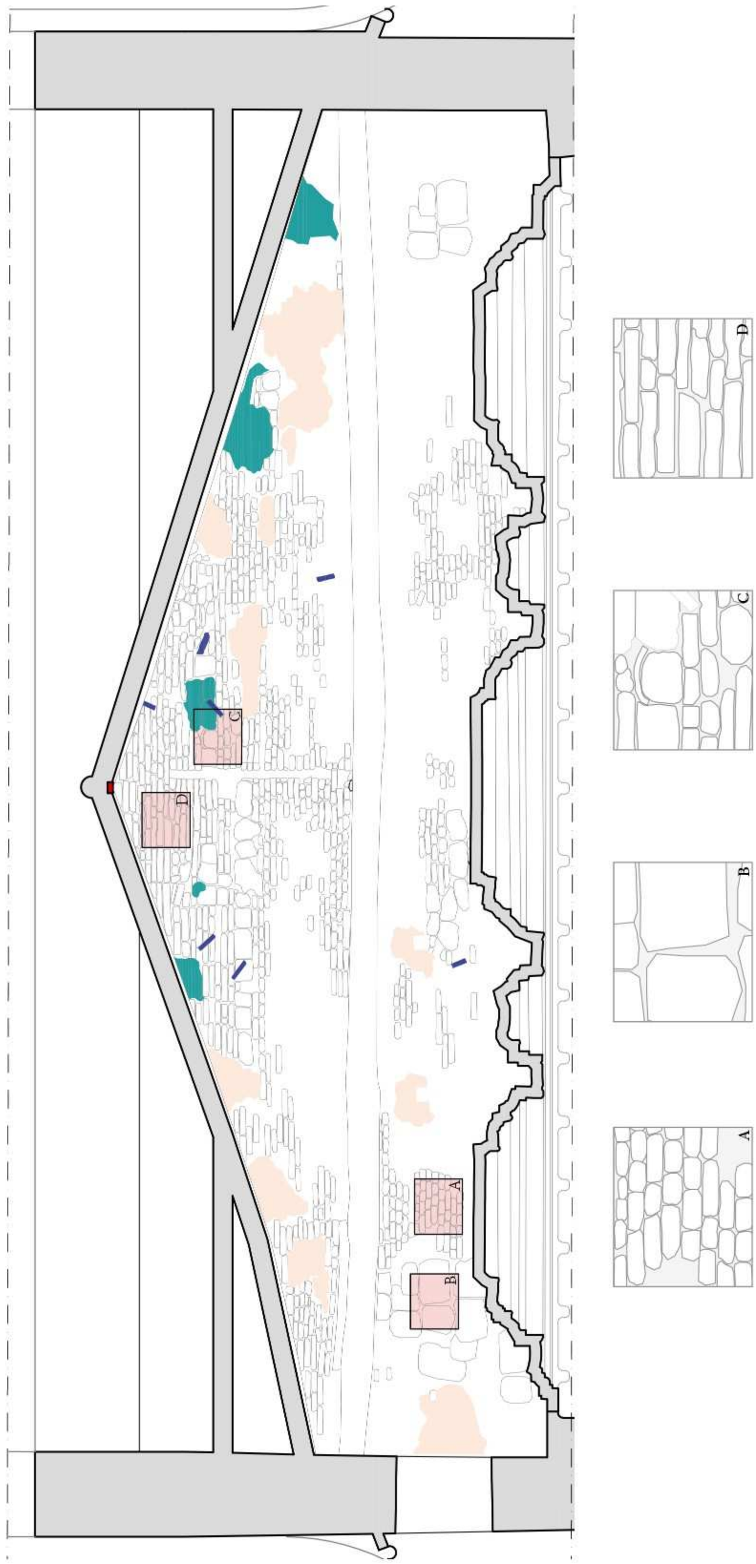
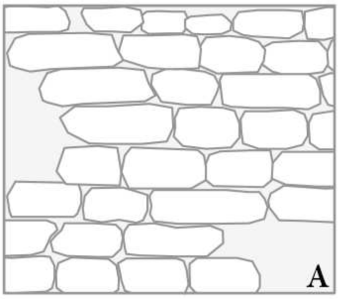


Figure 5.95: Map of the wall weaving samples, Elaboration: Carla Borriello



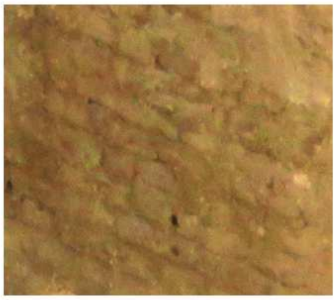


Figure 5.96: First sample of wall (A), Elaboration: Carla Borriello

The first sample in **Figure 5.96** is referred to the lowest part of the wall where the bricks weaving seems to be laid in a regular way with courses of headers.

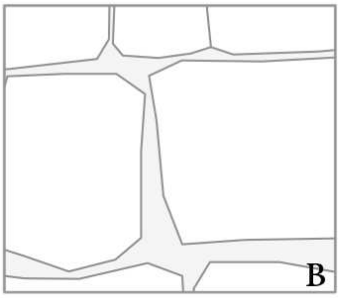


Figure 5.97: Second sample of wall (B), Elaboration: Carla Borriello

The second sample in **Figure 5.97**, it's located on the left low part of the wall too, but despite the previous weaving, this one is completely different: blocks of irregular stones and laid without any laying rigour, let me think about a delayed work. Maybe an attempt to wall an ancient opening up. This could be corroborated by two clues that I envisioned graphically in the **Figure 5.101**: a wooden trace of an hypothetical header, located on the left near the beam, for a window on the Church main façade, while the second clue is the use of different constructive materials rather than the original bricks. On the other hand, the window hypothesis could be retracted by the apparent lack of symmetrical trace of the header on the opposite side, even though the photographical documentation and the drawings have proved

the presence of other big stone blocks similar for dimensions and age, but no trace of the right header. The reason may be the façade wall has incorporated the wooden beam and with it the right header of the hypothetical window.
Furthermore, the possible existence of the two symmetrical windows on the façade, could legitimize the advanced profiles of the wall exactly near the extremities of the wall gable (that I analysed in the plumbing line investigation of the previous section of the thesis) which are also occupied by two big recesses in the current façade.

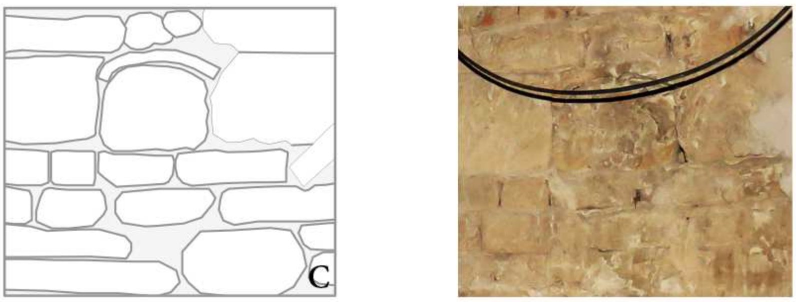


Figure 5.98: Third sample of wall (C), Elaboration: Carla Borriello

The sample C of the wall, **Figure 5.98**, is located in the middle-high part of the façade over the wooden beam. It highlights the presence of a mixed technique of materials that don't appear to belong to different ages: bricks mainly and some stone blocks of dimensions smaller than the stones located in the sample B (**Figure 5.97**) but, these ones seem to be laid with a more constructive rigour rather than the others. This is also the area where it has been spotted a really strange anomaly on the centre of the wall or more precisely a cross-shaped trace that seems intentionally built like that: indeed the bricks result to be chosen for the purpose and not to be smoothed over or intentionally damaged.
So, this let us think that probably, in the XIII century the first façade fitting the typical iconography of the late XIII century of the religious architectures belonged to the first simple pre-Romanesque façades characterized by exposed brickwork, the presence of windows on the façade and sometimes little roundels or little central cross-shaped openings to let the light enter from the front (**Figure 5.101**) as it's possible also to notice in other same aged Romanesque architectures Basilica of Agliate and the Pieve of Galliano both in region Lombardy of Italy (**Figure 5.99**).

Figure 5.99: Basilica of Agliate (left) [12] and Pieve of Galliano (right) [225]

Figure 5.101 is just a theoretical hypothesis implemented by the study of the wall weaving. In red is highlighted the presence of a central beam that, as already disclosed, has a different height in comparison with the trusses and a different purpose of being a brace element for the façade reinforcement. In black, it's possible to find the lateral exact points of the wall gable where it has a different plumbing line in comparison with the central area: this could be also corroborated by the idea of ancient windows or recesses highlighted with dotted red boxes. Another important factor, is the material quality employment near this area, in yellow, indeed, it has been highlighted the materials, stones despite bricks, employed for stopping up the theoretical lateral ancient windows.

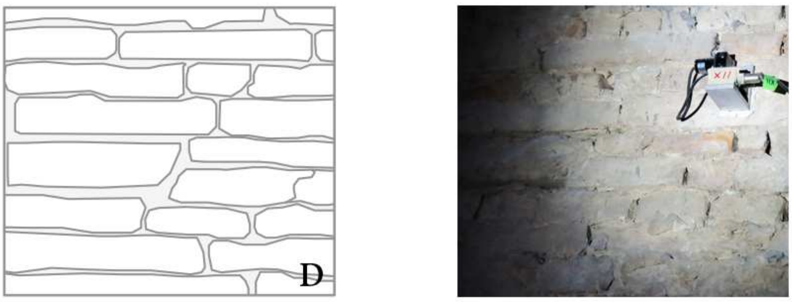


Figure 5.100: Fourth sample of wall (D), Elaboration: Carla Borriello

As regards the fourth sample D, the wall weaving appears again different cause the brick lines are mainly stretcher-coursed. This could be probably due to the constructive extension in height of the façade to hide the hut rooftop system.

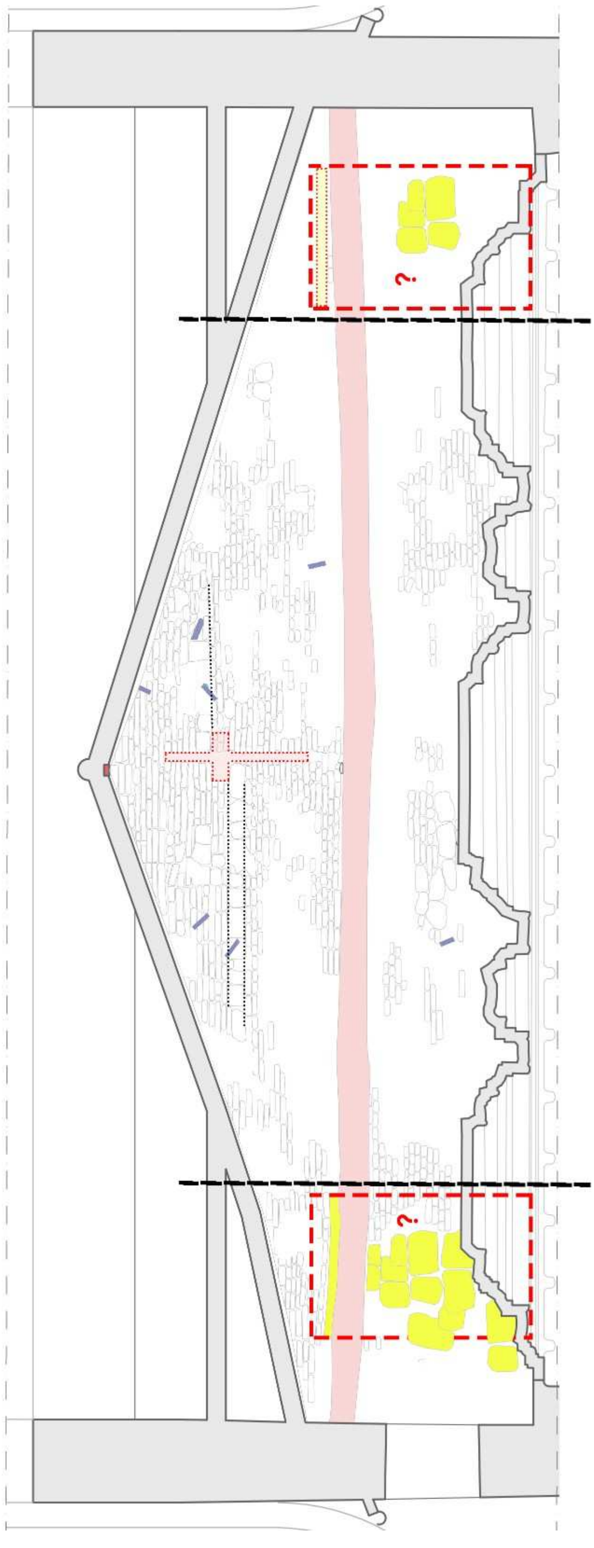


Figure 5.101: Crawl space wall façade: hypothesis, Elaboration: Carla Borriello

Chapter 6

From 3D model to VR model

This chapter takes into account the processing path that has as final aim the creation of an immersive and interactive model-tool in VR: it hasn't just a general value of cultural heritage at risk fruition for the mere visualization itself, but it has mainly a new value of being an architectural additional support focused on the story telling and on the **analysis of all the structural damages**, the analysis of all the **vulnerabilities** for all the field experts or students who can't properly inspect it in first person, for geographical distance reasons and more, and who can instead in a preliminary way have a general point of view about the vulnerabilities location or the weaknesses in structural terms.

This focused view is the difference key of this thesis as it's embraced by the preponderance of the **analysis** and **functionality** over the LOD **visualization** of the model: the presence of interactive possibilities indeed provides the audience architectural or artistic information, photographical documentation about the vulnerabilities and metrical measurements.

Presenting here my experience, I would like to give light to future scenarios where an apparent only game-based technology, like the VR, creates a change of attitude: an elevation of purpose from the hedonistic immersion to a communicative supportive tool for structural purposes that takes advantages of its *sustainable* approach declined in the virtual dimension.

The first step was the creation of a 3D surface model starting from the point cloud data. After the digital plotting phase of the 2D architectural drawing, it has been necessary to manage properly the 3D point clouds in order to create a surface model.

This phase has taken a relatively long part of the process because of the meshing phase of the high detailed and the architectural complexity of the case study. Indeed, fitting this principle and the need to have a lightweight file, the whole point cloud of the case study has been reduced of the only portion referring to the pipe organ and the adjacent chapels as we can see in **Figure 6.2**.
Furthermore, the limits of the LIDAR technique have made known two problems:

- A topology problem (holes around the point cloud), derived from the limit of acquisition in presence of obstruction objects in front of the surface to record and so the resulting gap of information as we can see in **Figure 6.1** below.

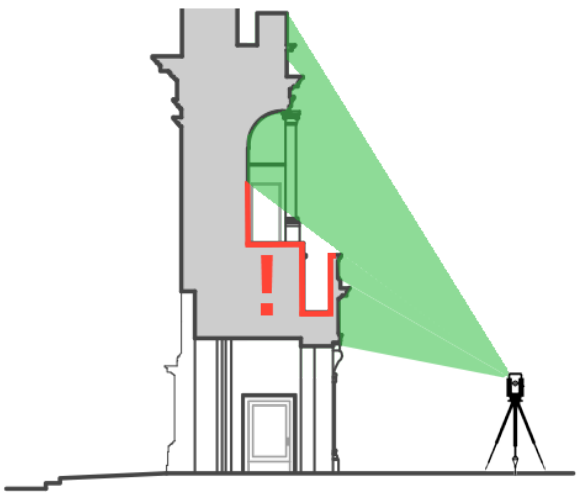


Figure 6.1: LIDAR recording issues in the pipe organ zone, Elaboration: Carla Borriello

- A texturing problem, which has been solved through another way we'll see in the following pages, derived from the lack of proper overlapped photographs of the interior part of the Church: let's have in mind indeed that the case study has really big dimensions in height and weight;

From now on, all the processes regarding the point clouds, passing through the meshing phases to the texturing phases have been performed thanks to the already cited **3D Reshaper** [3] software dedicated to the point cloud processing. While the processes that refers to the exportation of the final model until the visualization in virtual reality mode have been experimented thanks a game engine software: **Unreal Engine 4** that takes advantages of a way of visual coding instead of programming languages. The choice will be properly faced in the heart of this chapter.

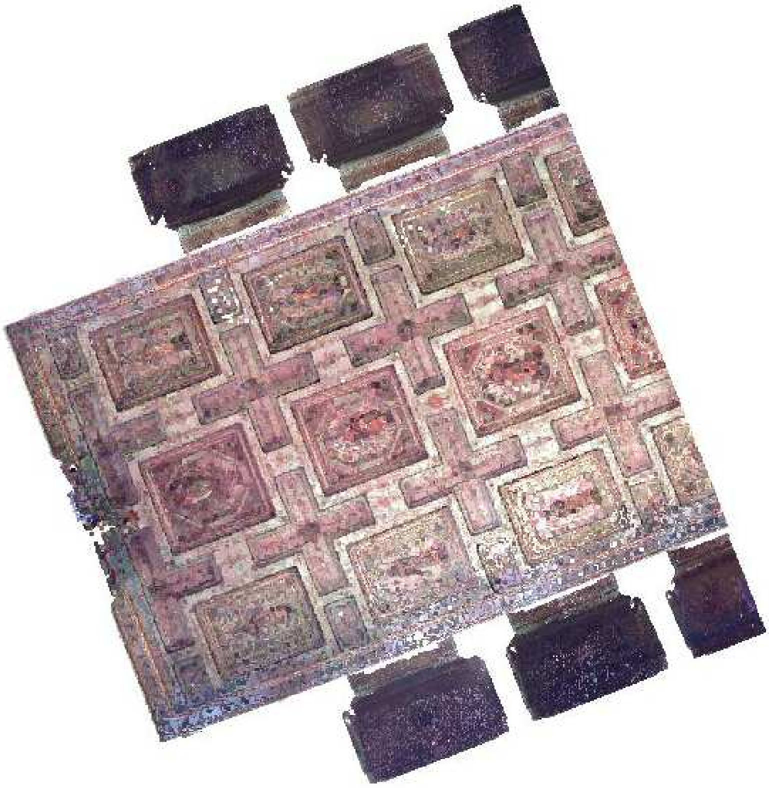


Figure 6.2: Top view of the case study portion, Elaboration: Carla Borriello

6.1 Point cloud cleaning phase

A first step to make the whole point cloud completely readable, is the manual cleaning and splitting phase of all those points which are not relevant or maybe we want to process them in a separate way according to their LOD.
Indeed, since the presence of a big amount of points of about 232 million points (**Figure 6.5**) also overloaded, these may cause a more demanding hardware power for their management, so the best step was to divide the point cloud into sub clouds and work with them separately in order to be able to delete and filter more easily the disturbing elements. This process is such of a great importance to halve the smoothing phase and the mesh correction processing times: in the figures below we can see examples in the general noisy point cloud **Figure 6.3** and the cleaned one **Figure 6.4**. An important issue spotted during the cloud processing has been the presence of high reflective rate materials that may cause aberration phenomena

since the laser technology presumes to work at the best of its potentialities with opaque materials, not with reflective ones such as glass, complex metals, golden plated surfaces and in a low manner marbles [19].

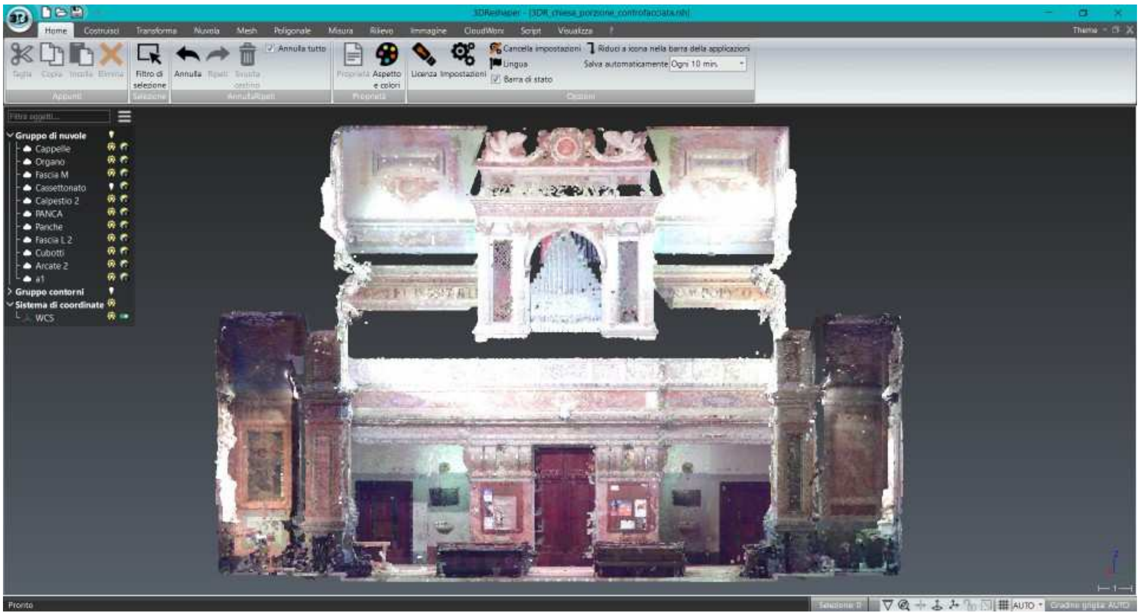


Figure 6.3: Noisy point cloud, Elaboration: Carla Borriello

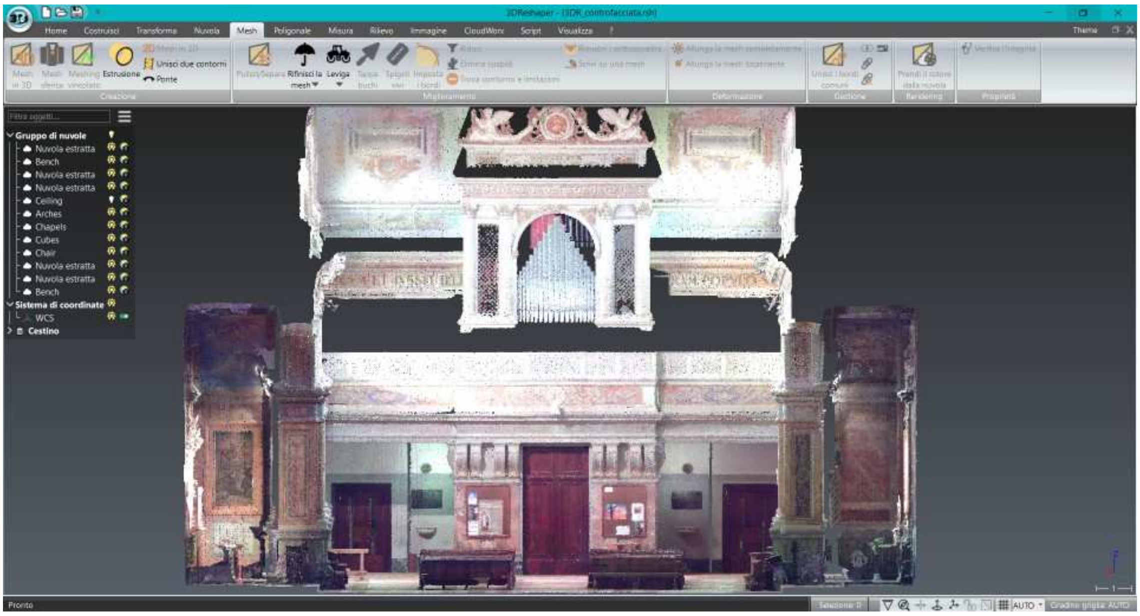


Figure 6.4: Cleaned point cloud, Elaboration: Carla Borriello

Nuvola estratta **: NUVOLA**
232.219.915 punti
Dimensione max: 24.281869
Casella di delimitazione min: 726.37744 344.964261 225.738509
Casella di delimitazione max: 750.118784 369.24613 240.560279
Dimensione: DX23.741343 DY24.281868 DZ14.82177
Punto più basso: 735.754644 357.159922 225.738509
Punto più alto: 746.096584 359.669068 240.560279
Centro: 737.487378 356.025222 230.632404
Colore: si
Ispezione: si
Direzione di scansione su tutti i punti: si

Figure 6.5: Point Cloud properties, Elaboration: Carla Borriello

Figure 6.6: Final point cloud, Elaboration: Carla Borriello

6.2 Mesh creation and smoothing phase

Once the point cloud was cleaned, it has been important to reconstruct facets between the points of the cloud and give birth to a mesh to give a basic surface for applying in the next step its real texture. A **mesh** is a network, whose concept is shown in **Figure 6.7**, made up of three elements that describe a 3D object:

- Vertex is a single point;
- Edge is a segment that connects two points;
- Face or "polygon" is a surface included by edges;

The creation of a surface model rather than a geometric one, makes sense when the objects in question are architecturally speaking really complex. Algorithms for the mesh creation are based on the Delaulunay triangulation [74].

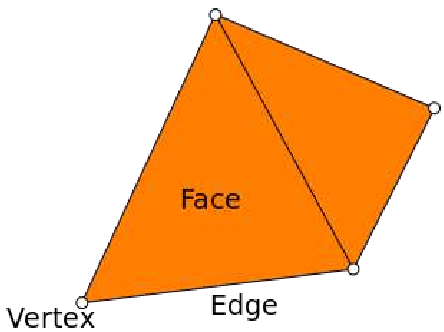


Figure 6.7: Mesh definition [226]

Due to the lack of data regarding the part of the pipe organ balcony, the generation of the meshed model has been pretty hard in this phase. Indeed, during the survey mission on site, it hasn't been possible to perform scanning sessions elevated in height, just on floor levels causing, as it has been shown in **Figure 6.1**, a missing part of data. Furthermore, it has been difficult to know which parameters to apply for the meshing phase, because it's recommended to mesh a point cloud according to the details level of features but at the same time it's important to manage it in a optimised way for avoiding large size of the produced files. The amount of points of the entire point cloud of the Church was about 232 millions, with little irregularities, noise and gaps of information derived from the previous issue. For the big dimension and the numbers of points, it has been necessary to maintain the same segmentation of clouds(**Figure 6.8**) used in the previous subsection phase, as shown in **Figure 6.9**: all this for making the meshing process easier and suitable for each feature of the case study.

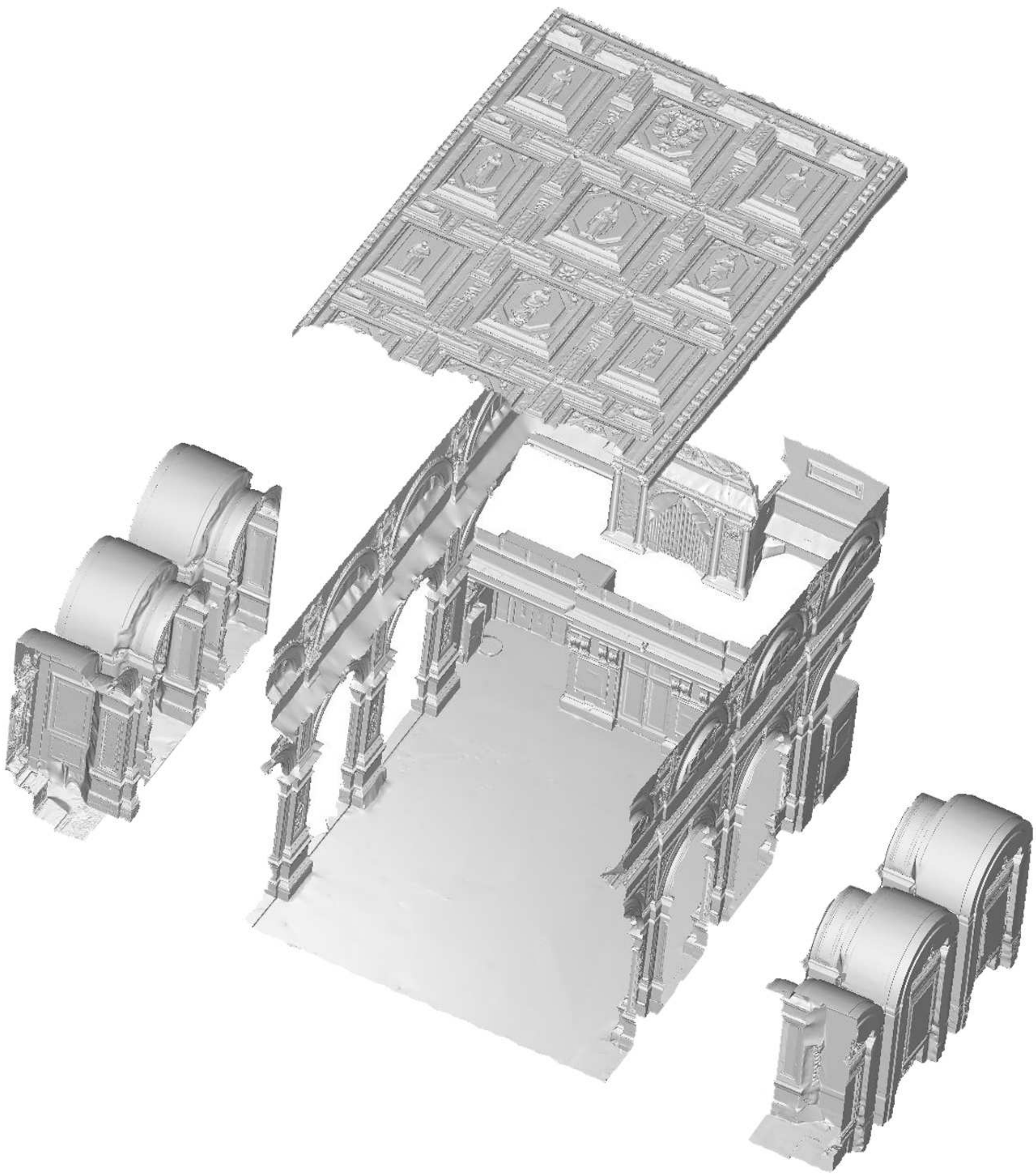


Figure 6.8: Axonometric segmentation view, Elaboration: Carla Borriello

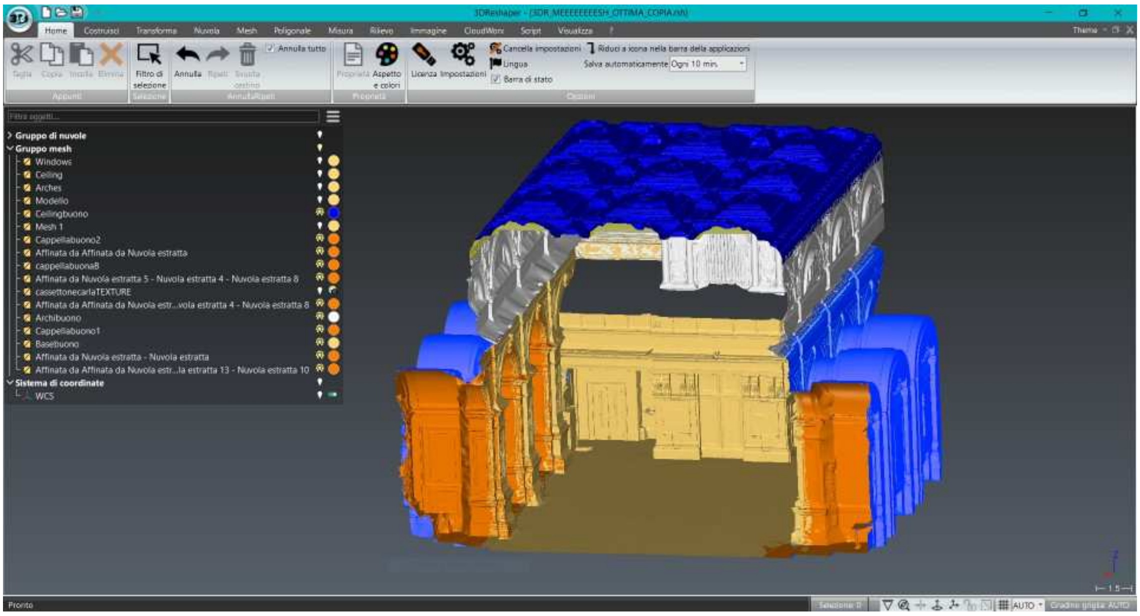


Figure 6.9: Mesh segmentation, Elaboration: Carla Borriello

The key point for making a good mesh was to find a certain balance between an acceptable **Level of Detail (LOD)** where every detail is visible and as less noisy as possible, and a good **Topology** preservation of the architectural geometrical elements in order to avoid holes above the surfaces.
So the first *test* to understand where this balance lied, was to make a rough mesh with default parameters and see the point clouds behaviour. Once it was checked the presence of big holes above the mesh and discarded that try, it has been made another rough mesh with customizable parameters set in high values just to cover the entire surface avoiding holes. I continued with the refining meshing method through two steps:

1. Using the points of the cloud;
2. Using new points interpolation;

Another issue observed during the meshing phase was the choice of parameters of meshing: the average distance between points that defines the geometrical dimensions of the triangles, and the deviation average that defines the maximum distance between the points used for the mesh and the original points of the point cloud. So it measures the effective deviation between the mesh and the point cloud. At the end of the meshing phase it has been managed the meshes trying to delete and clean them from external triangles or anomalies of the polyhedron such as the reverse face triangles of mesh (the blue face) which will determine black holes in the texture phase. It followed the smoothing phase of all the noisy surfaces and the fulfilling phase of holes in order to have an unvarying surface of the entire mesh (**Figure 6.10** and **Figure 6.12**). As we can spot in the final result, the meshed model made up of about 8 million triangles as it's shown in **Figure 6.11**, due to the presence of objects and occlusion spaces during laser acquisitions, the balcony area turn to be absent.

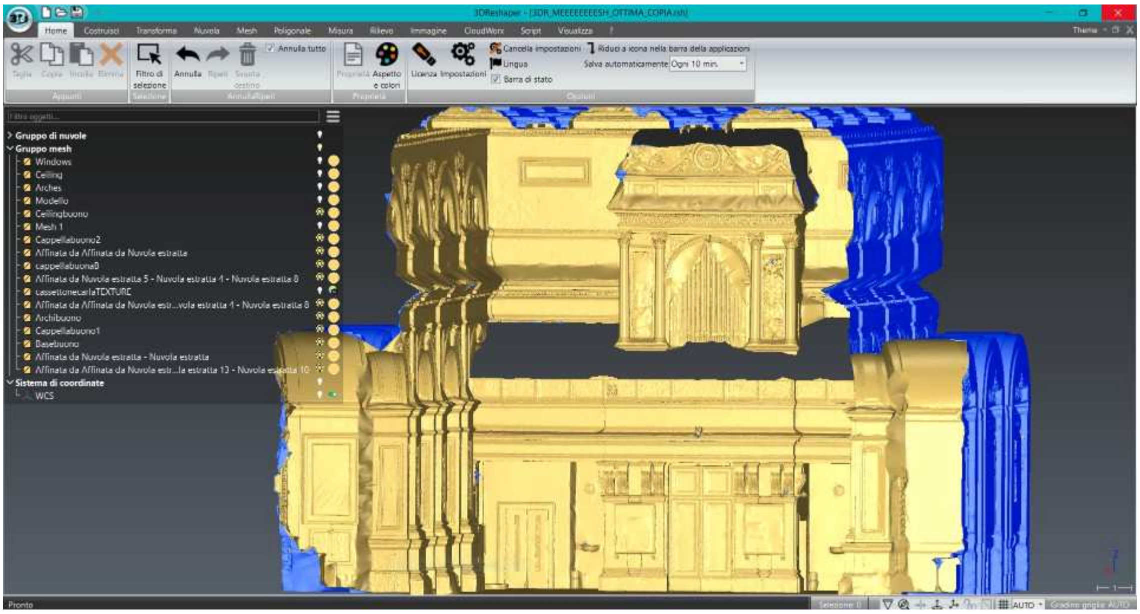


Figure 6.10: Smoothed mesh, Elaboration: Carla Borriello

Model **: POLIEDRO**
4012372 punti; 8007158 triangoli.
Numero di parti indipendenti: 151
Numero di buchi o contorni liberi: 233
Superficie: 2128.537109 m²
Baricentro della superficie: 757.315527, 285.447030, -12.924095
Casella di delimitazione min: 746.208574 274.553696 -19.482016
Casella di delimitazione max: 769.94288 298.831897 -4.672395
Dimensione: DX23.734306m DY24.2782m DZ14.809621m
Punto più basso: 761.794809 293.955937 -19.482016
Punto più alto: 761.075945 292.571299 -4.672395

Figure 6.11: Model properties, Elaboration: Carla Borriello

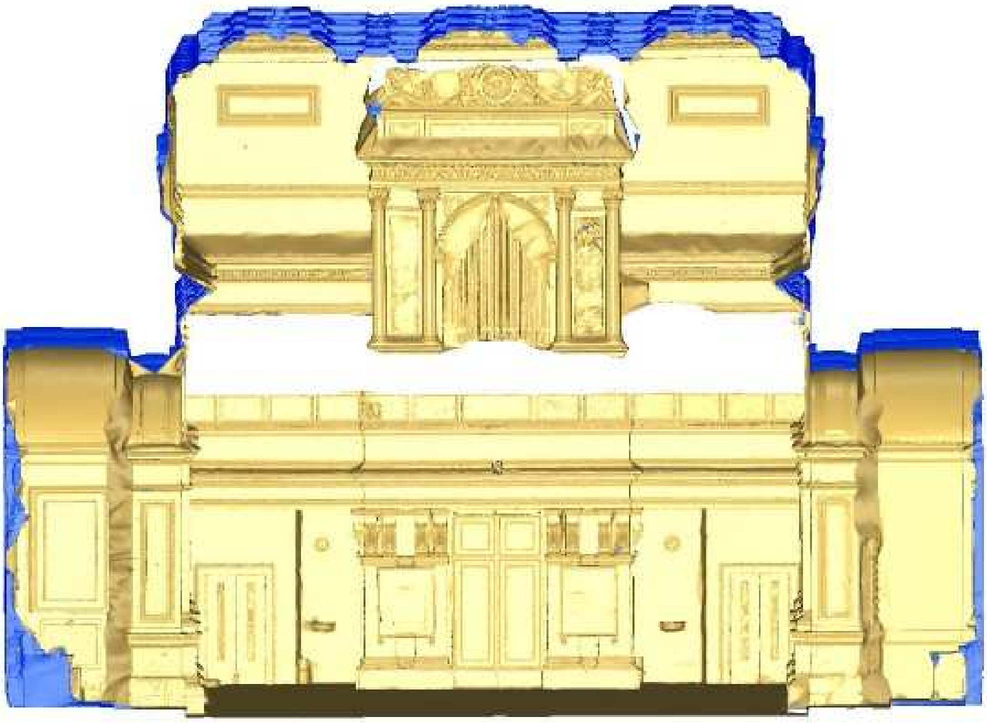


Figure 6.12: Frontal view of the final mesh, Elaboration: Carla Borriello

6.3 Texturing phase

The texturing phase provides to give a realistic rendering of the final model and it can improve its aesthetic aspect. This phase can be carried out thanks to artificial colours, default images of materials and real textures. Real textures have been applied in accordance with the LOD of the case study images and elements. I followed an integration of sources between:

- Photogrammetric acquisitions performed on the wooden coffered ceiling which required an high LOD;
- LIDAR acquisitions performed on the model of the case study;

For the wooden coffered ceiling, it has been taken advantages of the photogrammetric acquisitions processed thanks to the image-matching algorithm based software **Agisoft Photoscan** in **Figure 6.13**. Its benefit lays in the automation of a dense point cloud extraction and the generation of a 3D model whose textures are extracted directly from the acquired images(**Figure 6.14**).

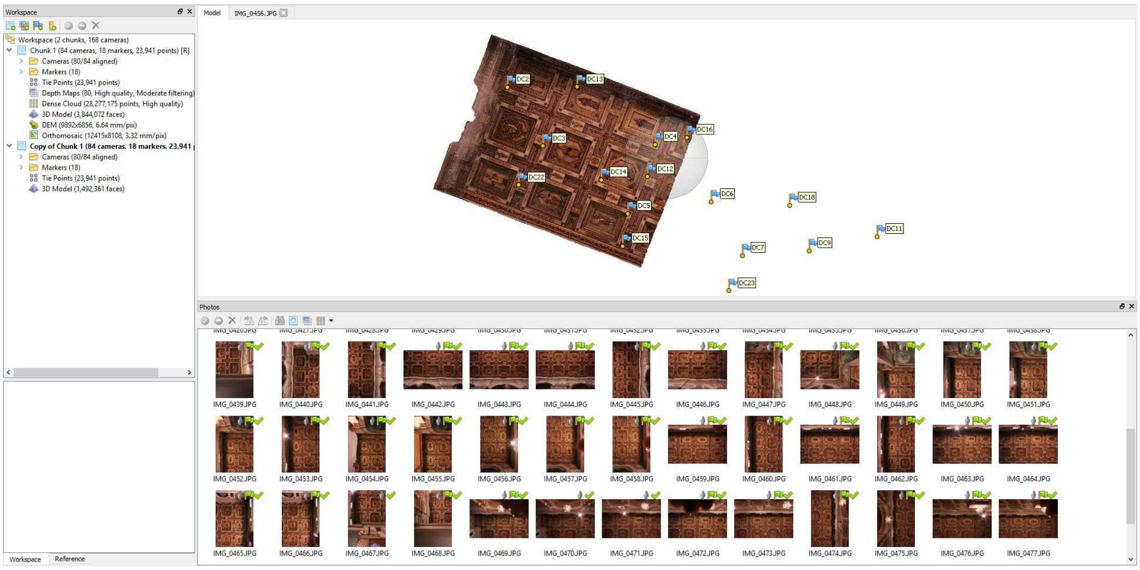


Figure 6.13: Photoscan elaboration, Elaboration: Carla Borriello

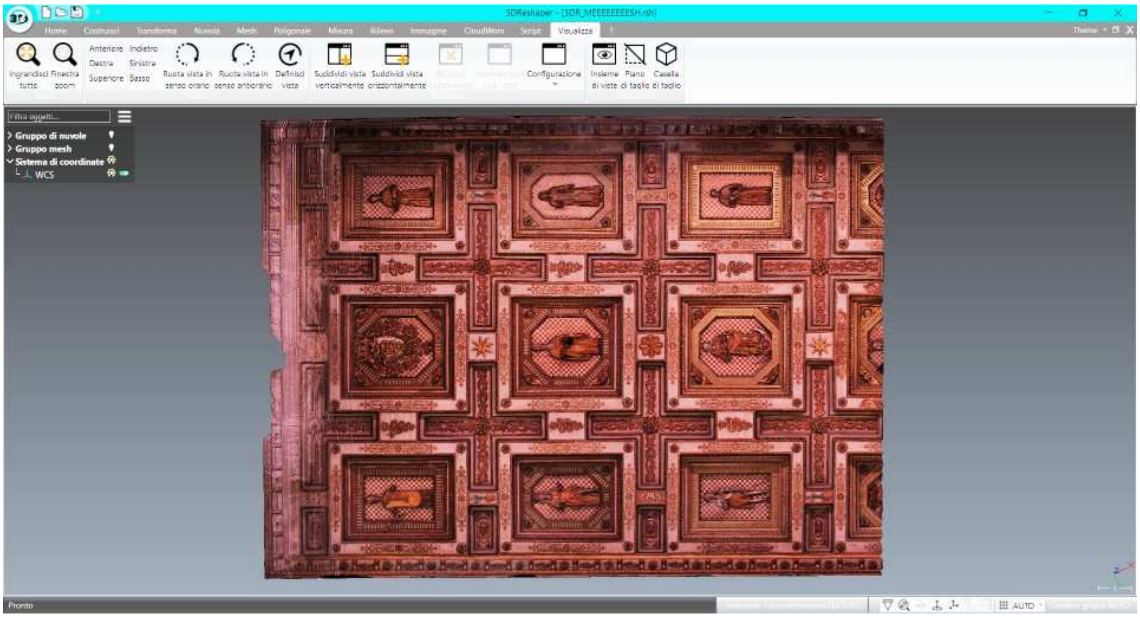


Figure 6.14: 3D textured model of the coffered ceiling, Elaboration: Carla Borriello

While, for the texturing phase of the entire model there wasn't any availability of accurate photographical documentation of the interior spaces, for this reason the texture issue has been solved starting from the indoor drone videos. Among them ithere have been selected the best drone videos in terms of quality around our portion of case study and the next step was to process them with an extraction of all the frames per second which gave sources of photographs. The frames extraction has been performed with the software **MatLab** [114] automatically with a specific script, shown in **Figure 6.15**. It extracted a huge amount of frames per second till the end of every video sequence. After doing this for each video,, the result is shown in **Figure 6.16**. Of course, the difficult part has been the manual filtering phase for each frame of all the indoor videos: indeed, not all the frames could reach the texture aim due to the drone camera inclination, the blurry quality, the speed and the distance of recording. So there have been selected the best frames in terms of quality for the projection on the meshed model as we can see in **Figures 6.17** and **6.18**. But, also applying this solution another issue occurred because due to the lack of accurate recording and the really low quality of some church portions such as the floor that has been hardly focused by the camera, the basements of the arcade pillars and the entire internal images of the lateral chapels that were really blurry and gloomy for illumination issues, it has been chosen to not proceed with the texturing phase of those areas in order to leave them with a white mesh base as it's possible to see in the results figures shown from **Figure 6.19** to **Figure 6.25**. All these were just issues derived from limits of acquisition: of course more accurate the recording phase is, and more detailed the final result will be.

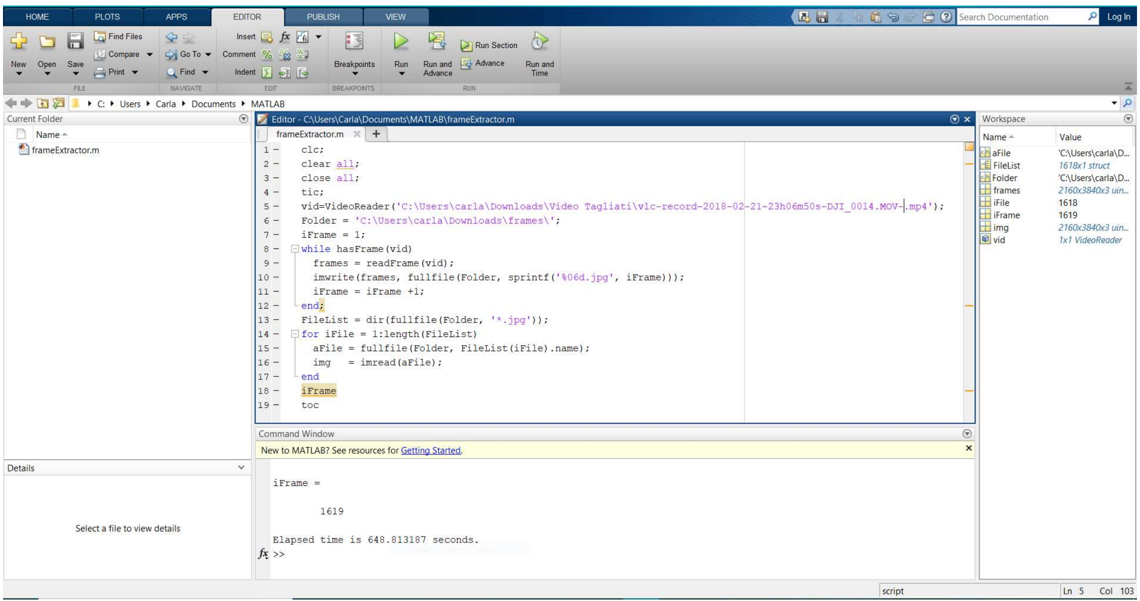


Figure 6.15: MatLab frames extraction code [114], Elaboration: Carla Borriello

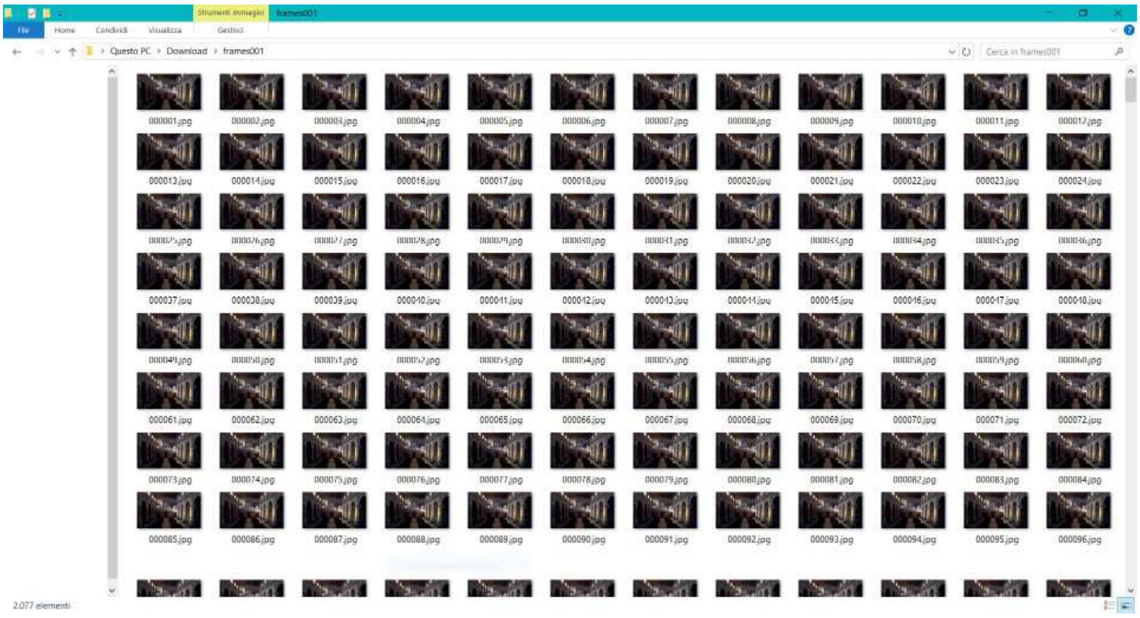


Figure 6.16: Frames extraction results, Elaboration: Carla Borriello

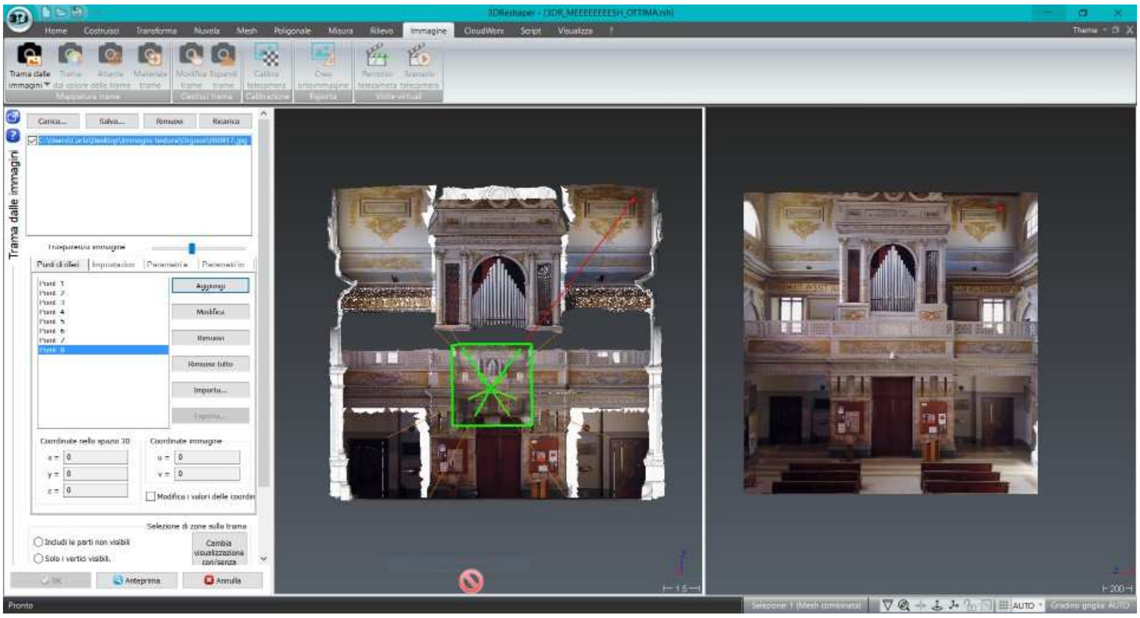


Figure 6.17: Texturing phase of the pipe organ zone, Elaboration: Carla Borriello

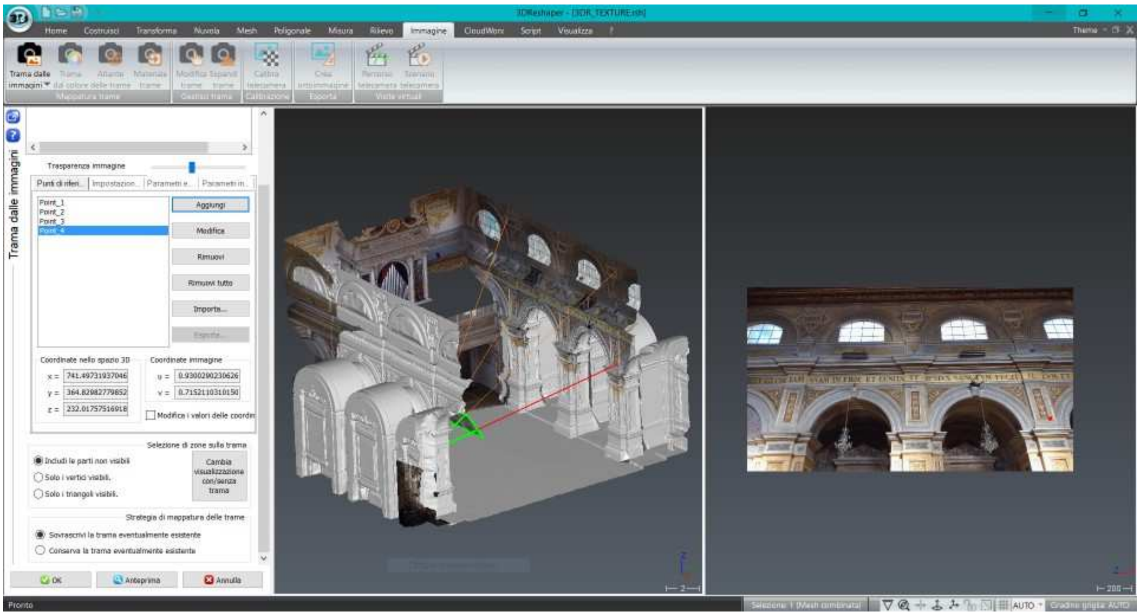


Figure 6.18: Texturing phase of the arcades, Elaboration: Carla Borriello

Figure 6.19: Front view of textured model, Elaboration: Carla Borriello

Figure 6.20: Top view model textured, Elaboration: Carla Borriello

Figure 6.21: Model textured without chapels, Elaboration: Carla Borriello

Figure 6.22: Complete textured model, Elaboration: Carla Borriello

Figure 6.23: Lateral view of the textured model, Elaboration: Carla Borriello

Figure 6.24: Central perspective view of the textured model, Elaboration: Carla Borriello

Figure 6.25: Perspective view of the textured model, Elaboration: Carla Borriello

6.4 Exportation phase

The exportation phase took into account some expedients for compatibility issues about file formats, file size and the file units supported by the output software. The 3D Reshaper model, set in metrical units, has been exported in **obj* file format that's not compatible with Unreal Engine 4, which accepts mainly **fbx* file formats used to preserve the interoperability among several application of 3D digital contents, and indeed it preserves meshed models associating their own textures.
For embracing better the software communication, I converted the **obj* inbto **fbx* through the **Autodesk FBX Converter** [16]. I also needed to check that no issues regarding the units occurred during the conversion phase, so opening the **fbx* file into another 3D modelling software was a good test to make. So, I imported my file into **Autodesk 3D Studio Max** [15], **Figure 6.26**, and re-exported it paying attention to the *fbx* exportation settings about the file units to set in **cm**: through this way I had the right units compatibility since Unreal Engine 4 has its own file unit (1 UU) that corresponds to our metric system (1 cm). The subsequent phase of importation of the final file into the real time rendering software in **Figure 6.28**, took long times (about four hours) due to the large size of the file and the high number of textures to associate them for each portion of the whole model.

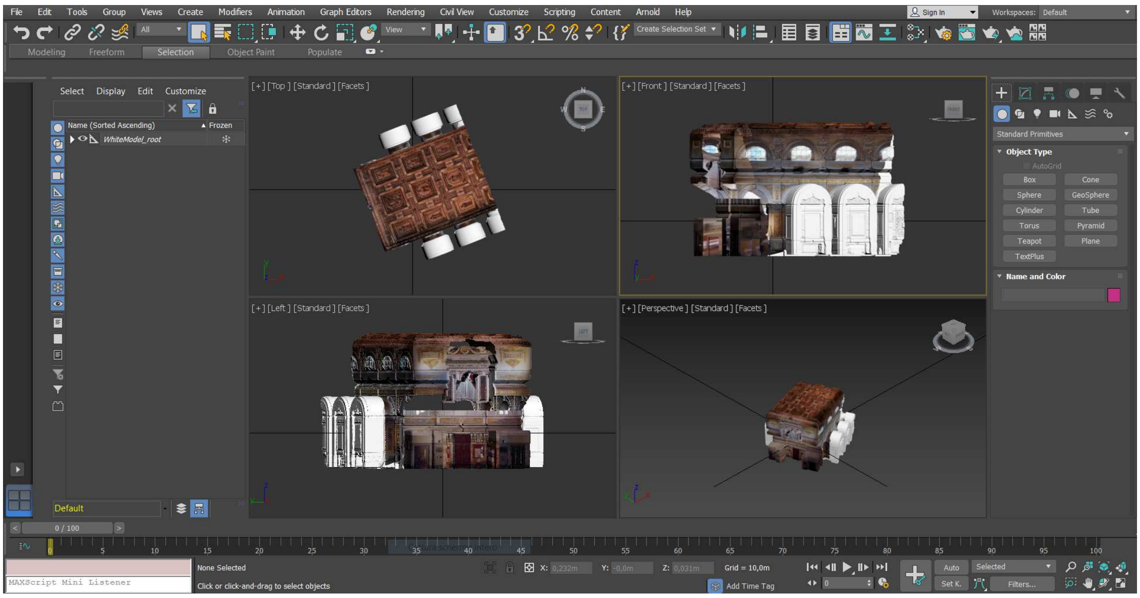


Figure 6.26: Importation into 3D Studio Max, Elaboration: Carla Borriello

6.5 Unreal Engine 4

Unreal Engine 4 [58] it's a game engine developed by Epic Games which gave name and birth to the homonym game *"Unreal"* (1998): the first FPT (first person template) shooter-game in games world to introduce environment implementation and audio extensions. It's open source, it doesn't have any restrictions about contents and it's totally free until the moment the customer will start to earn thanks to the developed game.
But what's the key point that marks the difference between UE4 and another game engine? As we know, while the price is a pass-by factor, the programming language is definitely up to the customer and to his coding skills. UE4 has a *"visual scripting"* language called **Blueprint**, a node based method that means the customer is not required to write a code line, this one is hidden through a visual interface. Of course, there are some limitations to the Blueprint potentialities, nothing you can't do with C++ coding, but it represents an important advantage for all the people who come from creative worlds and aren't skilled with codes and programming languages.

Recommended Hardware

Operating System	Windows 7/8 64-bit
Processor	Quad-core Intel or AMD, 2.5 GHz or faster
Memory	8 GB RAM
Video Card/DirectX Version	DirectX 11 compatible graphics card

Figure 6.27: Hardware Requirements for Unreal [58]

The UE4 graphical interface it's made up of:

- **Viewport** at the centre of the interface, in other words it's the Editor window where the rendering scene is created and the game starts. Inside the editor it's possible for the player to move with the default directional keyboard buttons (A,D,W,S) for the traditional templates, or through the mouse for the VR editor template.
- **Modes panel**, situated to the left side of the editor window. It allows the positioning of several objects inside the editor such as lights, meshes, visual effects and many others.

- **World outliner panel** on the right side of the editor, it shows a list and it represents every object that is inside the game scene of the editor. Each object is associated to its detail features (Mesh category, material, physics, collision, lighting, rendering, tags, cooking and navigation).
- **Content Browser** just below the editor window, it contains folders related to each content inside the scene with the correspondence of blueprint classes. The visual scripting of blueprint provides to give *causes* to objects inside an **event** in order to generate *effects* on the scene.

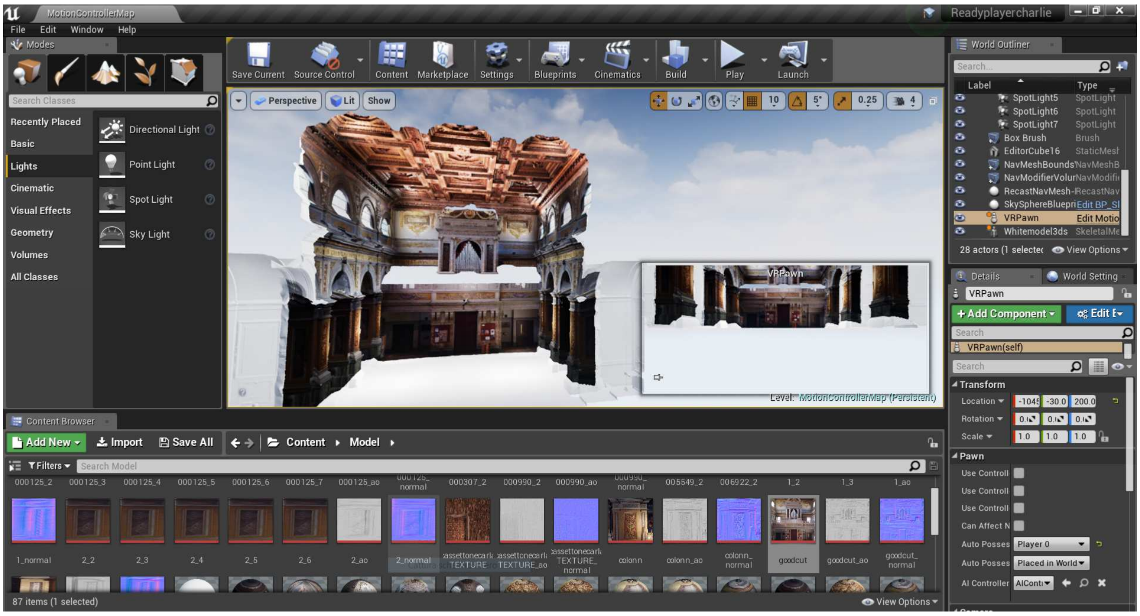


Figure 6.28: Final importation into Unreal Engine 4, Elaboration: Carla Borriello

6.5.1 VR Mode

The Unreal Virtual Reality mode allows the customer to design or to import an existent virtual project or environment thanks to the tools and the capabilities of the engine editor [58]. The immersive experience of navigation around the world and the possibility of interaction with it, is managed through *headmounted set* in **Figure 6.29** and *motion controllers* in **Figure 6.30** used inside the VR template in **Figure 6.31**.

Figure 6.29: HTC Vive headset [84]

Figure 6.30: HTC Vive motion controllers [84]

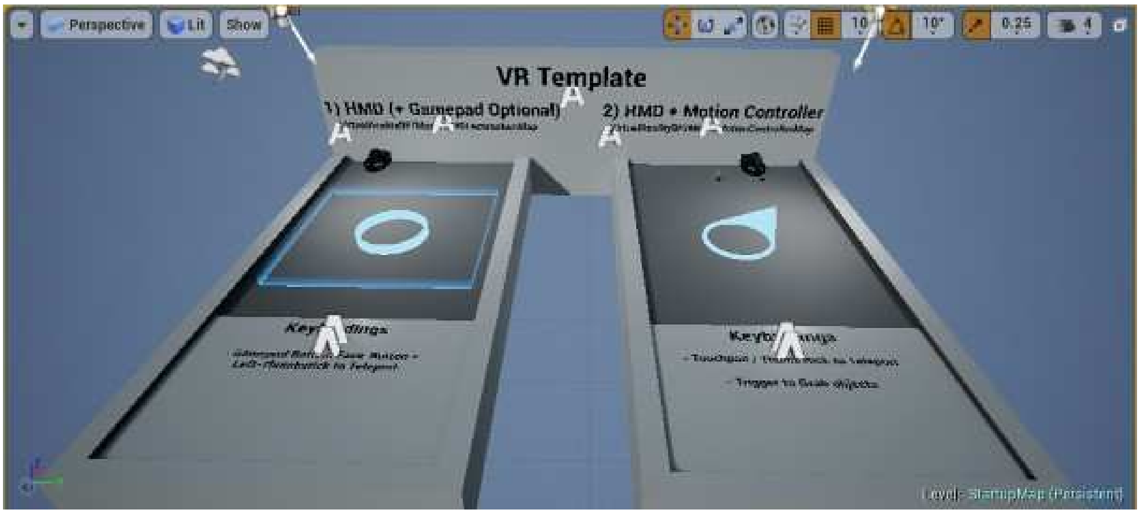


Figure 6.31: VR Unreal template, Elaboration: Carla Borriello

The great advantage of starting from this template, let us save time about the motion controllers settings (**Figure 6.32**) as regards the *teleportation*, the camera pawn settings and the rotation around the boundaries of the navigation volume since they're already set in a default blueprint event graph that changes according to the device in use (**Figure 6.33**). My model level is situated in the *Motion controller Map* where the imported mesh can be modified, scaled or moved around the space.

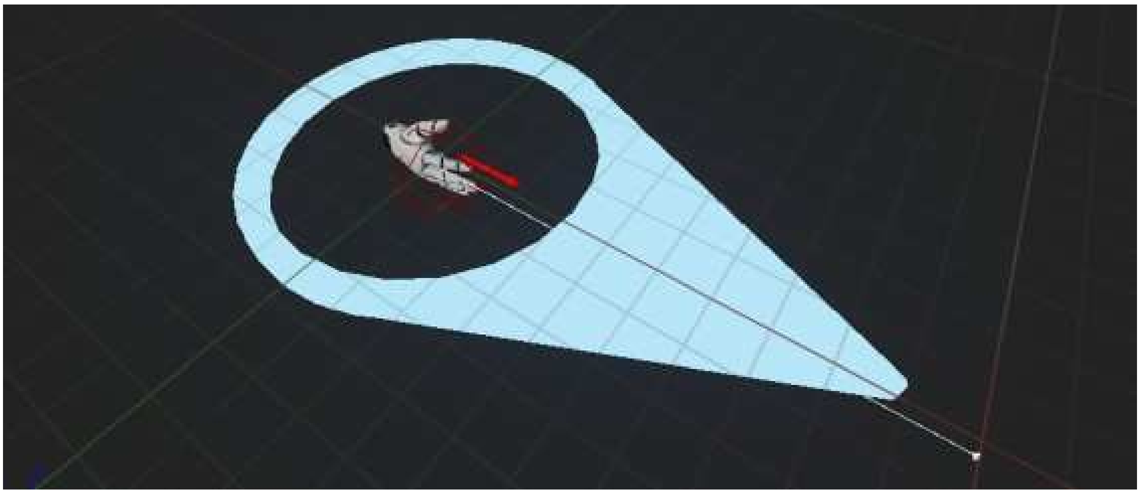


Figure 6.32: Viewport of motion controller, Elaboration: Carla Borriello

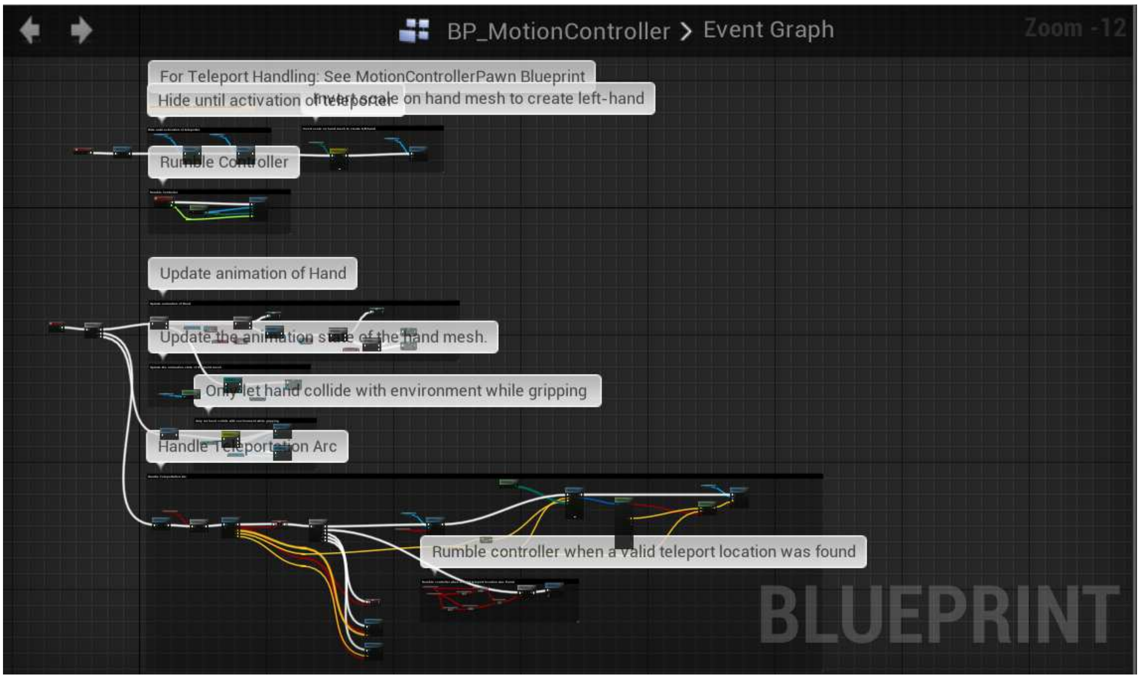


Figure 6.33: Default event graph of the motion controllers, Elaboration: Carla Borriello

6.6 Visualization and Interaction

In order to reach the goal of an immersive story telling model tool, it has been necessary to create a link between the model and the customer: an interaction. But before setting any kind of interaction with the model, I focused my attention on a preliminary aspect: the realistic rendering. As we know, the **fbx* format maintains the 3D object properties such as the textures, so it has just been necessary to give them a realistic aspect using some maps (as it's shown in **Figure 6.34**) which give the textures a deep aspect and they can be created through **Adobe Photoshop**. The **normal map** indeed, calculates the polygons normals and it transfers them into a bi dimensional image using RGB values where the *blue* defines the depth while *red* and *green* define the directions right/left and up/down. Another typical map associated to the normal one, is the **ambient occlusion map** that is related to the shadings effects: this one uses a global illumination method and it contributes to give a realistic aspect in terms of illumination, reflections and light attenuation in presence of big obstructed volumes.

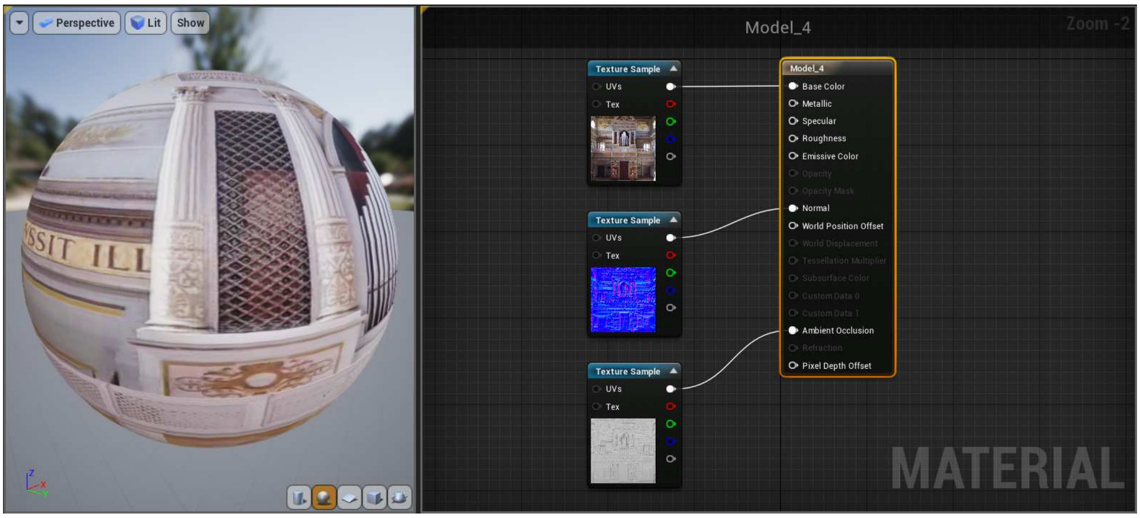


Figure 6.34: Normal and Ambient Occlusion maps application, Elaboration: Carla Borriello

Figure 6.35: Front view of the VR model, Elaboration: Carla Borriello

Another step was to give the model an as realistic as possible lighting context using less or more the same illumination sources of the Church.
It's important to remind in general to not overdo with the number of lights positioning because of the rendering difficulty: indeed, the static lighting and the light-maps are the cheapest options to optimize as possible the real time rendering that has a frequency, for HTC Vive, of 90 FPS (Framework per second).
But as I disclosed in the introduction of this chapter, the visualization aspects

have been compressed to the minimum requirements for a good visualization of the model in order to give more space, instead, to the functionality and to the the interactive aspects for structural purposes. So, I tried to set a to do list of the interactions inside the model:

1. Integration of informative panels;
2. Visualization of localized photo-documentation of damages;

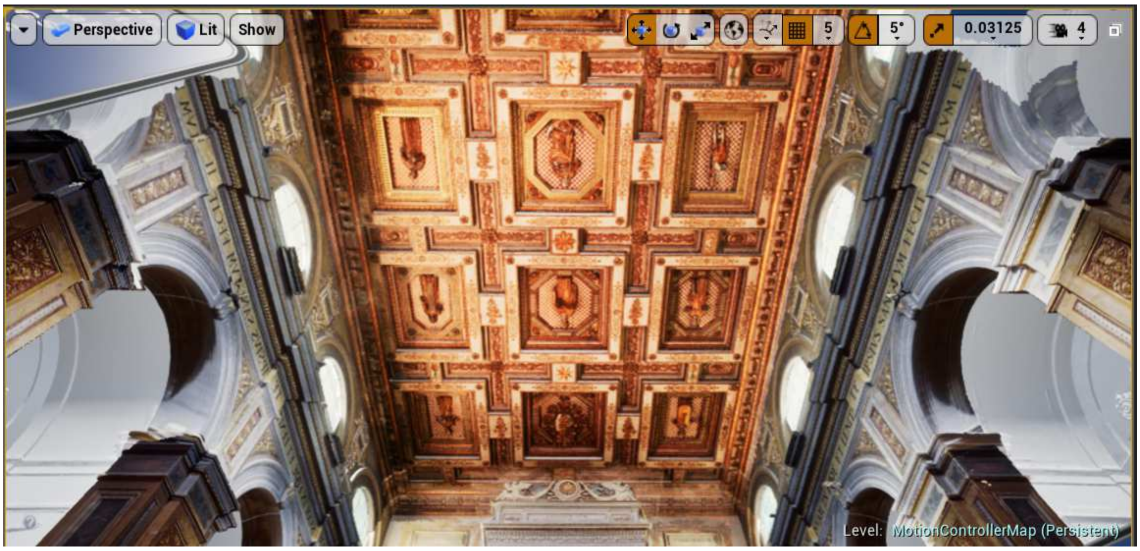


Figure 6.36: Coffered ceiling detail, Elaboration: Carla Borriello

6.6.1 Informative panels and photographs

The aim of the creation of informative panels is framed inside the new point of view of my model value: an architectural support focused on the vulnerabilities of the case study, an immersive story telling tool about the structural issues that the case study has deal with after the seismic happenings of August 2016. Everything would be spiced with supporting photographical documentation that will show more clearly the case study vulnerabilities and damage mechanisms that occurred. This is the key point that marks an important difference wit the previous works: now the VR tour for structural visualizations has a renovate value of being a supportive tool presented here as a physical story teller where the references are inside the model itself.

So, browsing the infinite tutorial documentations of UE4, there are lots of different solutions, easy or not, for the integration of interactive contents for giving the audience informative documentations in both the forms of bibliographic knowledge, photographs or digital contents as a real museum, art gallery or architectural site. In my several experiments the best and, at the same time, the easiest way to present them regards the exploitation of a simple but powerful concept based on the inversion of the visibility state of an object: the **toggle visibility** [203] blueprint function. Indeed I solved the first two priorities of my interactive model starting from a set state (visible in the viewport or not) it let me reverse that state through an overlapping event by the motion controller laser pointer [104] previously set.

First of all, it's important to create in the content browser of the user interface a *Blueprint Class* category, in a deeper way, an *Actor* and add to it a desired component (cube, sphere or other geometrical components). This *Actor Component* will be my physical object to be overlapped for displaying or for hiding contents (in my case it's a sphere as it's shown in **Figure 6.37**). It's important to give access the actor component to the *Generate overlap event* function in the viewport, otherwise it won't switch any visibility. It needs its child component, that can be a text or a textured cube to be displayed or to be hidden in the scene according to the starting visibility of it, which, in this case it's turned off to be inverted once the pointer will overlap our the Actor Component. Then, I focused to create a communication between the two components through Blueprint (**Figure 6.38**): so, in the Event Graph I added an event referred to the *Actor Component* called *Add Actor Component Begin Overlap Event* and I linked it to the function *Set Toggle Visibility* which has its target on the Child Component. The same script for the *Actor Component End Overlap Event* with instead, a delay of an amount of seconds till the end of the event. Then I framed everything inside a physical panel as shown in **Figure 6.39**, where as a real one and as I disclosed in the introduction of this section, I presented the most important information about the damage mechanisms of the church façade like a story telling tool: giving clues about the spotted chinks inside it, explaining the possible set of factors that made the situation worse, the reasons and the crawl space complexity.

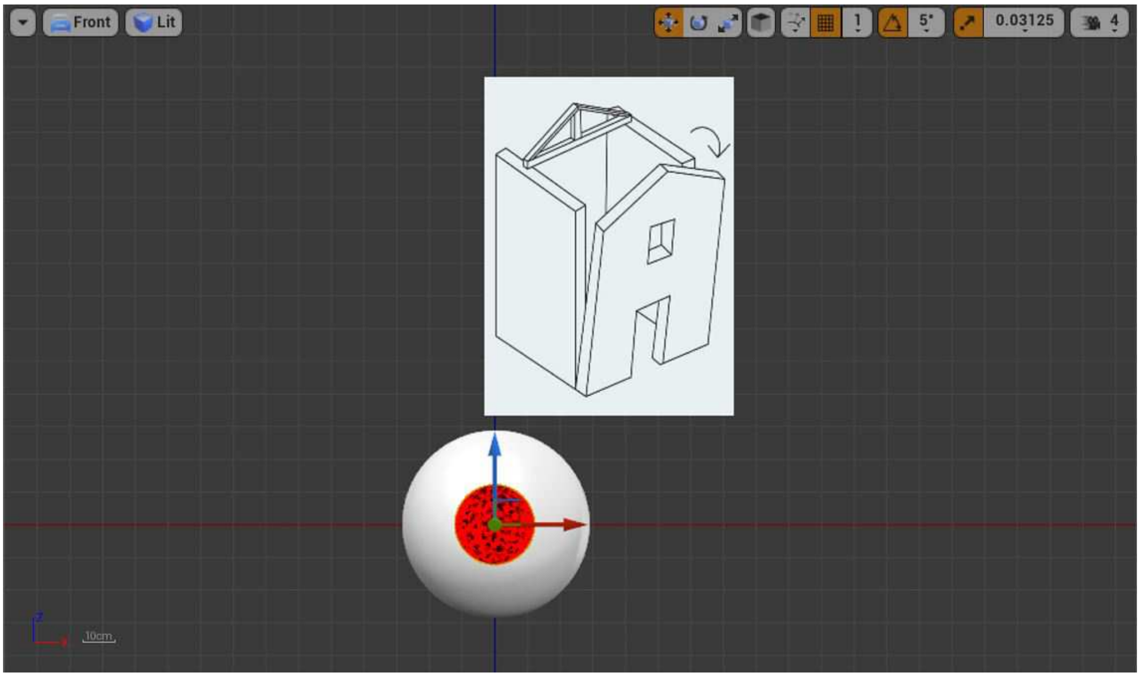


Figure 6.37: Photographs panel explaining the damage mechanism, Elaboration: Carla Borriello

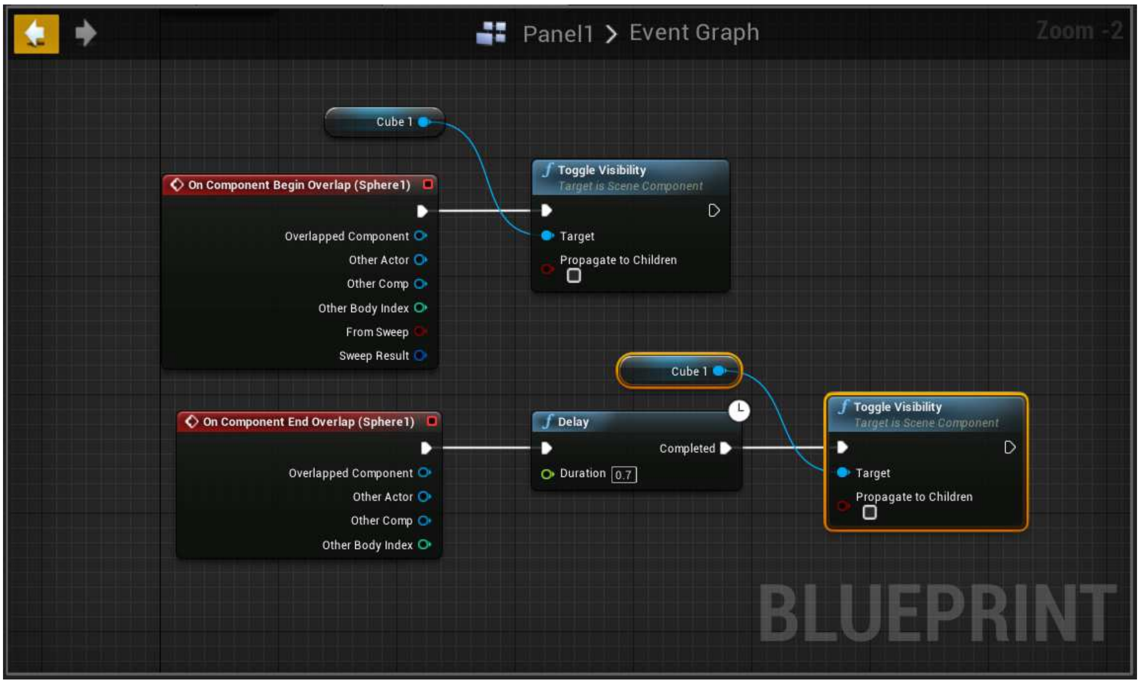


Figure 6.38: Blueprint nodes example of the toggle visibility, Elaboration: Carla Borriello

Figure 6.39: Informative panel, Elaboration: Carla Borriello

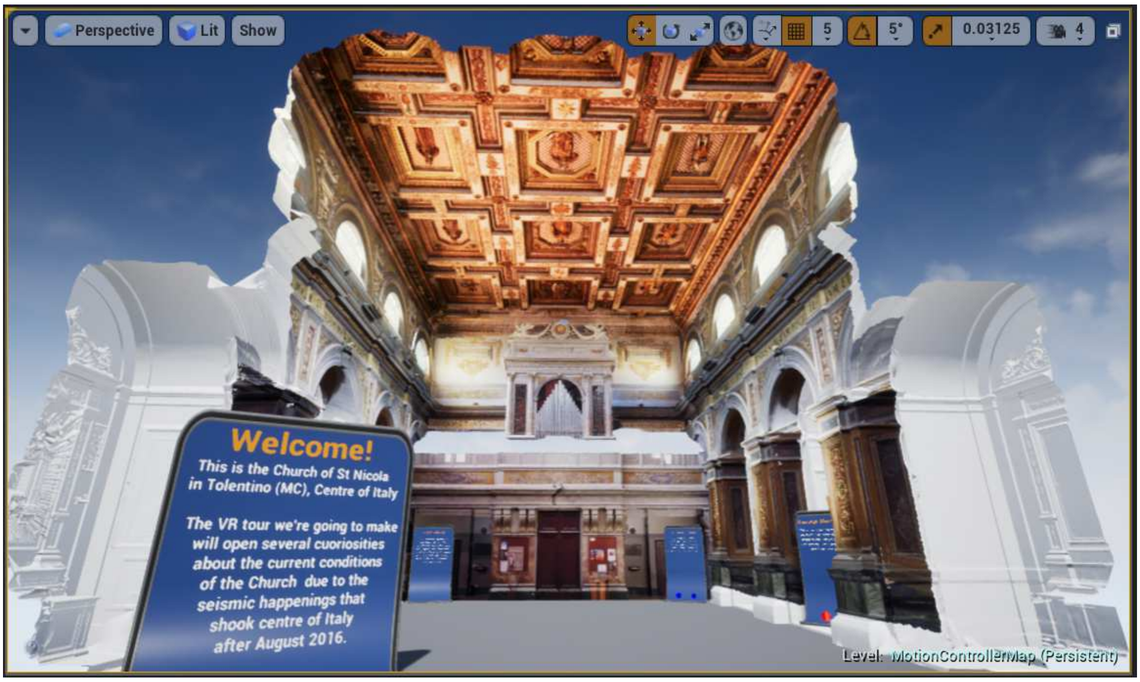


Figure 6.40: Model perspective view, Elaboration: Carla Borriello

6.7 Results

For offering a quick sharing way for the visualization result, I edited, thanks to Unreal Engine and other post processing video editing software, a teaser *trailer* summarizing in few seconds the potentialities of this experimental thesis. Then the trailer has been set available to the reader public through the **QR Code** below: it needs first of all a smart-phone and the QR code reader app, for scanning it, that is easily downloadable on the *Playstore*.

6.8 Conclusions

As already disclosed at the beginning of this experimental path, the thesis birth has come to world after the seismic happenings that shook the Italian territory in August 2016. My main goal then, was to concentrate the final study to the Cultural Heritage at risk cases and their analysis in order to create an additional architectural support model focused on the immersive learning and visualization of vulnerabilities for structural evaluations. So, since preserving our world Cultural Heritage from the unpredictability of hazards must be seen as a duty gesture towards whole humanity, the responsibility reclines on an appropriate documentation for preserving the historical memory of everything testifying a *civilization value*. This is the reason why a big piece of cake of this thesis outline consists of presenting the vulnerability of Heritage, the importance of documentation tools, methods and techniques belonging to the Geomatics field of application: from the traditional methods until the latest far sighted ones, passing also through crowdmapping and sharing methods as regards the results.
The added value of starting from Geomatics workflow methods in the Architecture and Restoration field let us have a direct connection and an architectural accuracy documentation in adherence with the real CH case study thanks to the *reality based* approach typical of the 3D metric survey operations. The mutual interpenetration between 3D survey tools, Architectural skills with the no-stop flowing wave of ICTs has strongly changed the way of looking at the Restoration field which acquires an important fellow in the sharing and learning knowledge that must be seen inside a common-sharing compartment and not inside separated sealed ones. Virtual Heritage, that finds its roots in a combination of the memory value and virtual technologies, really represents the future of CH documentation and enhancement in a virtual way corroborated by an *intellectual and technical rigour*.
The starting aim of this thesis has been carried out successfully despite several issues observed along the experimental *iter*. The first issues regarded mainly the recording limits of the LiDAR technology connected to the so called *shade of area*, that area obstructed by another surface or for example reflective material issues. The presence of a unobstructed surface is such of a great importance for the recording phase since the laser needs a matt surface to survey properly all the points. The entry LOD of each LiDAR acquisition, furthermore has made known

the need to reduce the acquired data in terms of file weight and this is also the reason why the experimental part has focused just on the pipe organ zone which is also the area proposed for the analysis phase according to the reconnaissances for visual evaluations in static and structural terms. Many other difficulties were about the integration between interior LiDAR point cloud and the UAV external point cloud during the digital plotting phase which has been performed trying to make realistic and logic hypothesis about the morphological elements of the Church, their chronological asset according to the materials age, conditions and laying ways. But without this integration the model wouldn't had the great amount of information that have been extracted about the geometrical dimensions of perimeter walls and hypothetical functions about the presence of empty spaces inside the complex walls. Furthermore, the importance of the level of accuracy and information that these 2D drawings carry out, is as wide as the importance of the Geomatics value it adds to them: the lack of human errors, the georeferencing value of these extracted and plotted drawings can make possible the use of them as a support for future studies that can be implemented or used such as project starting point. The large dimensions of the case study have really contributed to have few internal photographical documentations and this oppressed too much the consequent texture phase that has encountered issues for the photo-realistic texturing process that has been carried out thanks to a specific script reclined in the extraction of each frame, per second, from the indoor videos recorded by the drones. The manual choice of each frame for the projection processing on the meshed model, has been as hard as the several communication issues between the Geomatics and the Informatics workflows in terms of file formats compatibility and tools. For increasing the final model in terms of texture LOD quality visualization and at the same time in terms of adherence to the case study reality, I noticed that the **integrative policy** has fulfilled imperfections and gaps of information related to each method limits. Indeed, such as the integrative approach between LiDAR and UAV point cloud have helped to understand the wall consistence in terms of geometry and dimensions about the Church complex perimeter walls, the integration between the different sources recorded on the coffered ceiling, that has been treated in a different way in comparison with the entire model, have made known two results: the first one is the photogrammetric processing, based on high resolution images and photographs, has provided the coffered ceiling the texture

accuracy it needed to be more realistic and detailed in a deep way, while the LiDAR processing provided the coffered ceiling meshed model the surfaces LODs in terms of geometrical accuracy and reality adherence with the effective recorded surface. The difference of action policies is really vivid inside the model since the whole model, that has been texturized in 3D Reshaper through drone frames projection results to be a little blurry and inaccurate in comparison with the photogrammetric texture processed in Agisoft PhotoScan.
Anyway, since there's no a universal accomplished workflow that let the customer pass from the Geomatics field to the Virtual one, I proposed mine in this experimental flow to prove the accessibility that can be improved but more important it may give light to future ideas and scenarios where the sustainable approach of technology, and VR techs in this case, are applied to Architectural fields. Indeed, **Interoperability** is the key word that characterizes the employed sources, applications and purposes of this outline and at the same time, it must be the primary aim for creating opportunities that there weren't before now. Just let's think about the million possibilities that these virtual technologies offer, not only in the CH field: we've already talked about concepts of Virtual Museums and Virtual Tourism but what about the chances of Simulating and *Virtual Testing*, without risks, the material interaction with chemical products before the real application, the possibility in future to detect in real time vulnerabilities about the building structure or maybe the potentiality of creating a communication system of issue detection for a building through advanced headsets or helmets that communicate with all the *smart* elements of the building in exam, such as architectural artificial intelligence (AI) sensor shells, that as our brain do, they learn how to recognize interactions between cause-effect and they emit for example impulses to report the trend of how materials, pollution rate, atmospheric agents and psychometric parameters may affect, during time, the conservative state of materials of CH or *ex novo* buildings.

Attachments

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