Old and New School, the Evolution of the Survey Campaign in a Case Study about the Maddalena's Bridge

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Abstract: How can we make the heritage built around us available through the new digital survey technologies?

The Maddalena's bridge, in Borgo a Mozzano (LU) Italy, called "Devil's Bridge", is a monument of particular historical interest and it has been analyzed here with the aim to identify new way about how to use the data of a survey campaign through using different technological methodologies (3D laser scanner and photogrammetry) and new "Structure from Motion/Image Matching" (SfM/IM) software. The use of both data allows a greater amount of detail and better management of the survey campaign timing.

Some buildings, such as a bridge, located in specific topographical conditions may present some difficulties with survey's technologies. In this case, the water affected the normal return of the data through the laser scan; also, the photogrammetric survey sessions obviously present physical barriers such as in our case the river, not navigable at the time of the survey campaign.

Therefore, the combined use of both 3D laser scanner and the photogrammetric survey was indispensable to provide better detail accuracy. The new survey made in 2018 and its graphic restitution of Maddalena's Bridge, wants to be a usable basis to benefit from a comparison with a previous survey carried out in 2006, allowing us to analyze and compare the status of the current fact with the previous one and thus allowing hypothesizing possible consolidation and redevelopment interventions if necessary. Thus, it was possible to highlight the changes offered by the new technological solutions that we now have available (the evolution of the 3D Laser-scanner, optical devices and cameras, software and digital components) and that allow us to implement the knowledge of the survey.

Thanks to the survey itself, it was possible to create a 3D digital model available for complete use of the monument for tourism purposes.

Key Words:
Photogrammetry, Structure from Motion, Maddalena's Bridge, Data comparison

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INTRODUCTION

The Case Study

The object of our investigation is the Maddalena's Bridge, also called Devil's bridge because of the legend about its construction, that is located in Tuscany (Italy) and joins the two banks of the river Serchio near the village of Borgo a Mozzano, a small medieval village in the province of Lucca and is located just after the confluence with the Lima torrent. The geographical context in which the Maddalena's bridge is located is the Serchio river basin, which characterizes the morphology of the whole area. The complex orographic system has characterized not only the infrastructural evolution of the territory, but it is also the origin of the singular "back of donkey" shape of this bridge. [Repetti 1843]

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HISTORICAL OVERVIEW

The lack of sources related to the Maddalena's Bridge hardly allows us to distinguish the myth from reality, history from legend. We can therefore advance hypotheses by collecting testimonies, representations, stories and traditions around this artifact trying to reconstruct the events around its construction and its use, from being an infrastructure work of great importance used largely for travel, until its final change of role.

For this reason, it is important to understand the evolution of the infrastructural and road system of the neighboring territory so that we not only understand the importance that the Maddalena's Bridge has taken over the centuries as a way of communication, but how it has come until today, even if with big changes and if its primary function had ceased.[1]

We will then make a brief chronological outline of the historical events that have characterized the monument:

Roman Age

The importance of speed in military travel has allowed the construction of direct and efficient routes. The Tavola Peutingeriana[2] describes a probable existence of a crossing on the Serchio river at Borgo a Mozzano. [Duè 1994]

Medieval Age, 6th century, Lombard conquest

The road network is in crisis with the decline of the Roman Empire. The paths chosen by the first Langobards developed along the ridges, thus avoiding the crossing of rivers and tracing much of the paths used for transhumance.

The Via Francigena and the Pilgrimage

With the arrival of the Franks, the network of Langobard streets is strengthened and becomes part of the most important arterial road between Europe and Rome, the Via Francigena.

Lucca is a fundamental stop for pilgrimages, which soon becomes a cosmopolitan dimension and enriches with churches, hospitals and shelters.

Matilda's Age, Canossa's domination 1002-1115

Matilde of Canossa controls much of the kingdom of Italy, from the area north of the Apennines to current Tuscany. Tradition describes the construction of the Maddalena's Bridge, by the will of the countess.

Republic of Lucca, and Castruccio Castracani

In these years Castruccio Castracani, lord of Lucca from 1316 gathered under his kingdom a large number of territories. Some sources attributed to Castruccio a probable reconstructions of the Maddelena's bridge following a collapse. The politics of the Lucchese state, not being able to rely on an efficient army, is oriented to make access to the territories of the state difficult, and maintenance is progressively neglected.

16th and 17th centuries, the Charter of Lucca

In the "Charter of the state of Lucca" of 1569 the main connection between Lucca and Garfagnana still follows the medieval route. Only in the 1600s the Lucchese government decided to build a new road on the left bank to replace the ancient route, but this one too was not very easy. The transport with ~~the~~ vehicles becomes widespread and instead of crossing of the Maddalena's Bridge (already complex for coaches and carriages) crossing the river on special boats is preferred. Now the bridge becomes an infrastructure almost exclusively for the inhabitants of Borgo a Mozzano.

New unitary state and new infrastructures: The railway

At the end of the 19th century the new government supported the development of the railways, with both a military and commercial purpose. The Maddalena's bridge is located along the second stretch of the Lucca-Aulla railway.

[1] I luoghi del silenzio. http://www.iluoghidelsilenzio.it/ponte-della-maddalena-detto-anche-del-diavolo-borgo-a-mozzano-lu/
[2] Tutta Toscana. https://tuttatoscana.net/curiosita-2/la-toscana-rappresentata-nella-tavola-peutingeriana/

The construction of the railway has modified the physiognomy of the bridge, making the bridge even more uncomfortable for the increased slope.

From infrastructure to monument:

The Maddalena's Bridge ceases almost exclusively of its usefulness, thanks also to the construction of the Umberto I's bridge (1902), except after September 1944, where it remains the only passage after the destruction of all the other bridges over the Serchio that were practicable for the German vehicles, more cumbersome than the American ones. It was this "inefficiency" that kept its charm intact to this day. [Gucci et al. 2010]

THE MYTH

The Maddalena's Bridge is not the only bridge in Italy (and in Europe) to have been renamed "Devil's bridge". In the Middle Ages, in fact, the construction of a bridge was considered almost prodigious and magical, partly due to the loss of familiarity with the construction practices of the Romans, the lack of new buildings and the abandonment of existing ones. This is why the construction of new architectural works of ancient engineering have given rise to many legends, often starring the Devil himself, because joining two places that nature (and God) had wanted separated was seen by many as a "diabolic" gesture that only the devil could complete.[3]

In fact, many "difficult" works, in popular tradition, were built by the devil: from the Cologne Cathedral to the Abbey of Mont Saint Michel in France and even to the Verona Arena. To these great enterprises must be added numerous palaces, castles, mills, and fountains. But what was attributed as a devil's bridge? The devil's bridge is a stone, brick, wood (today we add reinforced concrete), and iron "donkey's back shape" placed in a "steep gorge to overcome impetuous waters". There are also "devil's bridges" of natural origin, carved into the rock or ice by water or other atmospheric agents. Therefore, there is no ideal model of "Devil's bridge": it is the legend that, to "certify" the final work, assigns the construction to the Devil, since man would not be able, with his strength, to realize such an impressive undertaking. [Lera, 2014; Cenami 2002][4]

THE SURVEY CAMPAIGN

The surveys and subsequent digital evaluations were conducted between December 2016 and July 2018 together with a group of Architects of the Department of Architecture of the University of Florence coordinated by Prof. Giorgio Verdiani. The aim was to carry out a detailed digital and photographic survey aimed at creating the correct foundations for the following studies and analyzes.

In the first analysis we conducted a survey campaign with a 3D laser scanner. (Fig.1).

The principle on which a 3D laser scanner is based upon is to acquire the spatial coordinates of an object automatically, systematically, and quickly thanks to the projection of a laser light beam on the object and the analysis of the return signal. The laser scanner unit emits a laser signal in one direction and on the basis of the variation of the phase present in the reflected light towards the unit the distance of the reached point is identified, this measure, combined with the measurement of the horizontal and vertical angles, according to which the signal has been emitted, it allows to position with good precision the point reached, thus going to create, for reiteration of the operation, a three-dimensional digital model. The overall model of a series of measurements performed through the laser signal thus constitutes a three-dimensional digital model that today is generally referred to as a "point cloud". For each single point the RGB values of the "reflectance" are stored (its value depends on numerous factors, among which the characteristics of the materials, their processing, the angle of incidence of the laser signal, the atmospheric conditions and the distance of the measured object) and therefore the color of the laser reflected signal which has a chromatically altered, but well-differentiated version of the real object. Among the most important features of this survey methodology are the accuracy of the acquisitions (the accuracy with which it is detected can have a precision of four millimeters) and the speed of data acquisition. The survey establishes a precise measured image that becomes the basis of the knowledge of the shape of the monument over time.

[3] Wikipedia: https://it.wikipedia.org/wiki/Ponte_della_Maddalena
[4] Castelli Toscani: http://www.castellitoscani.com/italian/diavolo.htm,
La tela Nera: http://www.latelanera.com/misteriefolclore/misteriefolclore.asp?id=121

Fig. 1. One of the 44 laser scanner stations in Maddalena's Bridge

It will always be possible, by carrying out a new survey at another time, to check for any changes in the monument, to understand the reasons and to carry out significant safeguard operations.

The point cloud is transparent, discontinuous and composed of dimensioned elements, chromatically altered and is not easily transferable outside specific data management software. The problem arises, therefore, of making transformations on the cloud of points that allow the model to be returned in a comprehensible manner, keeping the aims very clear.

Currently the hardware and software tools in use can lead to transformations that see from an extreme the maximum correspondence to the model and the other to the perceived real. First it is necessary to have a transition from the discontinuous model to a single continuous model, in such a way as to bring it back into a context of more usual graphic rendering for the designer and for the multimedia designer. In this way the elements acquire their real opacity, complicating the model to the point of requiring hardware resources that are very expensive to visualize. For this reason, it is necessary to resort to simplification operations of surfaces, more or less massive, which lead to a reasonable level of management of the model in progress such as the use of generic textures or specific textures derived from photographs of the real model. For multimedia productions with development of animated or interactive sequences it is necessary to use a simplified object to such an extent as to arrive at rough approximations in favor of a better perceptual performance. [Recati 2017]

The scanner used was Zoller+Fröhlich Imager 5006h. The 3D survey with the laser scanner was carried out in a single day, positioning the instrument in different points suitable to cover the whole of Maddalena's Bridge, called stations. In this case, 44 stations were necessary to have complete coverage of the monument.

The instrument must be able to "see" at least two targets that reconnect it to the support network or another station, while the third reference is given by the verticality of the instrument, certified by the previous leveling.

The greater the number of targets beaten for each scan, the more precise the collimation will be achieved when recording the point cloud, subsequently processed through the use of the *Autodesk ReCap PRO*[5] software.

[5] https://www.autodesk.com/products/recap/overview

PROBLEMS WITH WATER

One of the problems that were found through the 3D survey performed with the laser scanner was the presence of the water under the bridge. Water has created disturbances in transmission and rebound of light. The laser has processed erroneous points that have come to rebound and have been identified as material. The original model thus becomes "dirty". In fact, the surface of the cloud of points in areas near the water's reflection is not exactly clean, does not follow a single surface.

PHOTOGRAMMETRIC SURVEY

To integrate the data provided by the relief described above, it was necessary to create a photographic covering of the article in parallel. Photogrammetry is a technique that allows the acquisition of form and position of an object through the analysis of two stereometric frames. Used in cartography since the second half of the 18th century, it has had an important impetus in recent years with the development of digital photography and computers capable of handling relatively large amounts of data. It is, therefore, a method of economic importance, non-invasive and that provides rapid and highly effective results.

The photogrammetric survey consists of a precise sequence of operations performed with adequate instrumentation:

- Nikon DSLR D800E, a camera with high image quality (the higher the pixel resolution of the camera sensor, the better the image will be captured), at 36.3 Megapixels and mounting high quality lenses (a 24-120 mm F4 Nikkor Zoom and a 150-500 mm F6.3 Sigma Zoom Lens)

- A tripod with adequate stability and adequate characteristics

- High performance personal computers and amount of RAM memory

- Software for photogrammetry

- Software for the management of surface models and for the production of rendered images

For the photogrammetric survey of the Maddalena’s Bridge, a Nikon D800E was used, with a 36.3-Megapixel FX sensor, with a Sigma 150-500 mm focal length telephoto lens for long-distance shooting by the ENEL dam facing one side of the bridge. Other shots were necessary with different focal lengths and framing angles for better and greater precision in the subsequent restitution of the photogrammetric datum, made with an 18-105 mm and a 70-200 mm both with the aid of a tripod and by hand free.

Constant photographic exposure problems:

Managing the camera totally in manual, the main trick that has been taken into account was to try to maintain an always constant exposure in all the shots, although the lighting conditions of the object varied, due to the different position of the sun during the shooting phase (which is why the shots were taken in the shortest possible time) both in the shaded areas or in the light of the bridge itself. To maintain the best possible homogeneity, the exposure management parameters (ISO, diaphragms, exposure time) have been changed, keeping the diaphragm constant, to try to keep it always with a setting that is as closed as possible to obtain a better depth of field, both the ISO, as low as possible, to 200, to avoid the creation of digital noise that would disturb the quality of the shot. So, with the aid of a tripod to avoid blurred or micro wavy shots, we have lengthened the shutter speed when it was necessary for exposure in the darkest areas or in the shade. (Fig. 2).

POINT CLOUD MANAGEMENT WITH AUTODESK *RECAP PRO*

As a first processing of the survey data, it was necessary to import the scans made by the laser scanner on the Autodesk *Recap PRO* software to make a preliminary "registration" of the starting data. After importing the laser scanned files into the RCS format, the software is able to "record" them, that is, to compose them according to the shooting scheme to form the complete three-dimensional model. The software reads the individual scans and compares them to find collimations with the others. To perform this function, it uses an internal self-registration function, to which a manual registration part is added in case some scans are not recognized and remain vacant. This procedure has allowed us to obtain a cloud of points rather light considering the least amount of data within it and accurate in terms of average error. We are talking about very small errors, in the order of +/- 0.6 mm. (Figs. 3-4). [Piangiani 2018]

Fig. 2. Photographic acquisition phase: example of a sequence of shots taken under conditions of constant exposure. Photographs taken with a telephoto zoom lens at a focal length of 500mm from the ENEL sluice overlooking the bridge. For a better photogrammetric reconstruction, due to the perspective distortion given by the telephoto lens, it was necessary to include shots made with less extended focal lengths to allow the correct restitution of the depth of field.

MERGING THE DATA: A SAFER AND OPTIMIZED ANALYSIS

In conclusion to these two relevant campaigns, we find ourselves having two data in our possession: the photogrammetric data and the data acquired with laser scan. The procedure for the correct analysis of the survey is to compare the two data in order to have greater precision, and it is important to be able to compare the two findings if any problems were encountered.

When, however, after a comparison between the two surveys, discordances are observed, even if minimal, it becomes complicated and laborious to understand which of the two is incorrect and which one is with the least possible margin of error.

For this reason, it was used a software like *Reality Capture* that allows the processing of both data simultaneously, just to go to eliminate this type of error. Through the use of photographic texture mapping we can project photographic images directly on the 3D metric model obtained in output from the scanner. This methodology involves the combined use of photogrammetry and laser scanning. The scan provides the metric data and the “digital

model of the object" (DSM); the photograph is then projected onto the model. To make this procedure possible, the external orientation parameters of the DSM must be known. In this way the scan obtains the radiometric information from the different photos, obtaining, in output, a DSM with applied photographic textures. The effect obtained is remarkably realistic and pleasant; moreover, it allows to more accurately investigate the state of conservation of the object. From this product, by performing an orthogonal projection on any plane, it is possible to obtain the precise orthophoto.

We have therefore optimized the times and at the same time a much greater precision, because the integration between the two data allows a better return, with the aim of giving new life to our cultural heritage, of which the devil's bridge is the first in question.

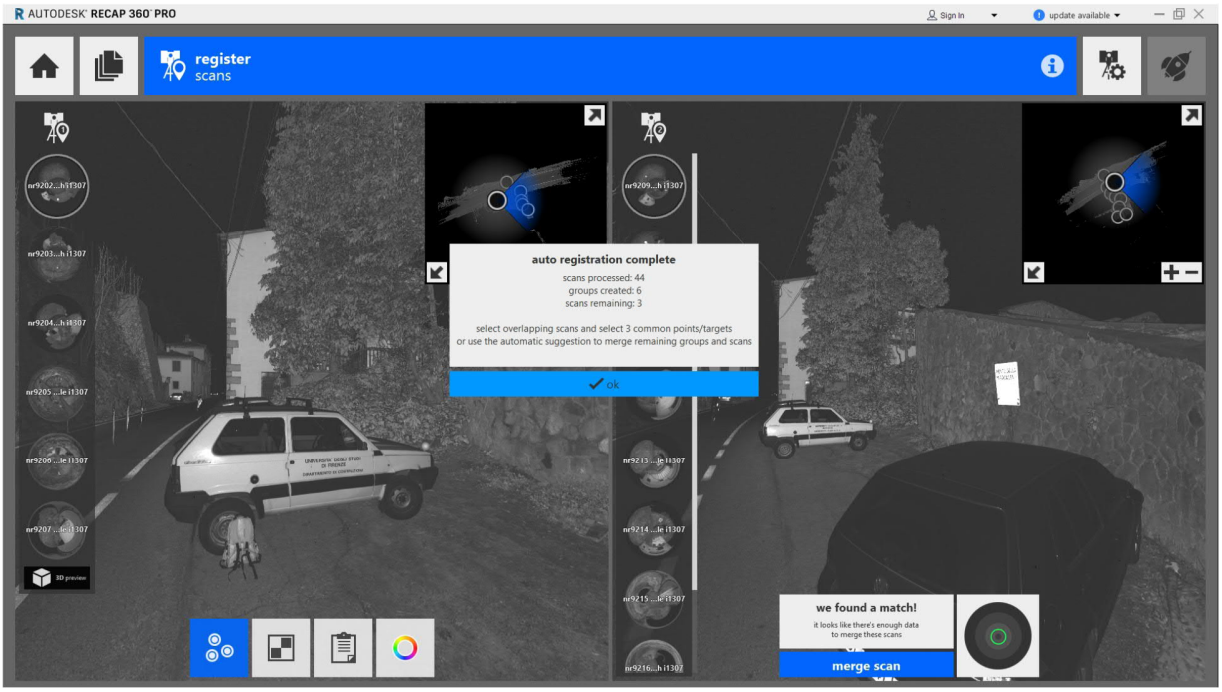

Fig. 3. Screenshot of Autodesk ReCap Pro. Scans registration

WORK MANAGEMENT ON *REALITY CAPTURE*

The working procedure on *Reality Capture*[6] is the same as other photogrammetric software like *Photoscan*[7]. In the first analysis, after having imported the point cloud and the photographs of the survey campaign, it is necessary to align it by identifying corresponding points both on the point cloud and on the photos that will subsequently be projected onto it. The next step is the reconstruction of the 3d model and finally the application of the texture. The procedure does not change with respect to *Photoscan* because it is always a procedure on a geometric basis: a point is obtained from three positions with different radius. (Fig. 5).

Another advantage is that *Reality Capture* has a faster algorithm both in data management and in physical computing.

[6] https://www.capturingreality.com/
[7] https://www.agisoft.com/

RESTITUTION

Thanks to the processing and comparison of the data of the survey campaigns carried out, it was possible to investigate and create a solid base for graphic restitution of the architectural survey of the Maddalena's Bridge, which can be used in the following ways:

Vector: Creation of a two-dimensional and easily readable, quotable and highly accurate DWG file (the survey has an instrumental error of 4mm). This is necessary and essential for the development of restoration projects and/or new constructions, for the archiving of the state of the places, and cataloging and structural interventions.

Photogrammetric: Non-invasive economic technique that provides rapid results and high detail. It is very interesting for a possible analysis of the materials, research of injuries and damage to molds, storage of the color data and the different warping of the materials.

Three-dimensional model: Three-dimensional processing performed through the comparison of the laser and photogrammetric data has allowed us to obtain a three-dimensional textured model, or with a real photographic correspondence, of possible application in various fields of use. It is the most advanced and usable cognitive method as it is possible to create interactive animations to be used on site or via the web and print easily three-dimensional models.

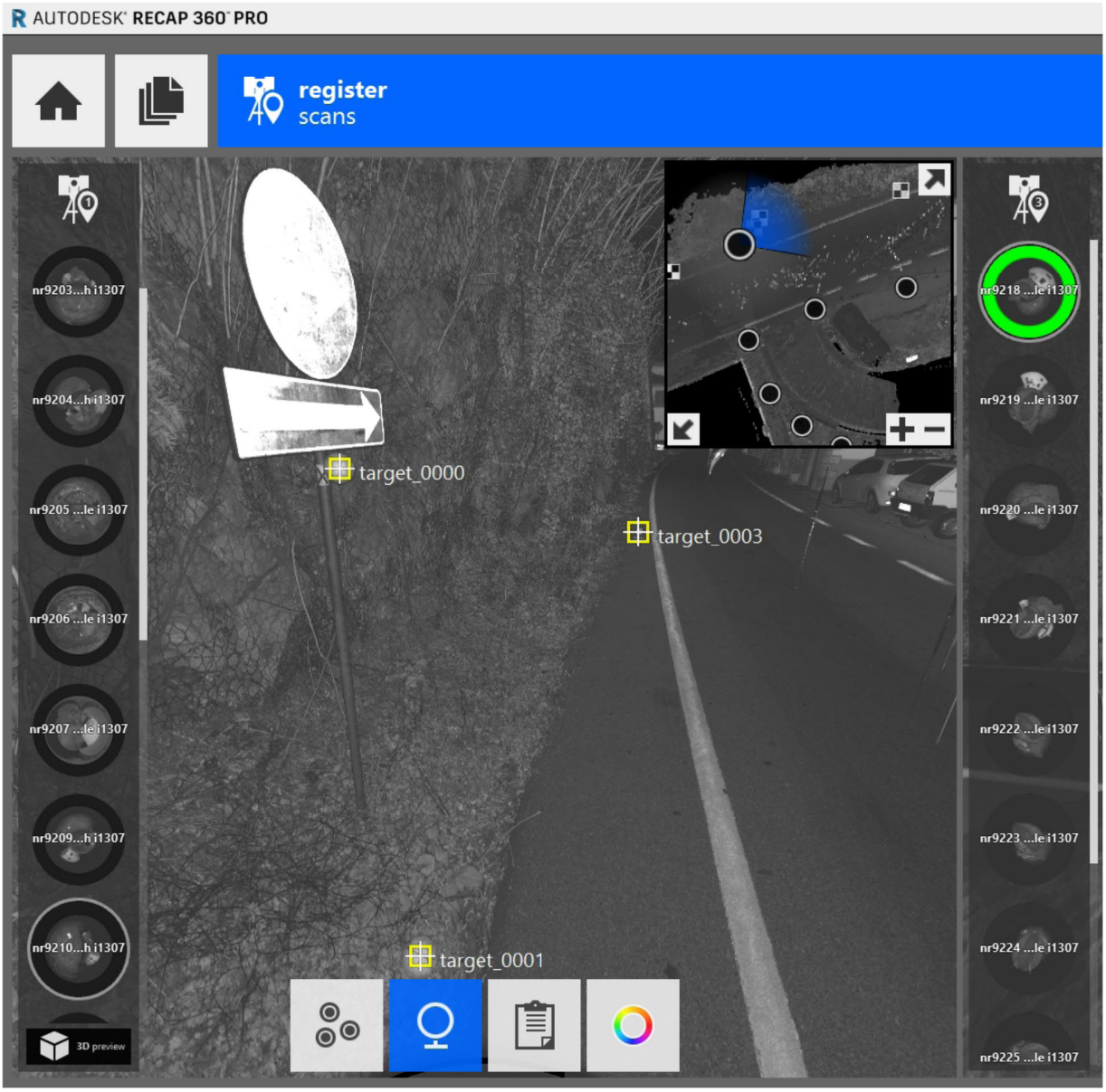

Fig. 4. Screenshot of Autodesk ReCap Pro. Target detection

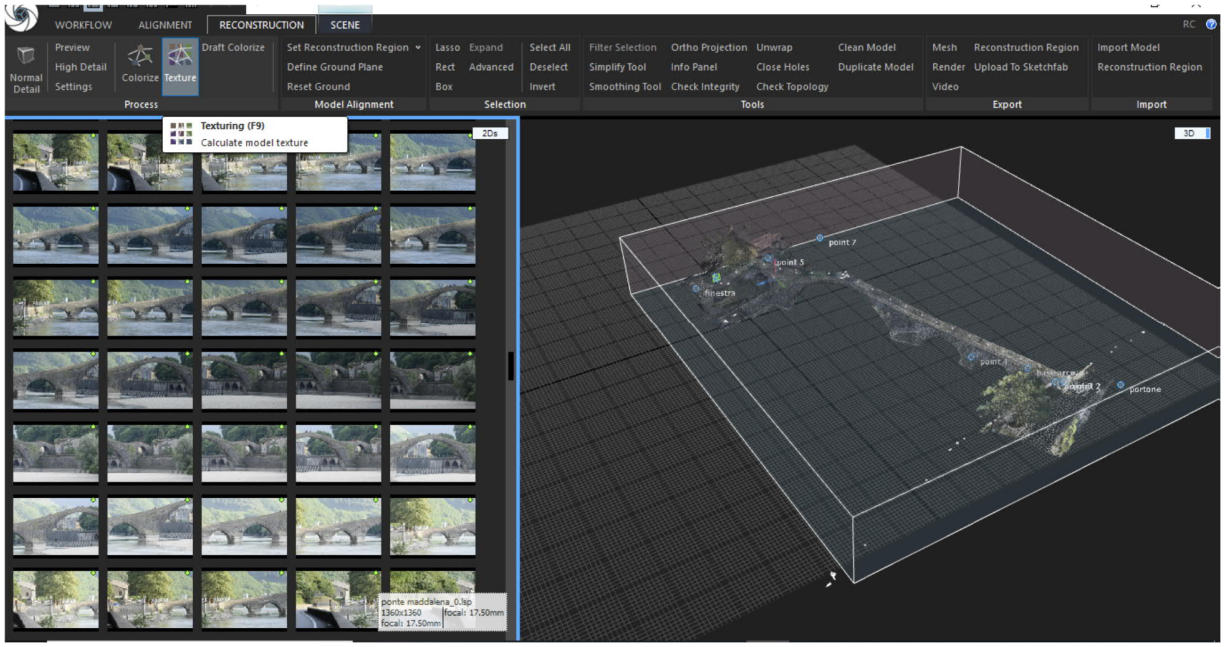

Fig. 5. Screenshot from Reality Capture. Three-dimensional model with applied photographic texture

AUGMENTED AND VIRTUAL REALITY: A NEW METHOD OF KNOWLEDGE WITHIN EVERYONE'S REACH

Thanks to the optimization of the three-dimensional model through *Reality Capture* it was possible to investigate a new aspect of the use of the survey data.

The question we initially asked ourselves was: how is it possible to make the results obtained easily and easily accessible? And how, these, can they add an element of value to the studied monument?

A logical consequence of this reasoning has led us to investigate the approach of augmented reality and virtual reality, now available to everyone as supported by the increasing technological advancement of the devices that are part of our lives.

HOW DOES IT WORK

"Augmented Reality" (AR)[8] is a technology that has been growing in interest and development in recent years. It is possible to define it as an enrichment of the observed reality through the overlay of information, contents and virtual objects in real time. Augmented reality is not to be confused with virtual reality; while in the latter the whole observed scene is entirely virtual, in the augmented reality a lot of attention is required in the research of the three-dimensionality of the environment with respect to the observer (or the capture instrument) to position the virtual object in coherence with the reality. Augmented reality allows adding artificial elements to the scene observed in real time by the person. To be able to add this virtual information it is of fundamental importance to be able to define the position of the observer in the observed scene. It makes it possible to make artificial objects one with the real scene and not make them look randomly glued. The augmented reality is generally divided into two types: Marked-based or Marker-less. Marked-based augmented reality focuses on the recognition of an object of known form (target or marker) to be able to identify the position and orientation in the environment and its perspective with respect to the eyes of the observer. Pointing the device used on a marker, its shape is obtained, through image processing algorithms. By comparing how the object was acquired with its original form, a formula is determined that describes how the object has been deformed from perspective. The user must always be careful with positioning

[8] http://www.augmentyourjourney.altervista.org/

himself correctly in front of the marker so that the whole surface is framed by the device and is not hidden by any object.

Several technologies are used in the rendering of augmented reality. You can generally classify in:

• Optical projection systems and monitors

• Portable devices

• Wearable display systems

Portable devices, such as smartphones and tablets, are the most used tools in this technology. The advantage of being available to all users, the presence of both the acquisition tool (camera) and playback (screen), the orientation through advanced sensors such as GPS and gyroscope and mobility have allowed an investment of augmented reality in this technology.

AUGMENTED REALITY AND VIRTUAL REALITY IN MADDALENA'S BRIDGE

In this specific case study, we decided to use Marked-based technology for the benefit of greater monument usability: in this way anyone can view the exact and truthful reproduction of the Bridge without having to go to the place where it is located;

However, those who are already observing the monument live will be able to enrich their experience with more information.

Operation by the user is very simple and intuitive:

In the first case, thanks to the use of a target chosen by us, the observer will only have to frame the image through smartphone or Tablet in order to view and manage the three-dimensional navigable model of the bridge that will appear exactly on the marker we inserted into processing phase.

In the second case, however, temporary and / or replaceable markers were designed to be inserted along the path that follows the devil's bridge. These do not affect the monument as easily dismantled and constantly updated, and even in this case just a simple smartphone to frame the target and get simple and immediate information on the monument.

The application we have used is *Augment*[9], an evolving online platform that allows the storage of three-dimensional models online to be used with or without marked-based technology. Once the three-dimensional model was elaborated (in our specific case, we exported the three-dimensional model texturized by *Reality Capture*), it was sufficient to upload to the platform and match the two-dimensional image that would later become the target for the model itself. Once you have done these steps, simply open the smartphone or tablet app to resize the three-dimensional object as you wish. Once saved, the model is public and available to anyone. Another interesting and well-developed application is *Sketchfab*[10]. *Sketchfab* presents itself as a Social Network for sharing 3D models; more than 600,000 3D elaborations are currently organized within it. *Sketchfab* presents a graphics engine much more powerful than *Photoscan* and this allows characterizing many aspects of our model and, above all, of its textures. Down largely used by private companies dedicated to the use of cutting-edge digital technologies, it is an innovative and immediate solution to describe and communicate the historical heritage around us.[11]

[9] https://www.augment.com
[10] http://www.sketchfab.com
[11] http://www.os-culture.org/index.php/sketchfab-tutorial

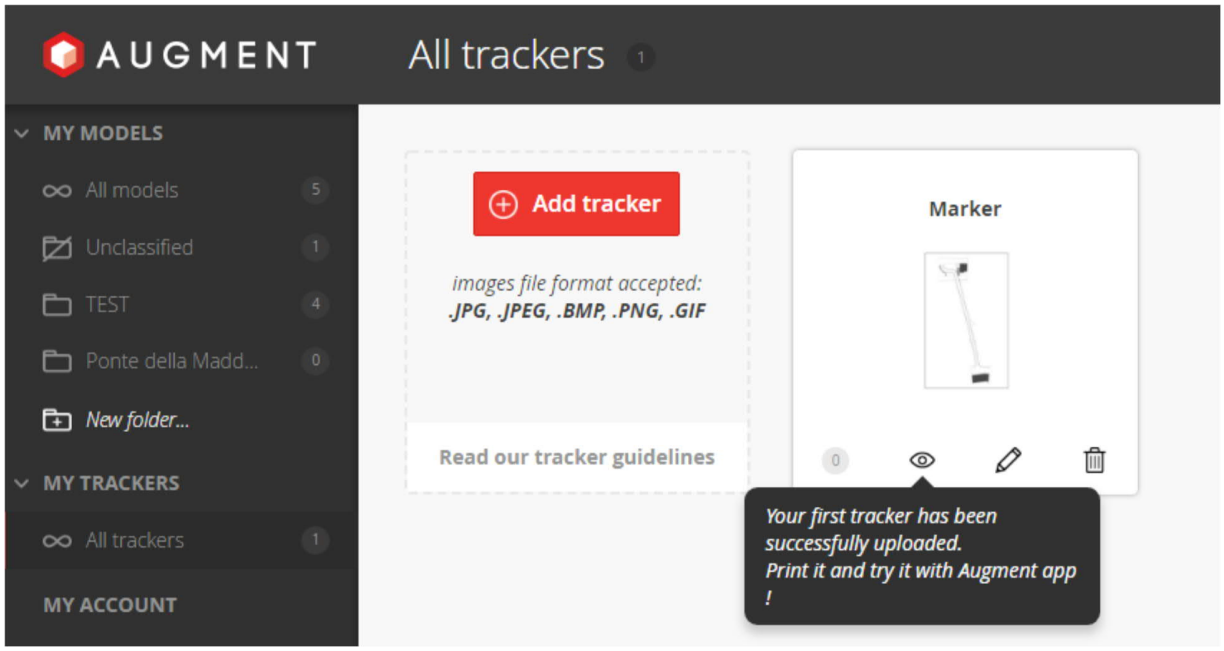

Fig. 6. Loading and matching the marker to the three-dimensional model on Augment

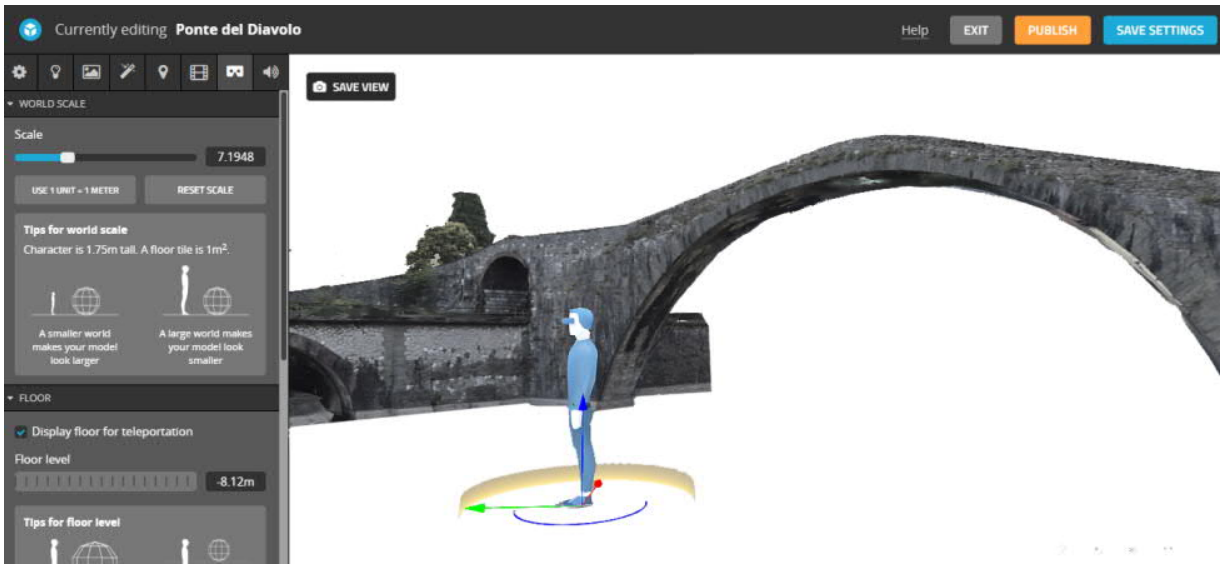

Fig. 7. Sketchfab virtual reality settings management screen. It is possible to set the observer's point of view. The representative model depicts in scale, the person who will wear the device for "Virtual Reality" (VR). So, it is possible, with reference to our three-dimensional model, to choose the scale of the subject, the position within the model, and the view.

Here it is taken into analysis as it allows to interact with the three-dimensional model through virtual reality. The three-dimensional model loaded here, made public and available to all the members of the platform, can be integrated with knowledge boxes where it is possible to add information about the model itself. Once loaded, it is possible to set the parameters to make it viewable through the use of wearable VR glasses, (also strictly economic,

such as *Google Cardboard*[12]), which allow the use of the totally immersive model. A final consideration is on the choice of platforms used. We have used services provided by third-party organizations, such as *Augment* and *Sketchfab*, to have a quick result both in terms of virtual modeling and in terms of use by the customer, tourist or simple user. They are platforms that offer both free services and additional paid services (for example *Sketchfab* imposes a maximum limit of 50 mb in upload), even if both support an unlocking of paid services or a facilitation for educational purposes. Despite the possibility of using others software, such as *Unity*[13] that does not involve the presence of third parties, our choice has remained to use these operators to greatly facilitate access to this information both by the average user, who through smartphones, tablets and other devices of medium-low range, so as to be available on a large scale.

FINAL CONSIDERATIONS

The study, analysis and survey carried out by Maddalena's Bridge, or Devil's Bridge, have allowed us to obtain a high level of knowledge of the building, which can be used both from a technical and historical point of view. But this study does not want to limit itself only to the single specific case taken in analysis. It wants to propose itself as a basis for a broader reflection on the methodologies of the survey: on the one hand regarding the use of software that, after overcoming the obstacle of the precision of analysis, also allow an optimization of the working times. On the other, it wants to be a starting point for a functional and fruitful integration of new technologies, whose exponential evolution cannot be kept marginal from our field of study.

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[12] https://arvr.google.com/cardboard/
[13] https://www.unity3d.com

Fig. 8. The poster presented to CHNT Conference, November 2018