A TOOL TO ACCESS UNREACHABLE SITES INSIDE THE ARCHAEOLOGICAL PARK OF OSTIA ANTICA IN ROME

Luca Gugliermetti*, Federico Cinquepalmi
Department of Architecture and Design, University of Rome La Sapienza,
Rome, Italy

Sara Marino
Department of Classics, University of Rome La Sapienza
Rome, Italy

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1. Introduction

With the computational revolution and the advent of information technology, the way cultural heritage can be communicated has been revolutionized. New technologies such as 3D vision, virtual and augmented reality, mobile applications, and new communication devices have brought new possibilities. In the most innovative museums and archaeological parks today, it is possible to carry out virtual tours using mobile or specific on-site digital applications. The inherent benefits of applications include not only the population, but also stakeholders, such as archaeologists, restorers, and cultural heritage professionals in general. Today, using computed tomography, computer vision, laser scanning and photogrammetry, it is easy to create three-dimensional (3D) models for production, sharing, and manipulation. Moreover, 3D data may be incorporated directly into the site or viewed remotely. Thanks to its low hardware and software requirements, photogrammetry has emerged from among other technologies to play an important role in cultural asset digital modelling. Moreover, photogrammetry requires very few tools to develop quality 3D models, therefore, it is a good candidate for surveying difficult sites when there is no electrical power available, as well as interior spaces where there is little room for manoeuvring or where it is impossible to use instrumentation other than cameras, lights and simple LIDAR (Light Detection and Ranging) systems.This paper discusses the development of an innovative tool for making virtual tours of unreachable sites using 5G technology, 3D photogrammetry models and information layers. Moreover, a case study is presented of the “Casa di Diana” (House of Diana) located inside the Archaeological Park of Ostia Antica in Rome. There are some important questions to consider when discussing photogrammetric reconstructions, as evidenced also in the work of Magnani [1]: “Does photogrammetry have greater interpretive potential than previously employed archaeological methods? Or is it best suited as a new medium for community outreach and visualization? In either case, does its practice address the needs of archaeologists and the communities we work with, or are we preoccupied with demonstrating the merits of the latest software and workflows?”. The following points answer these questions concerning the present

* Corresponding author: luca.gugliermetti@uniroma1.it

study: photogrammetry has been used as a tool to improve the accessibility of unreachable sites, thus increasing their outreach potential; it was considered a simple and effective methodology to create a 3D model of an asset that can then be used for site conservation and preservation (developing a fundamental "zero layer" for restoration processes) and a widely accessible and interoperable model to inspect the site. Moreover, any 3D model can be integrated with informative layers (historical photos, texts, etc..) or other 3D elements from different methodologies (LIDAR, 3D reconstructive hypotheses, etc..). This integration process can increase the capacity to communicate specific aspects of the asset as well as increase the scientific and scenic value of the result. Therefore, the authors encourage the use of photogrammetry as a base tool to create a more complex and valuable outcome, useful not only for outreach purposes but also for scientific and archaeological studies that can exploit the benefits of digital 3D models. Other elements worth noting, for example, arise from Shott's claim: "Certainly, the burgeoning literature on digital methods in archaeology has its share of 'See what I did because I could do it' contributions. There is nothing wrong with such papers when they serve as proof-of-concept, but they do not always contribute directly to the accumulation of archaeological knowledge" [2].

The same problem was also evidenced by Zubrow: "There is a tendency to use digital technological solutions simply because one has the available 'toys'" [3]. The present work is not intended to increase the archaeological knowledge for a cultural asset but as a methodology to increase the outreach capability of an otherwise unreachable site, a proof-of-concept for sites normally closed to the public due to their intrinsic nature following the idea expressed by Grosman [4]: "We should target issues that cannot be resolved using traditional approaches and benefit from data that are accessible only by applying digital methodologies".

The technology was developed in the VADUS project (ARTES 20 call), co-founded by ESA (European Space Agency) and the consortium led by NEXT Engineering Systems and with the participation of TIM, ENEA, the Archaeological Parks of the Colosseum and Ostia Antica, the Sapienza University of Rome with its research centre CITERA and the DIAG department. The name VADUS (Virtual Access and Digitalization for Unreachable Sites) comes from the Latin name for "ford", intended as a metaphorical passage to overcome the difficulties associated with physical access to unreachable archaeological assets.

2. Casa di Diana - Archaeological Park of Ostia Antica

The "*Casa di Diana*" (House of Diana) is located at "Regio I" the central area of the ancient city of Ostia, near the most important public and sacred buildings.

The demographic growth from the economic and commercial activities linked to the ports of Claudius and Trajan between the end of the first and the beginning of the third century, increasingly favoured the construction of large multi-storey buildings, the so-called *insulae* [5–7]. The *Casa di Diana* is one of the most important buildings in ancient Ostia (the harbour of Rome, Italy) and was used both for residential functions of the middle class and for commercial activities. Built in brickwork during the first half of the second century A.D., it has a quadrangular plan with an internal courtyard from which various access corridors to the apartments and common areas branch off. The *Casa di Diana* was unearthed in Ostia between 1915 and 1918 during the Paribeni-Calza excavations from which the first graphic reconstructions by Gismondi come from [8]. Since then, numerous other research and restoration campaigns have followed. The building takes its name from a terracotta tile depicting the goddess Diana, discovered on the walls of the central courtyard. It is hypothesized that the *Casa di Diana* was originally a five-storey building (Figure 1).

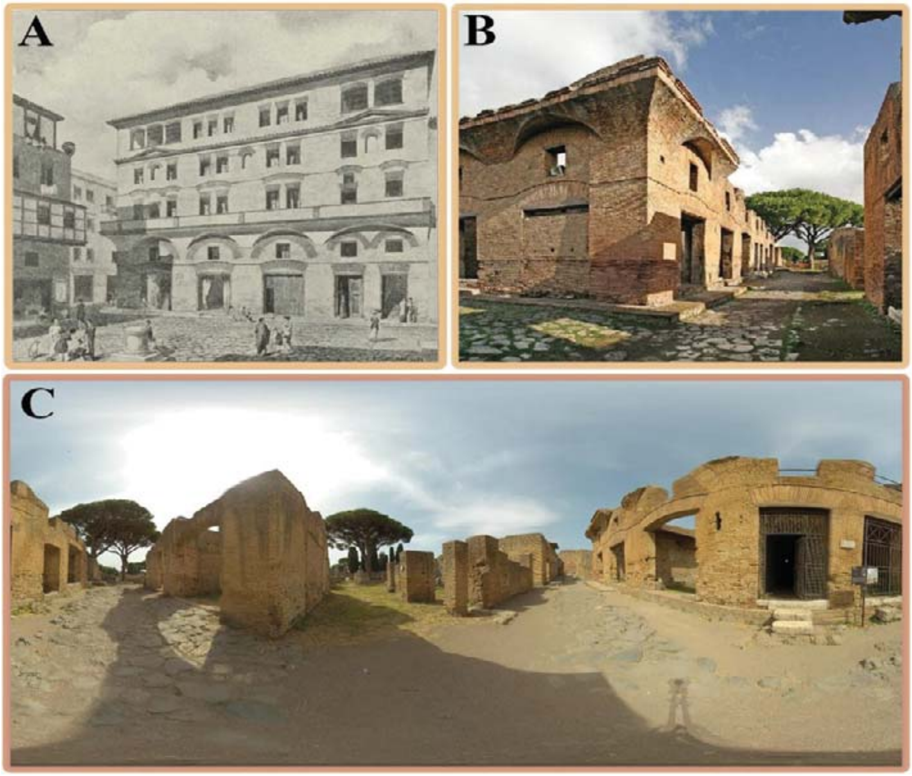

Figure 1. A: Gismondi's reconstruction of the Casa di Diana (Wikimedia Commons, CC BY-SA 3.0); B and C: Casa di Diana, present-day view (C is a 360° panorama).

On the ground floor, there were shops overlooking the street, while private apartments and common areas were placed on a mezzanine floor and accessed by internal staircases. The first floor had an external balcony overlooking the street of which part of the walls and the valuable pictorial decoration are still visible today. The upper floors, on the other hand, were intended as a residence for the poorer social classes. However, there are other functional interpretations for the *Casa di Diana*, as it was used both as a hotel and as a boarding school.

During the ages, a series of structural changes were performed as evidenced by the analysis of the walls, the decorations and the overlapping of different floor levels [9]. These transformations involved not only the distribution and organization of spaces and the renewal of decorative elements [10], but also changed the function of some rooms. In the second half of the second century, for example, a fountain decorated with a polychrome mosaic was built inside the porticoed courtyard (C) and was later replaced by a less elegant one in *opus latericium*.

Another significant example of architectural transformation was recorded during the third century B.C. when the floors were raised and fitted with new mosaics.

Among the most significant interventions of re-functionalization, however, was the construction of a *mithraeum* (F), in the innermost rooms, consisting of an *aedicula*, a marble altar (reused) and some *podia* in masonry. During a later phase, a stable was built inside the *tablinum* (E), the main representative rooms were decorated, and a fountain was placed in the centre of the building in front of the porticoed courtyard (C).

3. Visual storytelling

The *Casa di Diana* is a site that cannot be accessed, due to its fragility and conservation issues, therefore, it was selected, under guidance from the park officials, as a demonstrator site within the VADUS project. The site was digitally reconstructed using photogrammetry techniques, developing a 3D model for the most representative and best-preserved rooms in the building.

Only the rooms on the first floor were chosen for the virtual tour, which was modelled with information layers populated by references, reconstruction hypotheses and general information about the history of the building.

The environments selected were those which surround the porticoed courtyard (C) and are fundamental for a complete reading of the archaeological palimpsest. Moreover, a storyboard was realized consisting of 5 main historical-archaeological informative layers positioned in the 3D photogrammetric model near the entrance corridor (A), at the *Tablinum* (E), at the antechamber of the *Mithraeum* and in the *Mithraeum* itself (F), as well as a topographical frame outside the house along *Via di Diana* (the ancient street in front of the building, visible in Figure 2).

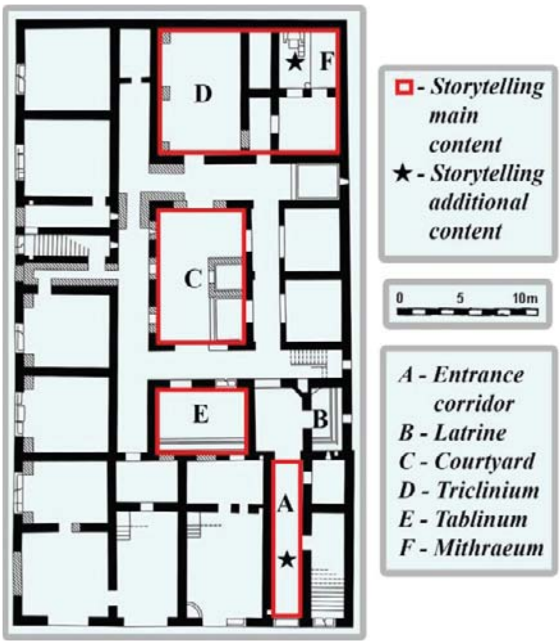

Figure 2. "Casa di Diana" plan on right, with indications of the environments involved in the storytelling.

Multiple data and details make up each of the five informative layers which, in turn, are made up of multiple elements based on available information, also visible to the user (inside the 3D model). For instance, one of the informative layers placed in the virtual tour is related to an inscription visible on a leaden fistula at the fountain in the porticoed courtyard (C). It is interactable by users and is positioned inside the entrance corridor (A). The inscription bears the name of *Marcus Cornelius Secundus* and that of a woman belonging to the *Sergii Pauli* family, who probably owned the house around the middle of the second century AD.The virtual tour also has high-level informative layers (not detailed as for the fistula), which were developed to show a more generic and large-scale historical framework for the site. An example is the *Mithraeum* (F) information layer, which describes Mithraic cults in Ostia and introduces the tourist to the ancient religions of Rome. Other layers aim at keeping and capturing the visitor's interest, as well as directing them toward other monuments and archaeological sites connected to the *Casa di Diana*. Furthermore, an attempt was made to describe some details of the site that are generally little known to non-experts. At a methodological level, the storytelling was developed with reliable and scientifically correct information after it was thoroughly researched; it involved: archives studies, interviews with archaeologists and on-site scientific measurements. Moreover, the storyboard was created following the requirements expressed by the authorities responsible for the management and conservation of the site, as well as with indications from the stakeholders. The choices made in developing and preparing the information layers allow for a "conscious" visit: that is, it can be enjoyed according to the cultural level and personal interests of the tourist, who has the possibility of accessing graphic, audio, video and textual information, including that deriving from diagnostic measurements (LIDAR and hyperspectral imaging). Therefore, different users can find different information, both from a general and a more specific/scientific perspective.

Furthermore, the different information layers, which provide the tourist with a clear picture and a connection to their surroundings and the available information, are all related to visible elements belonging to the site or another that is nearby and accessible. The content was organized within a narrative structure that could combine scientific needs with the interests of the visitors [11]. For this reason, an experimental campaign to test the visual storytelling capabilities of the tourists was made at the archaeological park of Ostia in the autumn of 2022. The aim was to understand if the narration was effective and interesting for visitors. The outcome was positive showing that the storytelling had been greatly appreciated, with visitors also making suggestions on how to improve the service.

Visual storytelling was developed as multilingual and all contents are scalable in terms of time duration and available information, based on users' choices. On a technical level, considering that the virtual tour runs on a smartphone APP, it was decided that video and images could be skipped or paused to best suit users' wishes and could easily be followed on small screens, such as tablets and smartphones. The photographic material used comes from the park of Ostia's historical archives, restoration archives and recent investigations.

For the storytelling, the following steps were followed:

1. Development of a storyboard for content definition.
2. Elaboration of storytelling based on the storyboard, where the narration is built on a maximum of 1000 words to avoid excessive length.
3. Definition of additional contents based on visitors' interests and little-known archaeological aspects.
4. Accurate selection and processing of illustrative material from the archives of

the *Ostia Antica* archaeological ark.
5. Development of animated visual storytelling.

4. Photogrammetry campaign

As mentioned previously, the selected demonstration site was the "*Casa di Diana*" (see Figure 3) in ancient Ostia and the various data collected during the measurement campaign (planar and 360° views, planimetry, hypotheses about room destination and graphical façade reconstruction).

The archaeological park of *Ostia Antica* identified two rooms as primary and secondary reconstruction targets (Rooms E and F), whose location and visual appearance are reported in Figure 3.

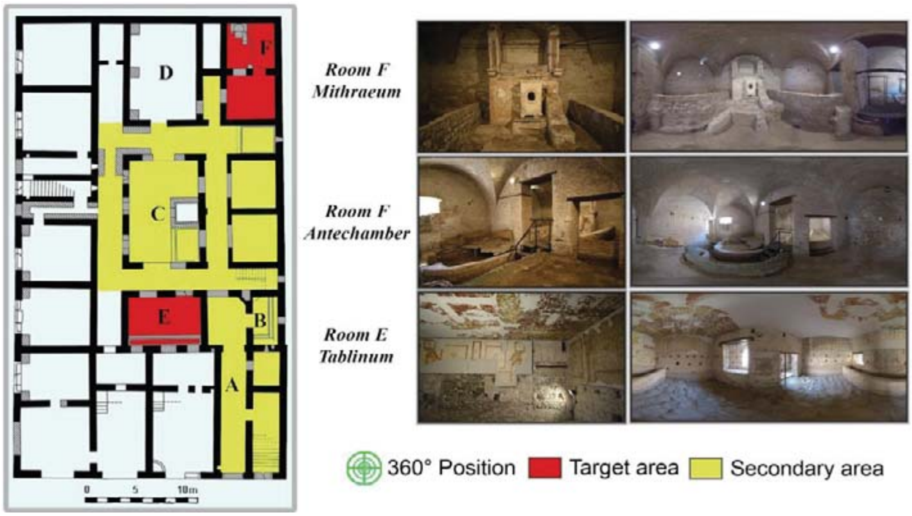

Figure 3. Target rooms and secondary areas for the reconstruction process (left), and views of the rooms in photos and 360° images (right).

The site was reconstructed using photogrammetry techniques at two different levels of details (LODs): the first level, used for the target rooms, has a higher reconstruction quality due to the higher number of images used in the photogrammetry software and is less decimated and simplified during the postprocess operations. High quality is mandatory where the rooms are of greater interest due to their importance in storytelling when compared to other locations on the site. In this case, a higher resolution was necessary to ensure the maximum quality for the frescoes, mosaics, and the *Mithraeum* altar in rooms E and F. The other rooms (A, B, C) were developed using lower quality, fewer images, and higher simplification during the postprocessing. This was done because the rooms had less important details and little available information. It must be underlined that the reconstruction is oriented at dissemination where it is more important to have an overall good performance for visualization of the models (due to the limited computing power of the rendering hardware) and to avoid any lag in loadings compared to having a too-high model quality for irrelevant details.

Moreover, the rooms/spaces A, B and C were captured to create a potentially continuous tour path for the virtual tourist. For unreachable sites, such as the "*Casa di Diana*", which is normally closed to the public, there are some issues to be considered during a photogrammetry campaign.

First, the site required preliminary access authorizations, inspections and interlocutions with the site and risk managers to:

- Define a timetable and security plan.
- Organize logistics as a function of the environment (clean the environment, get keys, move experimental hardware to the location, switch on the electrical system if present, etc.).
- Identify specific critical issues to be addressed and fixed before the start of activities.
- Define in detail the surfaces and target spaces for the reconstruction campaign.

Defining space and surface targets also needs archaeologists and personnel specialized in conservation, maintenance and valorisation, which are the same professional figures that are not only involved in the process of identifying the demonstration sites but are the main protagonists, with the Italian Ministry of Culture (MIC) and cultural institutions, in acquiring information to develop the "informative layers" and 3D reconstructions that enrich immersive visits.

The list of activities carried out for the photogrammetry campaign are listed below.

1. Preliminary activities (i.e., camera calibration, lighting preparation, correct positioning of photogrammetry markers).
2. Acquisition of physical dimensions for rooms using an EDM (Electronic Distance Measurement) device and coded markers.
3. Populating the photographic database with high-quality shots.
4. Taking photos for documentation purposes by frame and 360° cameras.

Other photogrammetric activities are summarized in Table 1. Before the campaign, preliminary camera calibration was performed in the laboratory using a checkerboard to completely calibrate the photographic lens [12], including non-linear and barrel distortion coefficients.

Table 1. Main computational photogrammetric steps

Computational steps	**Procedure**
Elaboration of photos	After the first visual analyses to identify missing elements (i.e., hidden building elements, small or occluded details, etc.), the available photos were pre-processed to analyse their quality in terms of focus, colours and over/under exposed areas. The areas with over/under exposure (luminance in hue colour spaces) were masked and excluded in the photogrammetry process.
Creation of a photogrammetry environment	The photos were loaded into the software's workspace creating a photogrammetry workspace and organized. The distance of the markers was then imported into the model to scale the photogrammetric environment.
Sparse and dense point cloud generation	The photos were aligned by the software generating the sparse and dense clouds. Then, the point clouds were filtered based on the number of correspondences in the photogrammetry

	database (the number of photos where the point is visible); the points which were not correctly aligned were removed.
CREATION OF 3D MODELS	The 3D models as well as the textures were generated by meshing the point cloud and using mosaic projections.
MODELLING POSTPROCESSING ACTIVITIES	The 3D models were post-processed using Open-Source software (Blender, Meshlab) to remove any remaining artefacts and to check the resulting model quality.

As a preliminary activity, about 73 coded markers were placed around the rooms and their spatial coordinates were measured with an EDM device to develop a matrix (“distortion” or “distance” matrix) for model scaling and validation. The matrix is symmetrical and was made using all the distances (expressed in meters) between markers (distortion matrix).

It is shown in Equation (1):

$$\begin{pmatrix} 0 & \cdots & P_j - P_i \\ \vdots & \ddots & \vdots \\ P_i - P_j & \cdots & 0 \end{pmatrix} \quad (1)$$

Where: "P" is the vector containing the coordinates of the “i” marker inside the reconstruction relative space and “j” is the total number of markers (73).

A Python script was used to transfer the distance data to the photogrammetric software to reduce transcription errors. The markers were 12-bit coded and placed in the target rooms (E and F) and in rooms (A, B, C) that connect the entrance with the target rooms. Table 2 reports the total number of markers used, their location in the rooms and the number of the resulting calculated inter-distances.

Table 2. Distribution of coded markers, number of resulting distances and location

Room	**Markers Total number**	**Distances Total number**	**Location**
E	10	45	Target area
F *Antechamber*	13	78	Target area
F	5	10	Target area
A	18	69	Secondary area
B	6	15	Secondary area
C	20	99	Secondary area
D	4	6	Secondary area

It must be noted that the maximum number of distances is different from the theoretical maximum due to the visibility between the markers that reduces the number of distances directly measurable by the EDM.

About 70% of the distance data were imported to the photogrammetry software to obtain a correct scaling of the model, while the remaining parts were used to validate the model by comparing their values with the corresponding measured distance in the developed 3D model.

During the photographic campaign, colour checkers and a grey-white balance target were used to support the colourimetric accuracy of the reconstruction and to balance the white temperature in the photos.

This was particularly critical because of the presence of different types of lighting sources, both natural and artificial (i.e., openings, windows and artificial lighting systems).

Artificial lighting sources had to be used in rooms/spaces where a too-low level of illuminance was detected by a lux meter to avoid dark areas in the photos.

An example of the visual environment with its different light sources and the checkers' position in the target rooms is reported in Figure 4.

Figure 4. Visual environments with different light sources and white-grey-colour checkers.

The photographic dataset was populated with 7360 x 4912 pixels photos in TIFF format with EXIF metadata; this format is suitable for photogrammetric processes due to its lossless quality and the metadata containing GPS information to help the software in the reconstruction process. The photos were taken with a very large overlapping area (~70%) to capture the same detail in at least three different images.

As a function of the environment, a parallel or circular close-image technique was used to improve the quality of the reconstruction and to evidence the details of the objects (Figure 5).

During the campaign a full-frame Nikon D810 camera was used, set at a fixed aperture and focus length, but with variable exposure time, to produce shots as uniform as possible. The lens used was a calibrated and stabilized Nikon AF-S 20mm 1:1 ED. Moreover, more photos were taken of important details, such as paintings, mosaics, opus sectile floors, and relevant architectural features.

The photos for the target rooms were taken at a mean distance of about 2-3 m, while for the less relevant surfaces (secondary areas and other rooms/space) the maximum distance was less than 5 m; the correspondent GSDs (Ground Sample Distance) were calculated on the base of the following Equation (2):

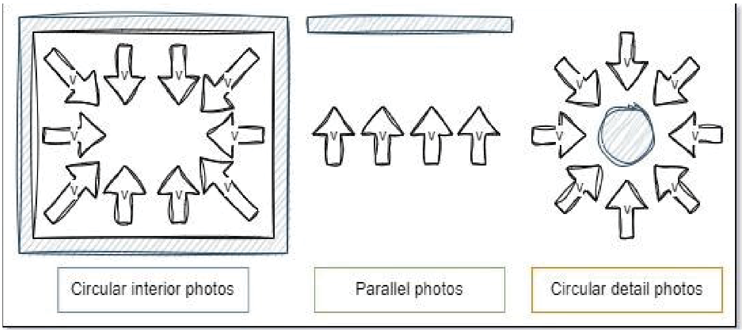

Figure 5. Different close-range image techniques.

$$\boldsymbol{GSD}\ \left[\frac{\boldsymbol{mm}}{\boldsymbol{pixel}}\right] = \frac{\boldsymbol{Distance}[\boldsymbol{m}]}{\boldsymbol{Focal\ length}[\boldsymbol{mm}]} * \frac{\boldsymbol{Sensor\ dimension}[\boldsymbol{mm}]}{\boldsymbol{Image\ resoultion}\ [\boldsymbol{pixel}]} \qquad (2)$$

The calculated GSD values for the target rooms are in the range of 0.5÷0.8 [mm/pixel] with a maximum of 1.4 [mm/pixel]. The number of photos taken for each room/space is reported in Table 3.

Table 3. Indicative distribution of photos among rooms/spaces

Spaces	N. of Photos	Location
Room E	295	Target room
Room F *Antechamber*	280	Target room
Room F	170	Target room
Connections to target rooms	390	Secondary area
Other rooms & miscellanea	1200	Secondary area

To exclude poorly focused images from the photogrammetric database it was manually analysed. The areas with over/under exposure were masked using a Python script and direct inspection, then the photos that were too dark or bright were excluded by the photogrammetry process (area with a luminance H <0.1 or H >0.9 in hue colour space). The remaining 2237 photos were loaded to the photogrammetry workspace and organized according to their content.

After the importing process, 70% of the distances were calculated and imported to the photogrammetry software to scale the environment.

The screenshot in Figure 6 shows the full sparse cloud model after photo alignment and scaling; as can be noted, the cloud is wider than the area interested in the project and the blue areas are the position where the photos were taken and reconstructed by the software; the software correctly aligned 2225 of the 2237 photos.

After the sparse cloud generation, a dense cloud model was generated by using the depth maps from the photos. The dense cloud model was then filtered using the number of correspondences in the photogrammetry database and removing the points that were not connected to the main cloud (artefacts).

Moreover, to reduce the elevated number of points (in the order of billions) the cloud was filtered to have no more than one point every 1.5 mm.

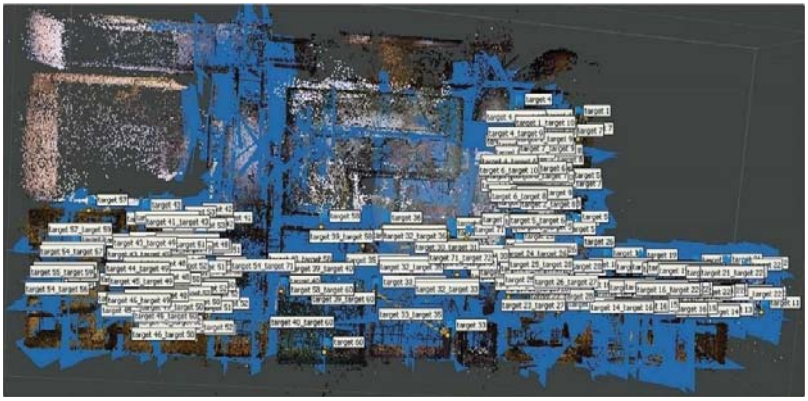

Figure 6. Screenshot of the full Sparse Cloud model with shooting positions (blue areas).

After the dense cloud processing, a complete 3D model was generated interpolating the point cloud, as can be seen in the screenshot in Figure 7; the red line encloses the secondary area and the yellow line the target rooms.

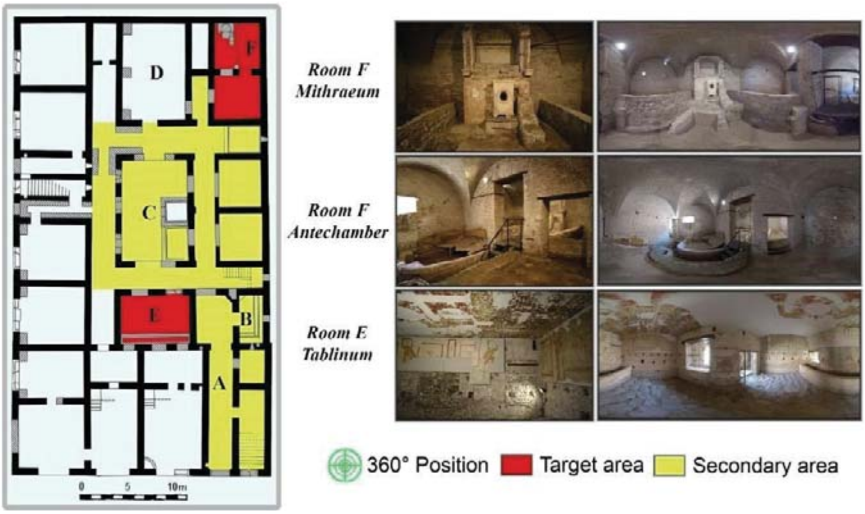

Figure 7. 3D interpolated model screenshots (primary target area is red coloured, secondary is yellow coloured).

To produce files suitable for virtual applications, the complete model was scaled again to a congruous number of points to reduce the number of polygons (from about 160M to about 13M points) and texturized with normal and occlusion maps from a high poly model (8 of 8K texture files); normal and occlusion maps are useful to give the depth information lost during the decimation process to the gaming engine.

After a visual inspection of the 3D model, it was revealed that there were no missing elements or artefacts in the interested rooms.

4.1. Model validation and quality

To evaluate the quality of the output a validation of the final 3D model for the target rooms (E and F) was developed by in-depth three-dimensional methodology, which considers dimension, colour, and perceived structure.

The methodology, developed by the authors, has already been used for other sites, showing its capabilities [12–14]. It involves not only the absolute pixel colour value from a singular pixel analysis but also considers the interrelation between pixels to analyse the “true” representation of an object and the clearance and discernibility of its details. This methodology is useful where dark areas and hidden details may degrade the quality of the representation.

To develop the methodology, the following indices were considered:

- Mean Absolute Percentage Error (MAPE) [15];
- Perception-based Image Quality Evaluator (PIQE) [16];
- Structural Similarity Index Measure (SSIM) [17];
- Signal to Noise Ratio (SNR) [18];
- Peak Signal to Noise Ratio (PSNR) [18];
- Mean Squared Error (MSE) [18].

The SNR, MAPE and PSNR parameters are more useful for comparison purposes between different types of reconstruction of the same model; moreover, they do not consider the perceived quality but only the difference between the original photo and virtual model. SSIM and PIQE, instead, are specifically developed to consider the perceived quality of an image by comparing the image structure. Instead, MAPE was used to evaluate the dimensional error of the virtual model if compared to the real site. This was done using the distances measured, using the distance matrix (Equation 1).

The MAPE parameter was calculated as a vectorial analysis using the following Equation 3:

$$\boldsymbol{MAPE} = \frac{\boldsymbol{100\%}}{\boldsymbol{n}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \left| \frac{(\boldsymbol{A_t - F_t})}{\boldsymbol{A_t}} \right| \quad (3)$$

Where A_t is the real measured value and F_t is the distance in the virtual model. This geometrical analysis is compared to a structural analysis which compares the information related to shapes and colours between two images (a real photo and a screenshot taken from the 3D model at the same coordinates and with the same lens characteristics. It must be noted that the “screenshot” is produced by the software using the same colour space as the original photo, not making a screenshot of the display), the indexes used for structural analysis in the present work are SNR, PSNR, MSE, PIQE and SSIM.

The following methodology was used to compare the 3D digital model with the corresponding photos: the camera position calculated by photogrammetric software, which is the point where the photos are supposed to be taken, is used to render an image of the virtual model. Then, the real photos and the screenshot were scaled to the same resolution (800 x 600 pixels) and converted into RGB colour space before applying the metrics. It is not necessary to operate with high resolution due to the greater importance of shapes over the number of pixels since the metrics are considered “full reference”. Finally, the calculations were made using uncompressed images (TIFF - Tagged Image File Format).

The Signal-to-Noise Ratio is a widely diffused index used in science and engineering to compare a signal to the level of background noise and is expressed in decibels (dB) as shown in Equation 4. The calculation formula for SNR is the following:

$$\boldsymbol{SNR_{dB} = 10\ log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)} \quad (4)$$

The Mean-Squared Error (MSE) measures the average squared difference between the real values and what is estimated. Given a noise-free M×N pixel monochrome image *I* and its noisy approximation K, MSE is defined as shown in Equation 5:

$$\boldsymbol{MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2} \qquad (5)$$

PSNR is another metric which is formulated as SNR, but it evidences the maximum difference between a signal and the environmental noise. It can be defined through the MSE (Equation 5) as shown in Equation 6:

$$\boldsymbol{PSNR_{dB} = 10log_{10}\left(\frac{MAX_I^2}{MSE}\right)} \quad (6)$$

Where $MAX^2{}_I$ is the absolute maximum possible pixel value in bits, PSNR is expressed in dB as for SNR. In this work, the signal is the value of the RGB channels of the real photo, and the noise is the colour difference between the real photo and the screenshot.

Structural similarity is a model for predicting the perceived quality of digital content; it is a perception-based metric that considers image degradation as a perceived change in structural information. It is based on the idea that pixels have strong inter-dependencies when they are spatially close. The index is usually used for measuring the similarity between two images, one compressed and the other uncompressed, but in this project, it is used as a metric for evaluating the quality of the 3D model. To calculate the SSIM the virtual model is compared with a section of reference photos. The SSIM can be formulated as showed in Equation (7):

$$\boldsymbol{SSIM(x,y) = \frac{(2\mu_x\mu_y+C_1)(2\sigma_{xy}+C_2)}{(\mu_x^2+\mu_y^2+C_1)(\sigma_x^2+\sigma_y^2+C_2)}} \qquad (7)$$

Where *x* and *y* are the two sample images (real and virtual) of the same size in pixels; *μ* is the average value between pixels of *x* and *y*; *σ* is the variance of *x* and *y* as stated by subscripts; σ_{xy} is the covariance, and *C1* and C_2 are two variables used to stabilize the denominator defined as shown in Equation (8):

$$\boldsymbol{C_1 = (k_1L)^2, C_2 = (k_2L)^2} \quad (8)$$

Where K_1 = 0.01 and K_2 = 0.03, L is the dynamic range of the pixel as in Equation 9:

$$\boldsymbol{L = \left(2^{bits\ per\ pixel} - 1\right)} \qquad (9)$$

The index is symmetrical; hence x and y can be changed in order. The three components, of which the index is made, can be calculated separately:

- Luminance *l*, Equation 10:

$$l(x,y) = \frac{2\mu_x\mu_y + c_1}{\mu_x^2 + \mu_y^2 + c_1} \qquad (10)$$

- Contrast *c*, Equation 11:

$$c(x,y) = \frac{2\sigma_x\sigma_y + c_2}{\sigma_x^2 + \sigma_y^2 + c_2} \qquad (11)$$

- Structure *s*, Equation 12:

$$s(x,y) = \frac{\sigma_{xy} + c_3}{\sigma_x\sigma_y + c_3} \qquad (12)$$

Where C_3 is expressed in Equation 13, and SSIM in Equation 14:

$$C_3 = C_2/2 \qquad (13)$$

$$SSIM\ (x,y) = \left[l(x,y)^{\alpha} * c(x,y)^{\beta} * s(x,y)^{\gamma}\right] \quad (14)$$

The three constants α, β and γ are weights that can be reduced to 1 to obtain the form shown in equation (5).

The SSIM can be applied both in the luminance space (Grey scale) or in the RGB colour model space; in the present work all indices have been analysed in the RGB space. A SSIM value of 1 indicates a perfect match between images and a SSIM ≥0.65 indicates a good match between images [17]. The last metric used for validation purposes is PIQUE. It calculates the no-reference quality score for an image through a block-wise distortion estimation and a Gaussian noise analysis. The evaluator generates a spatial quality mask that indicates the high spatially active blocks, noticeable artefact blocks, and noise blocks in the image. It is also possible to visualize the spatial quality masks by overlaying them on the image. The evaluator is useful to assess if the output image is of good quality and if each part is discernible. The formulation of this index is complex, therefore, to avoid a more detailed discussion of the topic it is possible to refer to the author's original article for more insight [16].

For this study, the quality threshold for SSIM is given in Table 4, a low score value indicates high output quality and a high score value indicates low output quality.

Table 4. PIQUE quality score range.

Quality scale	***Score range***
Excellent	*0-20*
Good	*21-35*
Fair	*36-50*
Poor	*51-80*
Bad	*81-100*

The expected values of the three-dimensional methodology indices are reported in Table 5.

Table 5. Expected values for the three-dimensional methodology indices.

Parameter	Range	Expected value
MAPE	0 ÷ 100 %	≤ 5%
SNR	≥ 0 dB	≤ 30 dB
MSE	≥ 0	≤ 1500
PSNR	≥ 0 dB	≤ 35 dB
SSIM	0 ÷ 1.0	≥ 0.5
PIQE	0 ÷ 100	≤ 50

Other metrics can be used to define the quality of the output such as BRISQE (Blind/Referenceless Image Spatial Quality Evaluator) [19] and NIQE (Naturalness Image Quality Evaluator) [20], but they use models trained specifically for compression issues and are not directly suitable for evaluation between a virtual model and a photo.

4.2. Results of the reconstruction process

To assess the developed 3D model quality, a comparison between 50 randomly selected original photos and the corresponding photogrammetry model was used to estimate the quality of the virtual reconstruction. The evaluations on a reduced database of photos and correspondent "high-resolution" virtual reconstructions, covering the main features of the site, were performed by MATLAB scripts.

The results are reported in Table 6. As examples, Figures 8 and 9 show the PIQUE evaluator output with spatial quality masks (Figure 9) for one of the images taken in Room E.

Table 6. Quality evaluation of 3D models by in-depth "three-dimensional methodology"

Parameter	Range	Expected value	Room E	Room 23-24	Mean
MAPE	0 ÷ 100 %	≤ 5%	1.01%	2.05%	1.53%
SNR	≥ 0 dB	≤ 30 dB	20.84 dB	22.05 dB	21.45 dB
MSE	≥ 0	≤ 1500	535.62	412.98	474.98
PSNR	≥ 0 dB	≤ 35 dB	11.34 dB	12.01 dB	11.67 dB
SSIM	0 ÷ 1.0	≥ 0.5	0.865	0.846	0.856
PIQE	0 ÷ 100	≤ 50	34.55	38.16	36.35

The output shows the noticeable artifact blocks, and the noise blocks in the image. Instead, Figure 10 shows the local SSIM value (large values of local SSIM appear as bright pixels); regions with large local SSIM correspond to uniform regions of the reference image, where blurring has less of an impact on the image.

After quality evaluation, the model was post-processed using Open-Source software to remove any remaining unrelated objects (i.e. markers, extraneous objects, and artefacts resulting from the photogrammetry process), to directly verify visual output quality after the shader applications (two examples are reported in the renders of Figures 11A and 11B).

Figure 8. PIQE evaluation (original image on left and reconstructed image on right).

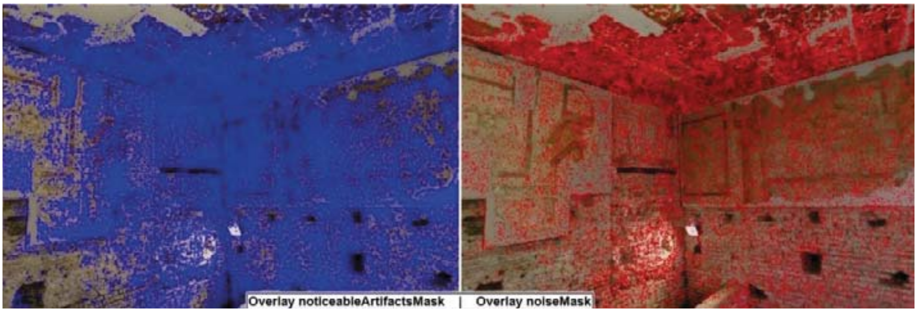

Figure 9. PIQE masks (Noticeable Artifact Mask on left and Noise Mask on right).

Finally, it was necessary to simplify the models by reducing the 3D polygonal mesh to fewer faces to avoid excessive computational loads on the hardware (Figure 12A).

The procedure is called mesh decimation (or simplification) and concludes with a visual inspection of the results to grant optimal accuracy and visual quality. During the process, the creation of new visual artefacts resulting from an oversimplification by the algorithm is avoided.

The tool used for this step was “the simplification of the planar algorithm” of the Blender software and was chosen as it shows good results [21].

The simplification process is fundamental to creating an adequate resulting model suitable not only for 3D gaming engines but also for storing data for documentation purposes inside archaeological park databases. Having an undecimated model results in a big dimension occupied on storage hardware (in the order of many gigabytes) with only negligible advantages. The use of gaming engines permits the tourist to visit the site as if it were a game, moving freely and interacting with the information content. Figure 12B shows an example of the 3D models obtained from the photogrammetric reconstruction. The model was also exported for further elaboration. The chosen formats were: *.obj* for the mesh, and *.TIFF* for the textures. The use of standard file formats to export data is a usual practice to ensure compatibility with different 3D engines, meshers, and visualization software. A render of the target rooms separated from the core model is also reported in Figure 12B to show the final output.

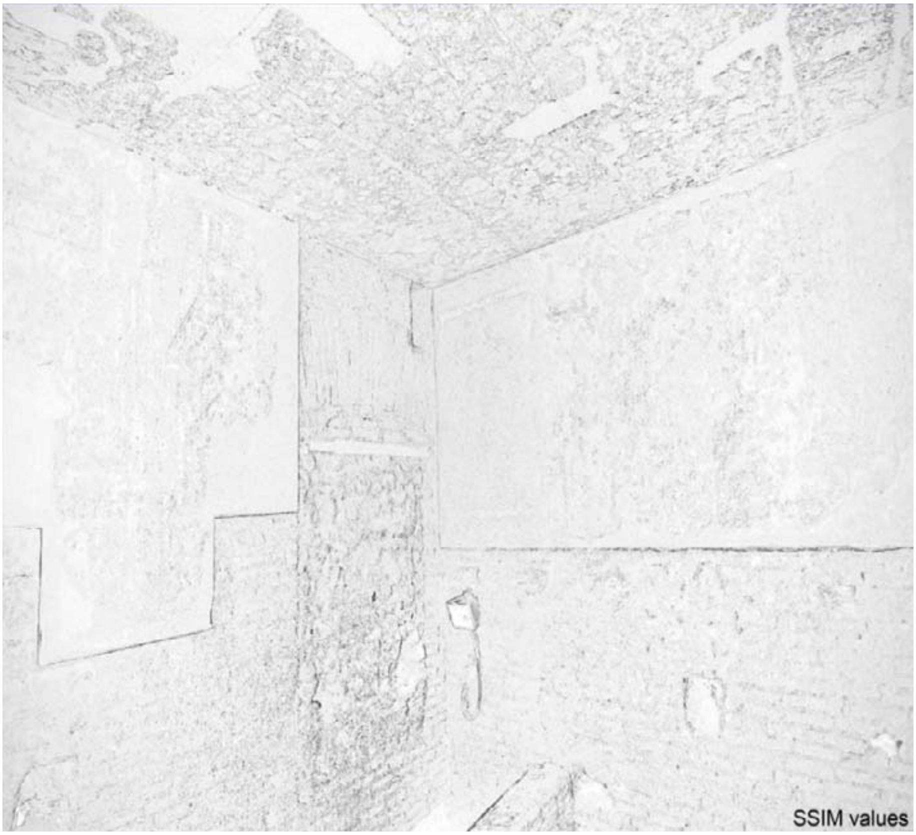

Figure 10. SSIM values.

Figure 11A. 3D render of the cleaned and shaded model (Room E, in front of the entrance door).

Figure 11B. 3D render of the cleaned and shaded model (Room E).

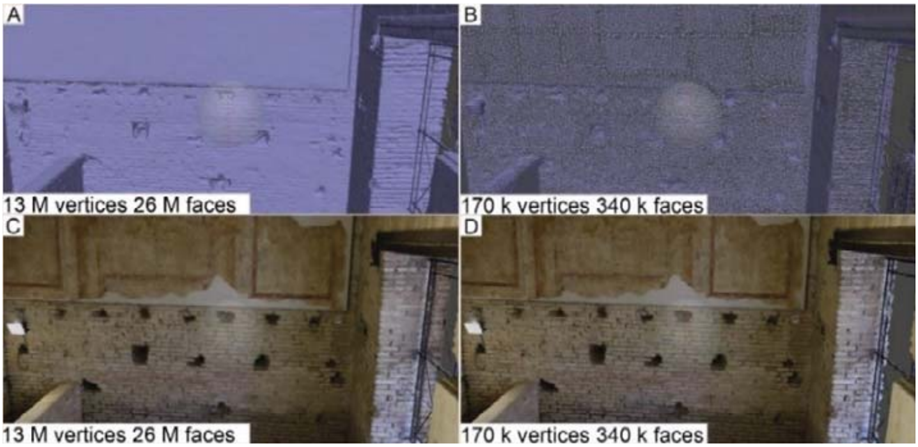

Figure 12A. Room E high-quality mesh with 13M vertices (A and C) and low-quality mesh with 170k vertices (B and D), wireframe render (A and B) and texture render (C and D).

Figure 12B. Rendered images from the 3D model for the target rooms (E on top and F on bottom).

5. The VADUS application

Photogrammetry was used to develop 3D models for the VADUS application aimed at resolving the problem of accessing unreachable archaeological sites. The latest innovations in telecommunication technologies and the introduction of the 5G network allow for the creation of virtual tours using remote servers enabling users equipped with a tablet or smart devices to access it through real-time data streaming. The idea beyond the application is to store the 3D models of a virtual asset remotely on a cloud database with all the inherent informative layers and GIS data in one place.

The database itself has two uses:

- Sharing the data with stakeholders for site monitoring and content updating.
- Linking the data to a rendering server containing a cloud application for virtual tours.

The rendering cloud server can share the virtual tour with users present on the archaeological site using the 5G network. Users could be tourists who buy tickets in advance to visit unreachable sites inside the archaeological park, enriching their tours with more content, which is usually difficult or impossible to access. Moreover, the application can be used by stakeholders interested in studying the site or programming maintenance routines. The GIS data coming from mobile smartphones can be used to show the nearest virtual tour in the park, if there are many of them, and is also useful to increase tourist involvement by taking them to the physical entrance of the virtual tour and contextualising the visit. Another use for the tool is for people with mobility disabilities, as they can visit areas that are usually unreachable for them.

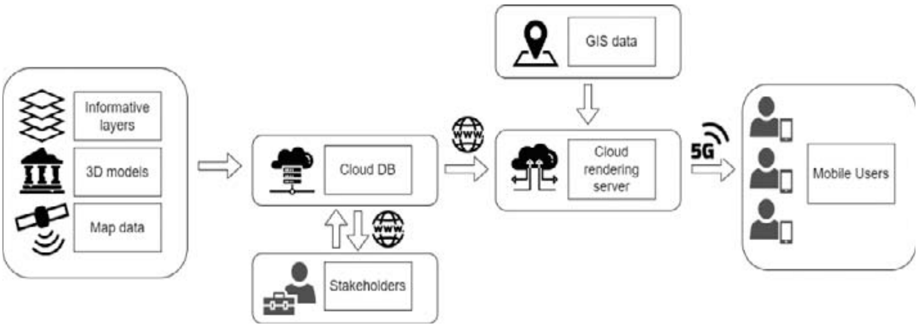

Figure 13. Unreachable site application conceptual scheme.

Moreover, thanks to the link to the database it is possible to update the virtual tour content with the latest discoveries and information, dynamically. The use of a remote render device also permits the development of a small-weight application (in terms of space on the disk and the computational load on smartphones) that does not contain heavy 3D models and data. The application also works on a 4G network with some trade-offs such as input lag and streaming resolution and was developed by "*NEXT ingegneria di sistemi*®", an Italian enterprise which aims to develop innovative solutions linked to space assets. A conceptual scheme of the tool is shown in Figure 13 where the different blocks show the data flows.

Thanks to the scaling possibilities of cloud computing the application is also simple to expand and scale to more users and more archaeological sites with little effort. Moreover, cloud computing has another advantage, its computational power.

Thanks to the latest improvements in graphical hardware, it is possible to render a good quality 3D model which is difficult to achieve for mobile phones without limitations, such as having a reduced number of polygons, low-quality textures, a lack of depth and normal mapping, etc. Cloud computing can dynamically adjust its performance in function of the number of connected users and their disposition in different locations worldwide, this is a major issue when considering other solutions such as centralized server facilities. The cloud infrastructure was developed by *TIM*® (*Telecom Italia*) using the *Google Cloud*® platform. The application needs information layers to enrich the content shown to tourists, therefore, the creation of a storytelling characterized by reliable and scientifically correct information is of mandatory importance.

The use of different layers allows for a "conscious" visit, enjoyable for everyone, according to the cultural level and interests of the user through the possibility of accessing graphic, audio, video and textual information through just a few interactions on the device.

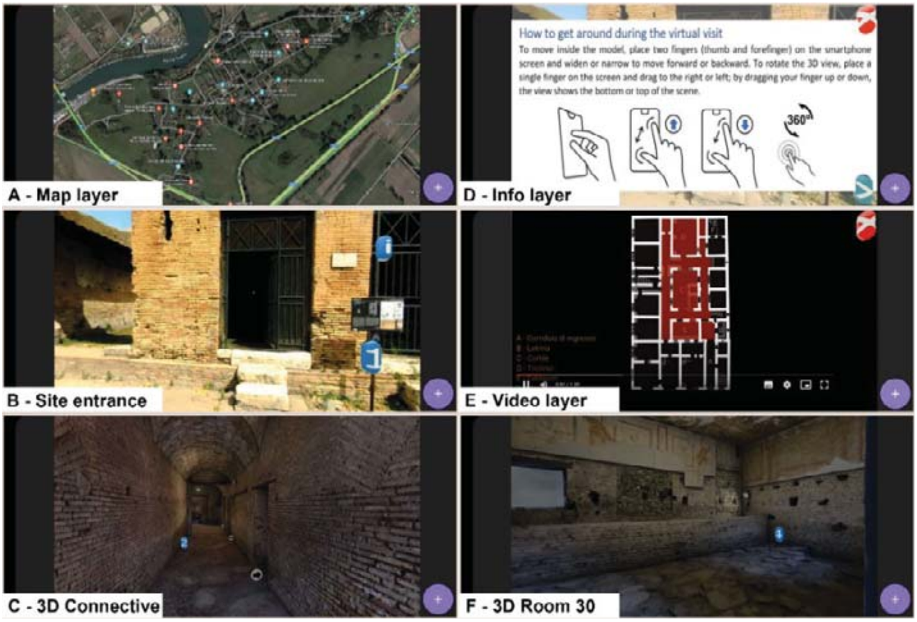

Figure 14. Screenshots of the unreachable site application showing map layer (A), info layer (D), 360° photo of site entrance (B), a frame from the video layer (E), a connective (C) and Room E (F).

Furthermore, the presence of different information layers permits a connection between what surrounds the user and the content they are viewing, without experiencing any sensation of "fiction" or "spectacularizing". To conclude, the storytelling must be multilanguage and the contents scalable in terms of time duration and available information, leaving the user the choice of what to see and what to skip.

Figure 14 shows some screenshots of the application's internal layout with icons, informative layer (video and images), map and textual content.

6. Conclusions

An innovative experience for cultural heritage virtual tours in unreachable sites can be offered by merging 5G networks, cloud infrastructure and satellite assets, as well as by developing a cloud-dedicated app supported by high-definition photogrammetry models and high-quality multimedia information layers. The importance of creating high-quality content is of mandatory importance for the wide diffusion of any digital application. This process involves the creation of informative layers, 3D models and a visualization pipeline. In the present work the building, *Casa di Diana,* inside the archaeological park of Ostia Antica was used as a case study to show a methodology able to reach the project goal of creating a quality virtual tour for unreachable sites.

The process started with the collection of information inside the site. Through proper communication with stakeholders and an in-depth analysis of the park's archives and scientific literature, it was possible to develop high-quality informative layers, created also considering the specific needs of tourists with different levels of culture and time. After site identification and definition of the perimeter for the virtual visit, a photogrammetry campaign was carried out to create an accurate 3D model of the site. To assess the quality of the site, structural and geometrical mathematical indices (MAPE, SNR, MSE, PSNR, SSIM, PIQE) were used showing good-quality results.

Then, the model was simplified and optimised so as to integrate quality information with the informative layers inside a cloud gaming engine to stream the virtual tour in real-time to remote mobile devices (such as smartphones and tablets) creating a virtual visit. With the use of a gaming engine, the user can move inside the tour, view the informative content and visit the unreachable site from outside identifying its characteristics. Once developed, the application was tested onsite showing good appreciation among the tourists and the involved stakeholders. Moreover, the use of cloud computing permits the number of connected devices to be scaled easily, while the 5G network permits smooth high-resolution streaming, making the application state-of-the-art.

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Biographical notes

Luca Gugliermetti (PhD) is a researcher at “La Sapienza” University of Rome (Italy) in the Department of Architecture and Design (DIAP). With a background in energy engineering, after his doctorate in 2018, he spent two years as a research fellow at the Department of Astronautical, Electrical and Energy Engineering of “La Sapienza” University of Rome, and another two years at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). His research activities include digital systems, sensors, planning and design, virtual technologies, energy systems for civil and industrial usage, space data and satellites.

Federico Cinquepalmi (PhD) holds a master’s degree in architecture from the IUAV University of Venice (Italy) and a PhD in Science and Technology for Industrial Innovation from the Sapienza University of Rome (Italy). Since March 2022, he has been a full professor of Project Management at the faculty of Architecture at the Sapienza University. Previously, from 2009-2022 he was senior researcher at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and at the Italian National Agency for Environmental Protection and Research (ISPRA). In the meantime, he was appointed Director of international affairs at the Italian Ministry of Universities and Research. In the last 30 years he has focused his scientific research in the sectors of sustainable development and policies applied to built environments, digital technologies for building management and cultural heritage.

Sara Marino (PhD) is a researcher at “La Sapienza” University of Rome (Italy) in the Department of Ancient World Studies (AWS) and is responsible for the Sapienza Laboratory of Archaeological Scoping for the Preventive Evaluation of Archaeological Interest (SAP-VPIA). With a background in prehistoric archaeology, her main research activities are focused on the Bronze Age civilization of Calabria and Sicily, in southern Italy. Among other research topics, she has worked on the effects of anthropization on archaeological sites, preservation, and monitoring of cultural heritage by digital means and underground archaeology.

Summary

Digital technologies are today used in many museums and archaeological sites. With the passing years, the diffusion of virtual tours, interactive projections and information totems has increased in all cultural places. Nowadays, new digital materials to be included in visits are very often developed during periods of renovation or the creation of new exhibitions. However, the addition of new material rarely includes what is unreachable and it is usually limited to the main content of the site. The present work aims to overcome this limit, making sites that are difficult to access or that are unreachable, virtually accessible. The creation of high quality and culturally accurate virtual tours can make sites that are usually closed to the public, enriching and enjoyable for visitors. To develop such tours, it is necessary to create 3D models, informative layers and to use appropriate communication devices. Photogrammetry can be used to create

3D models which can be evaluated using structural and geometrical analyses. Appropriately chosen video, textual and image material can be used to create the informative layers, considering tourists' needs and the specificity of the site. 5G networks and cloud computing can widen the possibility of implementation enabling a mobile application to bring the best quality to the tour. The case-study presented within the paper is the *Casa di Diana* inside the archaeological park of Ostia Antica.

Riassunto

Le tecnologie digitali sono ad oggi ampiamente utilizzate in musei e siti archeologici. Con il passare degli anni è aumentata la diffusione dei tour virtuali, delle proiezioni interattive e dei totem informativi. Ad oggi, parchi e musei archeologici durante il processo di ristrutturazione o durante la creazione di nuove mostre spesso sviluppano nuovi materiali digitali da includere nelle visite. Tuttavia, l'inserimento di nuovo materiale raramente include ciò che è irraggiungibile e di solito è limitato al contenuto principale del sito. Questo lavoro ha l'obiettivo di superare questo limite, fornendo una metodologia per rendere visitabili tutti i siti di difficile accesso e irraggiungibili. La creazione di tour virtuali di alta qualità può rendere accessibili siti solitamente chiusi al pubblico arricchendo e ampliando la visita di un sito culturale. Per sviluppare tale percorso è necessario creare modelli 3D, layer informativi e utilizzare opportuni dispositivi di comunicazione. La fotogrammetria può essere utilizzata per creare modelli 3D, da valutare mediante analisi strutturali e geometriche. Il materiale video, testuale e le immagini possono essere utilizzati per creare livelli informativi, tenendo conto delle esigenze dei turisti e della specificità del sito. Infine, le reti 5G e il cloud computing possono ampliare le possibilità di implementazione consentendo di sviluppare applicazioni mobili atte a migliore qualità del tour. Il caso studio presentato in questo lavoro è la "*Casa di Diana*" all'interno del parco archeologico di Ostia Antica.