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Original article

Digital replica of cultural landscapes: An experimental reality-based workflow to create realistic, interactive open world experiences

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ABSTRACT

In the last decades, the awareness of what cultural heritage is, as well as its definition, has changed and broaden its horizon. Important international institutions such as ICOMOS and UNESCO, which represent the reference points for documentation and protection, have revised the definition of cultural heritage to include not only the elements of historical-artistic relevance and the testimonies of a civilization but also the environment around them. In other words, the meaning of cultural heritage has been extended to the concept of cultural landscape. This article tries to meet this last definition of cultural heritage: through an extensive 3D survey of the ancient city of Sarmizegetusa (National Historical Monument), it presents a new perspective for the documentation and representation of cultural landscape that includes not only the structures of the city but also the areas that have not been excavated yet, and the surrounding natural environment. The term "digital replica" is presented to define this new perspective. The article deals in detail with the whole digitization process and the tools used to obtain a digital replica of a Roman city deepening the integration between photogrammetry and computer graphics. The detailed description is intended to make the workflow reproducible by the scientific community. Besides, as a final remark, experimented optimization procedures and navigation tools designed to manage and explore large three-dimensional datasets will be illustrated.

1. Introduction

The aim of the research was to carry out a 3D survey on the Sarmizegetusa site, combining geomatic and archaeological surveys. We realized, during the on-field activity, that the content to be surveyed was much wider and more complex than expected, including light, vegetation, environment in the broadest sense. Given that, we then become aware of the fact that such specific dataset had new requirements in terms of "representation", so we decided to make it accessible through both technical blueprints and 3D digital replica (or digital *copy* of the reality) within predefined parameters of quality, accuracy and visual resolution. We have experimented such task within a realtime engine, compatible with an Open World architecture (for an in depth description of the terminology used in this paper, refer to Section 3). The result of this research is an experimental workflow between photogrammetry and computer graphics.

In the last decades, the awareness of what a cultural site is, as well as its definition, has changed and broaden its horizon:

> "*The idea of the heritage has now been broadened to include both the human and the natural environment, both architectural complexes and archaeological sites, not only the rural heritage and the countryside but also the urban, technical or industrial heritage, industrial design and street furniture*" [1, p.5]

Important international institutions such as ICOMOS and UNESCO, which represent the reference points for documentation and protection, have revised the definition of cultural heritage to include not only the elements of historical-artistic relevance and the testimonies of a civilization but also the environment around them [2]. These aspects are defined as "cultural landscape"[1] which represent the "combined works of nature and of man" [3, art.1].

Cultural landscapes are also recognized by their association with works of art such as literature, poetry, myths, folklore, historical events, traditions. Cultural Landscape, after being internationally recognized, has been closely related to "Immaterial Heritage" [4]. According to the latest definition, the cultural landscape would not

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[1] http://whc.unesco.org/en/culturallandscape/.

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only indicate the mere site but also the whole natural, social and cultural ecosystem. This change of perspective is destined to radically modify the way in which cultural heritage is documented, protected, and valued.

In this paper, the term cultural landscape is used to indicate the last, wider in meaning definition of cultural heritage (combination of natural, anthropic, and immaterial heritage).

Therefore, this last definition has made it necessary to adopt new legislative instruments for the protection and prevention of the deterioration of cultural landscapes, as, for instance, in the case of visual pollution:

> "*[. . .] visually offensive degradation resulting either from the accumulation of installations or technical equipment (pylons, advertising boards, signs and other publicity material) or from the presence of inappropriate or badly sited tree planting, forestry or building projects*" [5].

In the recent decades, various national laws have included cultural landscapes among cultural elements that must be protected and enhanced like in the case of the *Codice Urbani* in Italy, which organically regulates cultural heritage and cultural landscapes (*Paesaggio Culturale*) as a whole [6].

During the period 2013–2016 the ITABC CNR (Institute for Technologies Applied to Cultural Heritage of the Italian National Research Council) performed an extensive survey on the ancient city of Sarmizegetusa, in Romania. During this research, we realized that the systematic and established geomatic methods for the digitization of large contexts should be improved to meet the last definition of cultural landscape. The term digital replica is presented to define this new perspective.

2. Related work

2.1. 3D survey of ancient cities

3D survey and visualization of cultural lanscapes are a big challenge in terms of efforts, resources, and time, and the results are often strictly connected to projects demands. Fortunately, the exponential evolution of technologies such as terrestrial and UAV [7,8] based photogrammetry [9,10], makes it possible to survey and document efficiently, quickly, and extensively on different scales, from objects [11] to architectures [12–16] and landscapes [17–20].

However, the technological innovation itself is not sufficient to disclose new perspectives but the "*full and proper development of a technique should allow the formulation of innovative procedures that match the needs of their field of application, facilitating the framing of new paradigms*" [21, p.7]. As researchers, we must take advantage of innovative technologies not only to make the same things faster and better but also to widen our point of view to arise new questions and developing paradigms, methodologies, and fruitful disciplines contamination. In the field of 3D survey, many recent scientific works are addressed in this direction trying to develop new approaches, to mix and integrate other disciplines and to try to create a synergy of professionals. One could mention the project about the Roman town of Ammaia which integrates technologies of survey Laser scanner, Ground Penetrating Radar, DGPS for the 3D survey, visualization, and reconstruction of a Roman town in Portugal [22]. Or the Paestum project whose goals are to develop reality-based digital models of the main architectures to compare 3D surveying and modelling methodologies and to deliver metric and accurate results for archaeological, architectural, conservation and communication needs through visualization tools and virtual reality [23]. Furthermore, the main mission of several international projects is the digitization of archaeological townscapes and sites. ROVINA project (Robots for Exploration, Digital Preservation and Visualization of Archaeological Sites) was born to develop methods for 3D recording of large sites in order to obtain semantic detailed models [24]. PROTHEGO project (PROTection of European cultural heritage from Geo-hazards) aims at making an innovative contribution towards the analysis of geohazards in areas of cultural heritage using specialized remote sensing techniques [25]. The literature about townscape digitization that one could mention is enormous; however, an accurate description of the tools used in the 3D survey of ancient cities and the adaptation of the methodology to the specific case of use are aspects which, despite their importance, are not sufficiently discussed. Indeed, the area that is most slowly receiving the last definition of cultural heritage (cultural landscape considered as an *integration* of artefacts, natural, and immaterial heritage) is the documentation activity, traditionally focused on the survey of landscape, monumental heritage and museum artefacts considered as separate elements. As a result, there are still no solutions in the literature for *integrated* digital documentation of "monumental" cultural heritage and cultural landscapes. In other words, the 3D models of the monuments surveyed within an archaeological context look like "islands" that can be visualized interactively only "one by one" (mainly due to hardware and software limitations), with a general lack of realtime tools and methods to explore and visualize cultural landscapes. The reasons for this delay are mainly related to the difficulty and costs of documentation, which imply the engagement of multifaceted team made up of professional figures belonging both to hard and soft science, and experts in realtime visualization.

2.2. Integrating 3D survey, computer graphics, and open world techniques to create 3D models of ancient cities

The majority of the projects about 3D recording of large sites are mostly oriented to documentation, analysis, preservation or restoration purposes (some of them: [26–33]) while just in few cases they keep in consideration the use of computer graphics as part of the 3D survey workflow[2] but are limited to the presentation of the data acquired through rendering or video animations.

Computer graphics is often used either for virtual reconstruction [34,35] or to optimize/re-model 3D reality-based architectures to visualize and analyze them in 3D GIS platform or realtime application, as in the case of the house of Caecilius Jucundus in the Swedish Pompeii Project [36] or MayaArch3D project [37].

Despite the fact that digitization creates increasingly impressive datasets in terms of data size on disk and in terms of resolution density of information (vector geometries and raster), there are technological solutions developed within the game industry that allow 3D data to be optimized, transferred, and made available within realistic virtual environments that can be explored in realtime (*see* Section 4.4).

Taking into account very extensive and complex models, this approach limits the possibilities of model reuse to the actual computational capacity of the computers that are utilized. The use of computer graphics techniques can help optimize meshes, transfer geometric information on textures, page models, edit textures (*see infra* footnote 12) extensively (colour correction) or locally (painting techniques) or to integrate photogrammetric datasets collected at different times.

3D survey of ancient cities is limited mainly to the architectural evidences and when it is extended to the environment, it is limited to the terrain. In the case in which vegetation is also taken into account, such as in the case of the reconstruction of the Trajan villa

[2] By means of 3D survey workflow we intend not only the field activities but the whole work that includes also the post processing and the creation of a digital asset that represents the real context.

of Arcinazzo [38], the tree species come from pre-existing digital libraries and not from a sampling of the data on the ground.

The autoptic reading of a surveyed monument by a specialist (architect or archaeologist) only in a few cases can be operated directly on high-resolution 3D models: in the case of small to medium-size single objects, there are solutions such as SketchFab,[3] 3DHop[4] or off-line viewers that allow the specialist to analyze the model with autoptic tools. Unfortunately, as the model becomes larger or there are even many complex models on a territorial scale as in the case of the ancient city of Sarmizegetusa, it is necessary to compress all the collected data within 2D technical drawing (derived from the 3D models) such as plans, orthophotography, sections and very high-resolution elevation plans (using images with internal pyramid techniques). This widely adopted solution is essential to make it possible for the assets to be displayed in a simple way by the specialist. The VHLab (Virtual Heritage Lab) of the ITABC has made a first step to extend the representation based on levels of detail and PBR. We are talking about ATON[5] and Landscape Services[6] [39] which make it possible to publish a digital replica online through modern HTML5/WebGL compliant browsers (the first versions of the digital replica of Sarmizegetusa have been tested on ATON, *see* Section 5).

Furthermore, the approach to make a digital replica of an entire cultural landscape, like in present research, has been made possible only by recently introduced tools – the evolution of modern Game Engines and Graphics Processing Units (GPU). Furthermore, we have Physically-Based Rendering (PBR) materials and already consolidated techniques such as the Level Of Detail (LOD and Hierarchical LOD) or GPU based instancing of geometry. The use of mixed photogrammetric and computer graphics techniques has been successfully used to create "open worlds" with natural environments (*see* the Unreal Open World demo representing a 100 square mile landscape from New Zealand and UK [40,41], and [42]) or historical scenarios with complex architectures like in the case of the Assassin's Creed Unity in 2014 [43] that represents detailed cities (Paris: 2.442.000 m2; Versailles: 218.400 m2; Saint Denis 101.000 m2, *see* Fig. 1). Despite the aims of these two open worlds were not to create a digital replica (the first one is a workflow proposal to ingest reality-based content from natural environments inside a game engine, while the second one is a re-constructive model of Paris from the eighteenth century), they provide a good example of how computer graphics and realtime engine solutions allow to create extensive scenarios (an unimaginable task until a few years ago) based on elements obtained with photogrammetric techniques or through manual modelling starting from reference images (Assassin Creed) or samples of real elements (Epic's Open World). There are, actually, isolated examples [44] of 3D surveys and environment's features (vegetation, realistic terrain) integrated within a game engine but without a scientific description of the workflow or about the methodology of data collection. The incompleteness of these examples testify to the need to develop a scientific debate on the strengths and weaknesses in the use of game engines to propose digital replicas of the cultural landscape.

In other words, although different technical solutions are available from computer graphics and the world of realtime engines, there are no examples in scientific literature of complete workflows that go from 3D survey (reality based models) to the creation of an interactive and realtime environment of a cultural landscape (both small artefacts, architectonic, urban, and territorial scale) using an open world approach.

3. Digital replica: definition and scopes

As highlighted in previous Section 2, the collection of integrated datasets regarding cultural landscapes is poorly represented in literature. We can say the same about the definition of methods and techniques that makes it possible to store and visualize in realtime multiscale data resulting from an extensive 3D survey of a cultural landscape, namely the digital replica method and digital replica workflow.

What is a digital replica ?: In general, the term "replica" means the reproduction of an original ("A duplicate of an original artistic work [. . .]" English Oxford Dictionary). How can this term be used in the world of the digitization of cultural heritage?

The purpose of digitization is to select some elements of reality to record them in a digital format [45]. This selection involves a deliberately human choice of characteristics (geometric, mechanical, physical, stylistic, chromatic) that belong to an object and that are recorded within a "grid of information" (an image, a vector, a 3D model, a table or a graph database or other formalisms to channel knowledge). Following this reasoning, a survey with digital technologies should be an approximation of reality according to some characteristics chosen *a priori* at the beginning of a survey project. The accuracy of a digitization lies in the quality and quantity of properties involved.

Virtual, from the Latin word "*virtus*", indicates a "potential" phenomenon and, by extension, an approximation of what reality should be. The phenomenon is sometimes closely associated with immersive digital technologies, as in the case of virtual reality. However, this association, despite being very widespread, is improper, because the term "virtual" exists before the introduction of the computer.

Therefore, while virtual refers to both the digital and analogical horizon, the term digital is specific to an area. It follows that a virtual replica can be either a physical replica (for example a mould of a statue) or a digital replica (we will see several examples below).

The existing term "Digital Reconstruction" defined as a

> "*Construction of digital, virtual objects or structures based on historic, archaeological, or other similar evidence. Includes manipulation via software of digital copies of damaged objects to effect a virtual restoration*" (AAT ID: 300387703 www.getty.edu).

does not match with the same meaning of digital replica since it seems to be different in scope: "reconstruction" itself is an ambiguous term because it has different meanings in different disciplines. In geomatics [46] it stands for the generic creation of a 3D digital content through semi automatic algorithms (mesh reconstruction from point clouds) while in archaeology [47] it is specific for the virtual reconstruction of no more extant heritage. We prefer to separate the concepts and use the term digital replica for an approximate, visually-credible copy of an archaeological site, on the other hand, we use the term virtual reconstruction to identify its hypothetical reconstruction.

Digital data collection (in a 3D survey) generally focuses mainly on aspects of geometric accuracy, resolution and precision of colour information. While the scientific literature has expanded the survey techniques by developing methods for observing cultural heritage outside the visible spectrum (such as XFR, infrared, etc.), the present contribution moves in a different direction, focusing not on the search for elements which are "not visible" to the naked eye but in the definition of methods and techniques to obtain a digital replica of cultural heritage assets that allows the user to "make

[3] https://sketchfab.com.
[4] http://vcg.isti.cnr.it/3dhop/.
[5] http://osiris.itabc.cnr.it/scenebaker/index.php/projects/aton/.
[6] http://landscape.ariadne-infrastructure.eu/.

Fig. 1. Massive open world scenarios with historical assets in Assassin's Creed Unity ©2014 Ubisoft Entertainment. All Rights Reserved. Assassin's Creed, Ubisoft and the Ubisoft logo are trademarks of Ubisoft Entertainment in the United States and/or other countries. All other rights are reserved by Ubisoft Entertainment.

an experience" and even perform some scientific analyses on an autoptical basis such as the stratigraphic reading of the masonry.

This article aims to stimulate the scientific debate on the necessity to extend the number and variety of aspects of a cultural site that need to be digitised, also through simplified solutions of "data sampling" in order to obtain a replica tighter to the complexity and physical extension of cultural heritage/cultural landscape.

Taking into account the last definition of cultural heritage (extended to the concept of cultural landscape), the extensive survey carried out at Sarmizegetusa Ulpia Traiana also required a deliberate selection of which and how much information had to be collected (geometries and colours related to monumental contexts, sampling of plant elements, and features that characterize the ethnographic landscape). However, the collected data proved to be insufficient to record and digitize this heterogeneous context: we realized that a better approach to understand, document, and communicate the site would be a series of graphic works accompanied by a general textual description in which the continuity and the interpenetration of archaeological remains, ethnographic aspects, and natural heritage was noted. Thus, by digital replica we mean not only the data collected in the field and organized in a scheme, but also the possibility of enable the telepresence on the site as if the users were really there ("feeling" of embodiment, through photorealistic realtime rendering techniques).

With the term digital replica, we want to express both a method (which includes various technical and methodological steps) and the possible products of the method itself (namely, interactive installation or dataset used to do the interactive installation). It is for this reason that in the article the term will have different meanings depending on the context in which it will be used (digital replica method and digital replica model).

By the term digital replica method we mean the massive digitization and realtime representation of heterogeneous elements that concern both cultural landscape (combination of archaeology, architecture, museum objects, and natural heritage). This digitization occurs through integrated methods and techniques of geomatics (photogrammetry, *see* Section 4.1.1) and computer graphics (*see* Section 4.3). The main goal is to collect real data in an extensive way (survey 3D) and to transform the sampling data (among the others: HDRI -or called Light Probe- sampling, vegetation sampling, 3D assets of repetitive elements, *see* Section 4.1.3) into a virtual experience (*see* Section 4.4) that is faithful and reliable from a perceptual point of view.

The goal of next sessions is to explain our workflow as a quick and effective way to gather 3D information of large archaeological site or cities and their context to obtain their digital replica through the creation of an interactive open world. The description is intended to make the workflow reproducible in its main steps by the scientific community with the aim to stimulate a multidisciplinary discussion to better match the expectations of archaeologists, architects, surveyors, engineers, computer scientists and landscape experts.

A digital replica allows different analysis tasks to be performed by specialists (among others archaeologists, historians, architects) like the autoptic visualization of the city, from a broader view and from above (high scale), to the perception of artefacts and the natural environment at human height (embodiment) and up to the close-up view of detail of specific elements such as the use of stones in the wall structures and the fragments of marble cladding or brick stamps and inscriptions, all within the same virtual environment.

Making a realtime experience requires an extra effort to optimize and create an articulate data architecture able to perform on demand smooth and automatic data visualization of large 3D environments. In Section 4.3 we will explain the open-source, semi-automatic tools created by the VHLab to speed up the process making it sustainable for large contexts. Taking into account the technical difficulties in this kind of workflow, why is it so important to have a realtime experience for a digital replica?

This perspective makes it possible to visualize the digital replica at different scale, from landscape scale to an architectonic scale, and even up to a 1:1 scale ratio for small elements like brick stamps or inscriptions. This approach is not intended to substitute the scientific 2D orthometric standards of representation, but it improves the understanding and analysis skills of the researcher by providing valuable information about the context. In some cases, it is impossible to understand an archaeological phenomenon without having access to the context like in the case of deformations in the shape of a building due to the presence of a big tree.

For scientific exploitation reasons, it is important to shorten the distance between the result of the 3D survey and the specialist's reading interpretation of 3D data. For this reason, as it happens for the Roman city of Sarmizegetusa, thanks to the techniques of CG and RT engine, it is possible to have a synthetic view of the whole city through a "bird's-eye view". We can also have a perception of the remains and of the environment at a human height, as if the researchers were personally on the spot, and even an exhaustive close-up view of the details is possible.

The digital replica method has been made possible due to the novel conjuncture of four opportunities:

1. the need for the inclusion of more aspects of cultural heritage (environment, light, vegetation, ethnographic aspects, etc.) is now considered crucial (*see* first part of this section) to allow comprehensive actions of preservation, management and valorisation of cultural heritage contexts;
2. the growing diffusion of tools and final users that are able to make 3D survey campaign (photogrammetry techniques, Unmanned Autonomous Vehicles (UAV), laser scanners, etc.) of

cultural heritage contexts with reduced times, budgets and high quality of the digital output;
3. the scientific community has prepared the theoretical background since 1970 on simulation, virtuality and cyber archeology;
4. the technologies of computer graphic offer us new tools to create theoretically infinite interactive and realtime digital worlds (such as Open Worlds, *see* Sections 2.2 and 3).

The experiment of extending the 3D survey of the ancient site of Sarmizegetusa to the environment follows these latest definitions of what a cultural good is and how it should be protected, studied, and communicated (*see* Section 1) and it presents some solutions to explore in realtime the whole 3D dataset with a high level of resolution.

The research carried out by the VHLab of the ITABC on the site of Sarmizegetusa Ulpia Traiana (*see* next section) and other sites, has been oriented towards the definition of digital replica of a cultural heritage with the aim of conforming to the new international vision for the protection, study, and enhancement of cultural Heritage.

3.1. *The Roman city of Sarmizegetusa*

The site we are going to deal with is *Colonia Ulpia Traiana Augusta Dacica Sarmizegetusa* (and from now on named in the text as Sarmizegetusa), it is a "mixed" heritage site containing elements of both natural and cultural significance (*see* Fig. 2). It is an important archaeological site belonging to the context of the Retezat Mountains which are part of the Southern Carpathians mountain range.

Sarmizegetusa was the only colony of veterans of the Roman province of Dacia, it was created after the Trajan's Dacian wars (A.D. 108–110). During the entire first century A.D., Sarmizegetusa was the most important cultural center of the province and the political, administrative, and religious center of Roman Dacia during the 2nd and 3rd centuries A.D. [48,49]. From the very beginning, it received the title of colonia and under Alexander Severus got the status of metropolis. It was the only city in the western Roman Empire to receive this important epithet. The city was destroyed by the Goths during the Late Antiquity. Sarmizegetusa was a quasi-square-shaped city with great fortifications and gates. It measured about 33 ha inside its walls and about 60–70 ha extra-moenia with a population extending between 20,000 and 25,000 people [50].

Only the circumscribed areas have been excavated so far, such as the Forum, the Amphitheatre, the Domus Procuratoris, and some temples that have been investigated in the recent decades. However, many parts of the city are still buried beneath the ground, as demonstrated in the latest survey and geophysics analyses performed by the ITABC group and the MNIT (National Museum of Transylvania) group [51]. Among these monumental areas that have been discovered, there are farmed fields, pastures, shrubs and thickets and, in the western part of the site, the modern village of Sarmizegetusa. If we had to describe the site of the ancient city following the last definition of cultural heritage, considering just the archaeological structures would not have been sufficient. In order to record the cultural context, it would be necessary to capture also the peculiar elements around them: country trails, corrals, hand-built straws arranged according to traditional methods, free pastures, the constant presence of wild animals descending from the Carpathian mountains and local spontaneous vegetation, as well as the presence of farms with inner courtyards and spaces used both for agricultural purposes and residential use. In addition, documenting the whole cultural context according to the digital replica method has immediate consequences on the understanding of cultural Heritage in its narrowest sense as an "archaeological remain": digitizing the status of places that apparently do not have ancient structures allows us to testify and document these "absences" and to create the conditions to perpetuate some comparisons and to study the change of the landscape over time (for example, between the site in 2015 and the site after ten years, in 2025). This kind of comparison may also be made in the case of sites under investigation or sites that have been excavated and covered (for conservation purposes) for several years.

4. Digital replica: methods and tools

In this section we will focus on the practical application of this method to this specific domain. This approach, halfway between photogrammetry and computer graphics, requires precaution, especially during the post-processing activities. Taking into account this fact, the whole workflow, from the acquisition to the optimization and visualization process will be described in

Fig. 2. Cultural landscape examples at Sarmizegetusa.

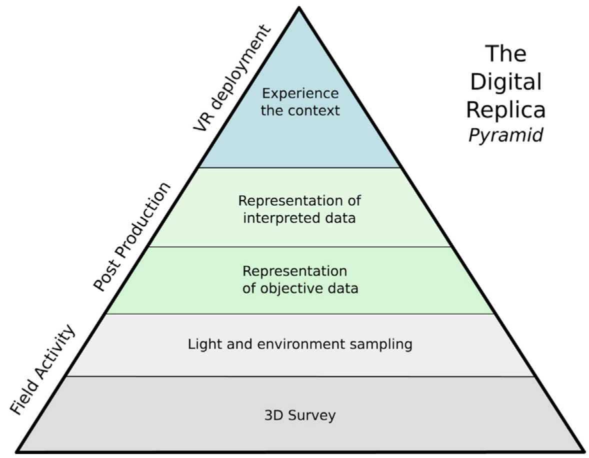


Fig. 3. The digital replica Pyramid summarizes the activities and the outputs involved in the creation of a digital replica.

details. One could sketch out our workflow in a pyramidal scheme (*see* Fig. 3) where every segment is strictly connected to the previous one. At the base are the field activities: all the photogrammetry and reference photography processes require the collection of raw data. In the second segment, is the post-production activity which allows 3D assets and 2D documentation (such as orthophotos, plans, sections) to be created from raw data. The upper segment of the pyramid deals with the production of the VR environment where 3D asset (from photogrammetry and computer graphics) are optimized and integrated to provide the digital replica. This allows the users to experience the “full” heritage site (archaeological remains in their context, namely landscape, vegetation, illumination).

4.1. Survey activities and asset capturing

The field activities and data collection were carried out using a structured and validated workflow used within the VHLab of the ITABC following several archaeological campaigns in Italy and abroad [52]. This section is divided in 3 parts according to the different image-based acquisition techniques: Photogrammetry, Panoramic High Dynamic Range Photography and vegetation sampling.

4.1.1. Photogrammetry

Nowadays several solutions are available for archaeological 3D survey, from photogrammetry [53–60] to 3D scanning [61,62]. Both solutions are exhaustive and perform similar results, but they present peculiar issues, advantages, and disadvantages that must be considered when planning a survey [63, pp. 149–150], [64]. According to the scale of the project, the desired level of accuracy, and the available budget, usually researchers choose between the two solutions or, in some cases, they work with a combination of the two technologies to produce a better outcome resulting in models with a good metric accuracy and true coloured information [65–69]. In our case, according to the type of scanner in our equipment (Faro focus 3D), we prefer not to use laser scanning solutions since the archaeological site to be surveyed is widespread and has many structures. Furthermore, the number of stations to be performed and the number of point clouds to be processed could have demanded too many post-processing resources. Another issue concerning the laser scanner is the colour information which is fundamental in our research project which aims at producing 3D meshes with textures. Even trying to combine the results of laser scanning techniques and digital photogrammetry would have been too laborious in terms of post-processing time, given the dimension of the site. Therefore, considering the peculiarity of the site and the need of a better visual representation of the textures, the photogrammetric solution was chosen as the most suitable approach. Furthermore, since the terrestrial images would have not provided sufficient detail in some areas to cover such a density of architectural remains, we decided to use both UAV and terrestrial photogrammetric approaches (singularly or in combination, according to the situation).

UAV: UAVs are nowadays an important tool for documenting cultural heritage sites and structures, since they allow to acquire high spatial resolution data and to generate reliable documentation in a reasonable time [25]. In our case, the drones used for the aerial survey activities are an octocopter assembled on the top of a Dji Spreading Wings S1000 and a Dji Phantom 2.

The octocopter Spreading Wings S1000 is a professional drone designed for high level photography and shooting.

We used this drone especially for high quality (in terms of resolution and accuracy values, *see* Fig. 7 at pag. 15) architectonic photogrammetry as it can bear professional sensors. The drone is equipped with a universal gimbal6 which permits to take photos from different angles (from 90 to 45 degree) and with a GPS Compass Pro Plus receiver. The drone is very safe and stable during the flight, the S1000’s V type mixer design provides large amounts of propulsion while improving power efficiency, and the DJI flight controllers like the A2 guarantee stability even with the loss of a rotor. The drone has a maximum horizontal speed of 25 m/s, a vertical speed limit of 5 m/s and a maximum wind resistant of <8 m/s (17.9 mph/28.8 km/h). The maximum recommended distance between the remote control and the drone is 500 m in a city and up to 1 km in open field. The drone weighs approximately 4 kg with a maximum takeoff weight of about 11 kg. It can easily carry heavy equipment as the Canon Eos 6D that we currently use in our survey. Used with a 6S 15,000 mAh LiPo battery it can fly for up to 13–15 min depending on the atmospheric condition. The group has four sets of batteries which allow about 50 min of flight. The Ground Station is composed by a team of 3 operators: pilot, pilot assistant, and camera operator. The pilot drives the vehicle using a Graupner MC-20 remote control and a ground station connected with the camera mounted on the drone, while the pilot assistant surveys the flight operation providing aid information such as vertical and horizontal speed, number of satellites available, and battery charge. The camera operator controls the gimbal using a Graupner MX-20 remote controller in order to orient the camera towards the area to be surveyed. The UAV can fly using the remote control in GPS, ATTI or Manual Mode but for this work the GPS mode has been preferred. On this mode the drone uses information from the GPS receiver to better respond to the instructions of the pilot and it keeps a stable position and altitude when it does not receive any command from the ground.

The DJI Phantom 2 is one of the most widely used entry level drone because it is ready-to-use, small, low cost and easy to carry and pilot. On the other hand, this drone cannot be used if the weather conditions are not perfectly stable. The drone has a maximum horizontal speed of 15 m/s and a vertical speed limit of 6 m/s with a communicating distance in open area of 1 km. The drone weighs approximately 1 kg and it is equipped with 12 megapixel Go-Pro Hero 3 Black Edition. It uses 5200 mAh 11.V 3SLiPo battery and it can fly for up to 20–25 min depending on the atmospheric conditions. The group has four sets of batteries, this means about 80 min of flight. It could only be operated in manual mode and needs just one operator but, since it is difficult to know the precise position of the drone in mid-air, at least one assistant following the drone was needed.

Sensors; During the survey we used different sensors according to the instrumentation available in the different campaigns. However, in order to get a homogeneous and consistent dataset, we used identical cameras and lenses throughout the shooting within each context when possible.

The camera mounted on Spreading Wings S1000 and used on terrestrial shooting to integrate aerial dataset is a Canon Eos 6D. It is a full-frame camera and it has a CMOS sensor (36×24 mm) with 20.2 mega-pixel matrix which can capture crisp and high-resolution imagery. The camera is connected to the drone with an Aerial Flex AF-10 Brushless Gimbal. The gimbal allows countering the inclination and vibration of the device due to its movement using the guidance provided by the inertial unit, in this way it maintains the sensor stable. During the survey, the camera was equipped with two fixed lenses: 14 mm and 35 mm. The capture of the pictures was controlled by Magic Lantern, a software add-on that runs from the SD card and adds some features to Canon EOS such as camera intervalometer.[7] Vertical and horizontal movements of the camera were driven by the camera operator who always controlled on his monitor what the sensor was shooting thanks to a micro-camera mounted on the gimbal. The camera mounted on the DJI Phantom 2 was a Go-Pro Hero 3 Black Edition, a low-cost wide-angle camera. The camera has a CMOS sensor size of 1/2.3 inches with 12 megapixels matrix and a focal length of 2.9 mm. It has a built-in intervalometer that can be programmed for timed shots in time lapses. The ultra-wide-angle lens of this camera (170°) is very useful for surveying large surfaces but a camera calibration certificate, to reduce the barrel distortion, is needed before using the pictures. For the terrestrial surveys, we mainly used a Nikon D3S. It is a 12.1 mega-pixel professional-grade full frame camera mounting a CMOS sensor (36.0×23.9 mm) with 12.1-megapixel matrix. During the survey, the camera was equipped with two fixed lenses: 14 mm and 24 mm. The professional quality of the sensor assured high quality and crisp pictures as the correction of lateral chromatic aberration as well.

Topographic survey: Preparatory work for the photogrammetric campaign was the creation of a topographic network (including a series of photogrammetric targets distributed evenly on the structures and measured with a laser Leica total station which allows us to perform distance and horizontal measurements with simultaneous calculation of target coordinates (Northings, Eastings, and Elevations). The format used for the targets was: A4 for aerial photogrammetry, and A5 and A6 for terrestrial photogrammetry.

The total station used is a Leica FlexLine TS06 Plus equipped with an EDM laser class 1 sensor, allowing an angular accuracy of 0.5 mgon and 1.5 mm + 2 ppm on the distances, according to the manufacturer. The topographical measurements of the targets were carried out performing several station positions according to the dimension of every excavation area. Given the large extension and complexity of the site, operating within an absolute coordinate system was mandatory in order to connect dataset coming from different excavation areas and to precisely locate derived orthophotos and DEM. Because of this, the topographic survey was oriented using some ground control points by cementing up on the ground some survey nails whose coordinates were gathered by means of a dual differential GPS South S82V. All the Leica stations were positioned on the mentioned ground control points and oriented using DGPS data in order to compute all the measurements in an absolute referencing system. The coordinate system used for representing the geographic data is Dealul Piscului 1970/ Stereo 70 (Datum: Dealul Piscului 1970 – Ellipsoid: Krassowsky 1940) which is a projected CRS used in Romania "onshore and offshore. Dealul Piscului 1970/ Stereo 70 is commonly used for large and medium scale topographic mapping and engineering survey. Using this local system,

Table 1
Survey campaigns.

	November 2014	April 2015	October 2015
Professionals	4	4	5
Days	4	6	6
Photos	+10,000	+20,000	+15,000
Panoramic Photos	13	12	–
DGPS fixed Points	11	–	18
Targets	52	85	112
Drone used	Phantom	Phantom	PhantomS1000
Sensors	GoPro Hero 3Nikon 3DS	GoPro Hero 3Nikon 3DS	GoPro Hero 4Canon 6D
Flights	20	18	15
Area Surveyed	-Amphitheater -Buildings -The Great Temple -Forum	-Domus Procuratoris -Thermal bath -Temple of Liber Pater -Aesculapius and Hygeia's sanctuary	-North gate -Forum novum -Basilica -Insula -East gate area -Thermal bath
Phantom 2 architectonic scale	36.054 m^2	24.165 m^2	9.034 m^2
Phantom 2 territorial scale	–	142.748 m^2	130.294 m^2
S1000 architectonic scale	–	–	8.572 m^2
Terrestrial survey	12.762 m^2	3.695 m^2	6.347 m^2

we were able to easily integrate in the GIS platform all the available Romanian geographical and archaeological geo-data.

Acquisition procedure After the topographical survey, two types of photographic acquisition were carried out (for the details about the areas surveyed with the photogrammetry approach, *see* Table 1).

The terrestrial was aimed at obtaining high resolution models of structures. Whereas the aerial photographic survey of the site was intended to collect data both for territorial and architectonic scale. The quality of the photos is an essential feature and the level of the post-processed 3D models depends mainly on the photo shooting campaign, as well as on the accuracy of the topographic survey. Therefore, the terrestrial campaign was conducted using two full frame SLR cameras (Canon Eos 6D and Nikon D3S). As a proven strategy of acquisition, we defined a regular path for every building to be surveyed. The path goes firstly around and then inside the monument of interest. The photos were taken at regular intervals, from different angles and with an overlap between pairs of pictures always higher than 70%. This was made in order to sample most of the affected area. The last shot must overlap the first one in order to avoid forgetting to sample some parts and to get a dataset compute in a clear ascending order. This strategy helped the users during the reviewing and selection of the photos before the computing operations.

The aerial campaign was performed both with the Phantom 2 and Spreading Wings S1000 (for the flight set-up, *see* Fig. 4). The latter was purchased only in 2015, thus it was used on the site only during the last campaign for surveying at high resolution the Forum, the Basilica, and the Thermal Bath of the *Domus Procuratoris*. In the previous two campaigns, we used the Phantom 2 to flight over the other areas of the site. We used it either stand-alone (territorial scale) or in support of terrestrial survey allowing the dataset to be integrated. In this case, given the lower quality of the sensor mounted on this drone in comparison with the ones of the SLR Cameras, we used only those photos which were indispensable to complete the parts of the monument lacking photographic coverage (such as the upper parts of the archaeological structures or the top of the wall).

The S1000 required about 30 min of pre-flight routine for assembling all the components "wings, GPS, batteries, camera and ground station monitors" and checking up a potential malfunctioning. The

[7] http://www.magiclantern.fm/.

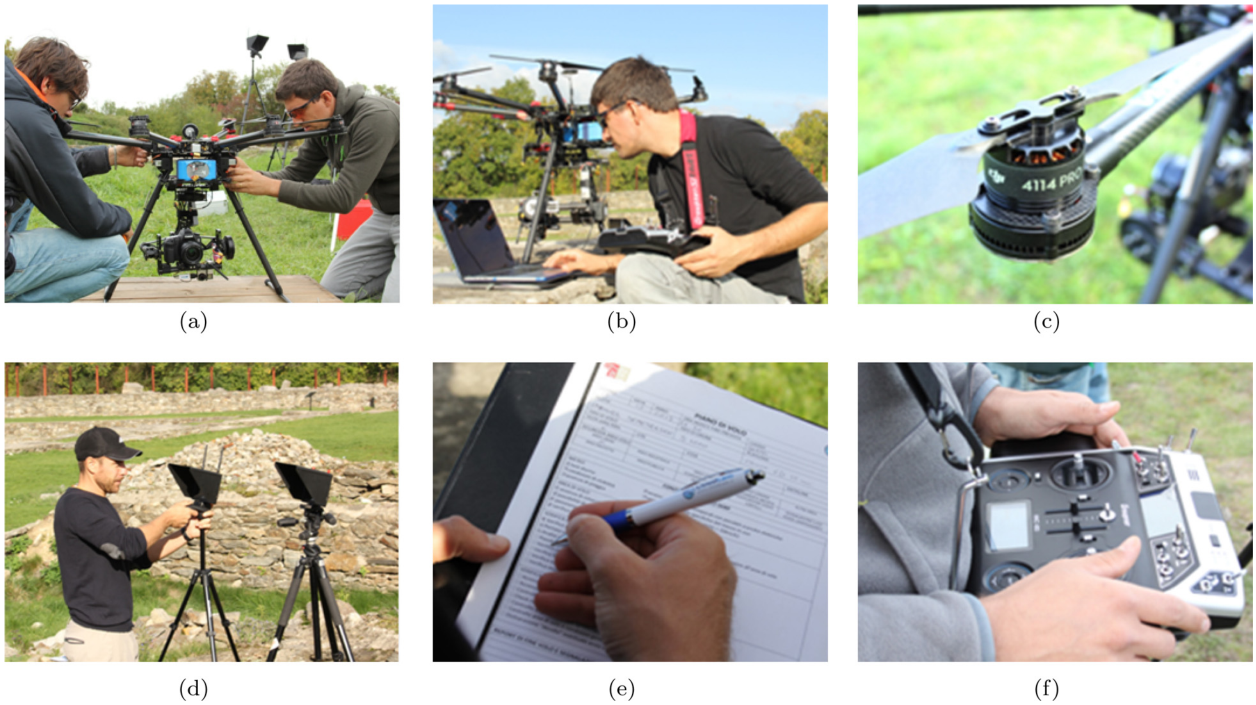


Fig. 4. Pre-flight routine: (a) camera setup and batteries plug-in, (b) fail safe setup, (c) helices and engines check-up, (d) ground station assembling, (e) flight plan preparation, (f) flight console check-up and engine power-on.

mounted Canon Eos 6D was programmed to take 1 photo every 2 s. The drone was piloted manually at approximately 5 m from the ground level to get the resolution of the photos close to one centimeter, and at an average speed of 4 m/s.

Both acquisitions were performed in the best light conditions possible according to season, preferably taking advantage of diffuse light (cloudy days) or in the absence of hard cast shadows, then avoiding the acquisition in the central hours of day. After some tests made to check the appropriate settings (to be remaining fixed throughout the shooting), we generally adopted an exposure time of between 1/400 and 1/800 with f/8 of diaphragm aperture (setup before the takeoff according to the light conditions). The ISO was selected at 400 in order to avoid noise in the pictures (aberrant pixels). In very few cases the campaign encountered exposure or white balance issues. The use of photographic RAW formats allowed a post production work (semi-automatic) for post-processing adjustment through the open source software Darktable: this solution has made it possible to obtain a homogeneous result (from an image-exposure point of view) for texture-building and parametrization of 3D models. The site was surveyed also at territorial scale using the Phantom 2. It was piloted manually at approximately 20 m or more (according to the site and the presence of forest trees) from the ground level. Even in this case, the installed GoPro camera was programmed to take 1 photo every 2 s using the built-in intervalometer to produce images with more than 70 percent overlap. The camera was set up in automatic mode (ISO and exposure) with a fixed focal length of 2.8 mm and using the widest lens angle (170°).

4.1.2. Panoramic high dynamic range photography

An important goal for our work, once obtained the 3D model of the monuments that we had surveyed, was to simulate also the environmental light conditions in image-based rendering applications to improve their realism and explore them in realtime [70]. To make it possible we had to record incident light and produce omnidirectional HDRI (High-Dynamic-Range Images). HDRI is a technique used in photography to reproduce a greater dynamic range of luminosity which aims at representing the similar range of luminance perceived by human vision which constantly adapts the eyes to the range of luminance of the surrounding environment. This kind of images is even adopted in computer graphics (often called "radiant map"). Render engines allow HDRI to be used to light up 3D models and virtual environments for realistic compositing, indeed.jpg images do not have enough dynamic range to represent the brightness of the sky and the sun. According to our purposes, we performed a special kind of HDRIs, called "Light Probes", which is a panoramic HDRI that records the incident light at a particular point in space. Practically, it is the result of merging a sequence of photographs taken with different intensity levels of a mirrored ball where the skylight and the panorama can be seen in all directions. This method would allow us to render the 3D models of the monuments with true illumination values data and sky backdrop (local outdoor light conditions and intensity with the correct dynamic range) improving the realism and correctness of the virtual scene (*see* Section 4.2.2, [71], and [72]).

In order to perform omnidirectional HDRIs, multiple photos of a steel mirror sphere with a diameter of 15 cm were taken shooting on a tripod from two different POVs (Point Of View). Two POVs were needed due to the following problems: objects reflected near the edge of the sphere are extremely distorted, giving a poor image when it is unwarped. Furthermore, in the center of the sphere there was the reflection of the photographer. To bypass these problems, two HDRIs of the mirrored sphere from different angles were needed, so that during the post production process, the two HDRIs can be aligned and the areas of poor sampling removed.

The ISO was selected at 200 in order to avoid noise in the pictures and the exposure time was spanned 15 stops, from 1/8000 up to 2 s, with *f*/5.6 and 250 mm of focal length. In this way, for every POV, we gathered a photographic dataset with different intensity levels (Low Dynamic Range Images) then each of them was merged together to obtain HDRIs (*see* Section 4.2.2, for the technical aspects, *see* [73]).

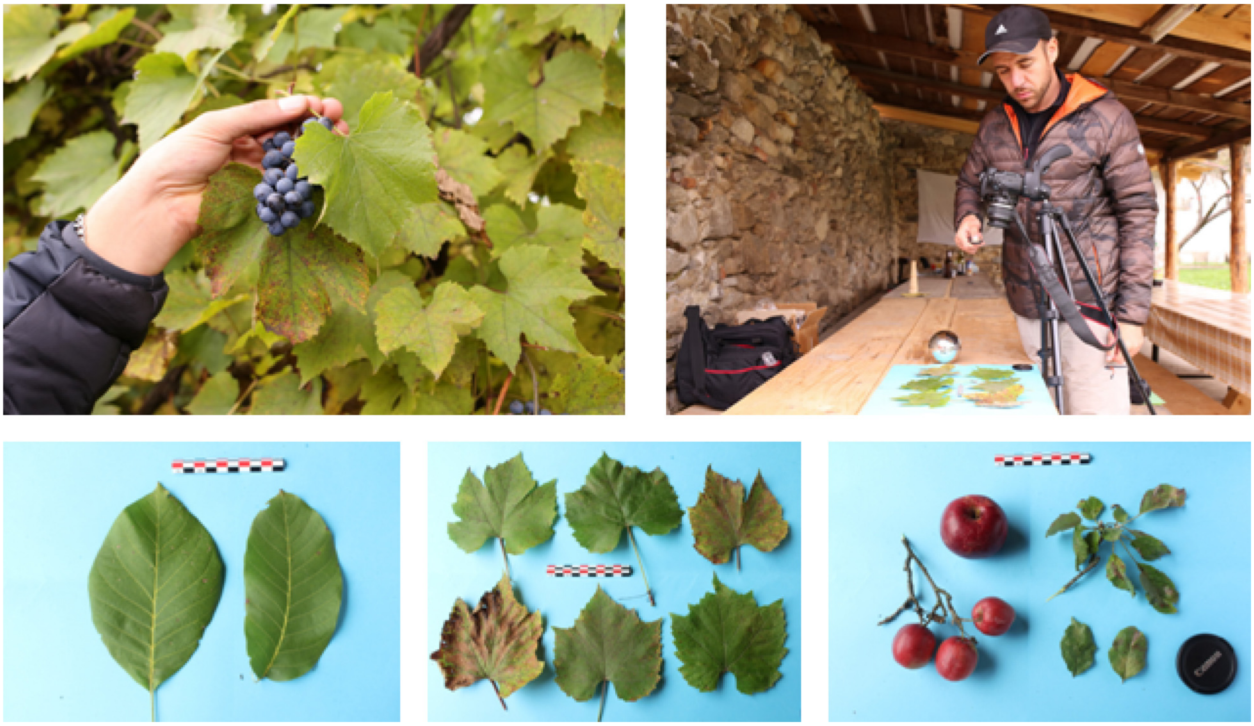


Fig. 5. Gathering sample of the local vegetation.

4.1.3. Vegetation sampling

In order to completely acquire the present environment and perform a better visual quality of the landscape model by placing local plants in their position, we recorded and modelled also the vegetation as well (barks and leaves). A library of the local flora was gathered directly on the field by sampling the most prevalent vegetal species, from trees to bushes like *Robinia Pseudoacacia*, *Malus Domestica*, *Juglans regia*, *Prunus Spinosa* and *Vitis Vinifera*. As in Fig. 5, the reference photography was done directly on the field: behind the leaves, a chroma-key backer board was set up in order to easily remove their backdrop in post-production; a colour checker for colour calibration and a metric scale as geometric reference were included in the photos. The camera was equipped with a lens of 35 mm and set up with f/16 of diaphragm aperture to guarantee deep depth of the field and to avoid blurred photos.

4.2. Post-processing and digitization

This section faces the thorny problem of post-processing such amount of complex and mixed data and obtaining 3D cultural assets to be used for documentation and visualization purposes. Therefore, we will proceed step-by-step describing all the problems, choices and solutions performed to get the result.

4.2.1. IBM

Image processing required a long work divided in several steps. The entire dataset of images was divided into different by groups corresponding to the names of the individual monuments. Then, we checked the photos and we made a selection in order to avoid an exaggerated redundancy resulting in a long time of computing. For each group, the photos were imported within Agisoft Photoscan (ver. 1.26), a dense image matching software, to perform the alignment of the pictures and create the photogrammetric model (*see* Fig. 6) and the workflow was set up as follow.

Firstly, we ran the camera matching process, then we obtained a sparse cloud as result of the alignment. During the photo alignment, Photoscan automatically finds tie points and estimates intrinsic and extrinsic camera parameters. The time computing necessary to produce the dense stereo matching model depended mainly on the number of photos and on the hardware. For example, using a Workstation equipped with an Intel core i7 260 GHz, 64 Gb Ram and Nvidia Gtx 960 and using a dataset of 500 photos, jpg format 5472x3648 px, it took about 8 h of computing for the matching process. Many factors can affect the accuracy of the model, such as blurred or under/over-exposed photos and, above all, the quality and distortion of the camera lenses. Given that, we estimated the image quality using the internal algorithm of Photoscan for each image disabling the ones out-of-focus. Then, the ground control coordinates of the targets were manually identified on the corresponding photos. This step allowed to set the coordinate system providing a correct scaling and geo-referencing of the model. After these first steps, we improved the camera calibration, in order to minimize possible photogrammetric errors, applying the following procedures:

- excluding photos that have obvious alignment problems;
- using point cloud filters, to find out points with high re-projection errors or removing points which present a high amount of noise, using these criteria:
  - reprojection error;
  - photogrammetric reconstruction uncertainty;
  - image count;
  - projection accuracy;
- running the optimization procedure (optimize cameras) to re-estimate intrinsic and extrinsic camera parameters.

Dense point cloud building: Once obtained the alignment and checked the residual errors, unwanted areas in the photos were masked, like the borders of the GoPro images, which have high lens distortions, and obstacles such as people, signals, trees were masked as well. The redundancy of the photos ensured a sufficient overlap despite the masked areas. After these precautions, the dense point clouds were calculated.

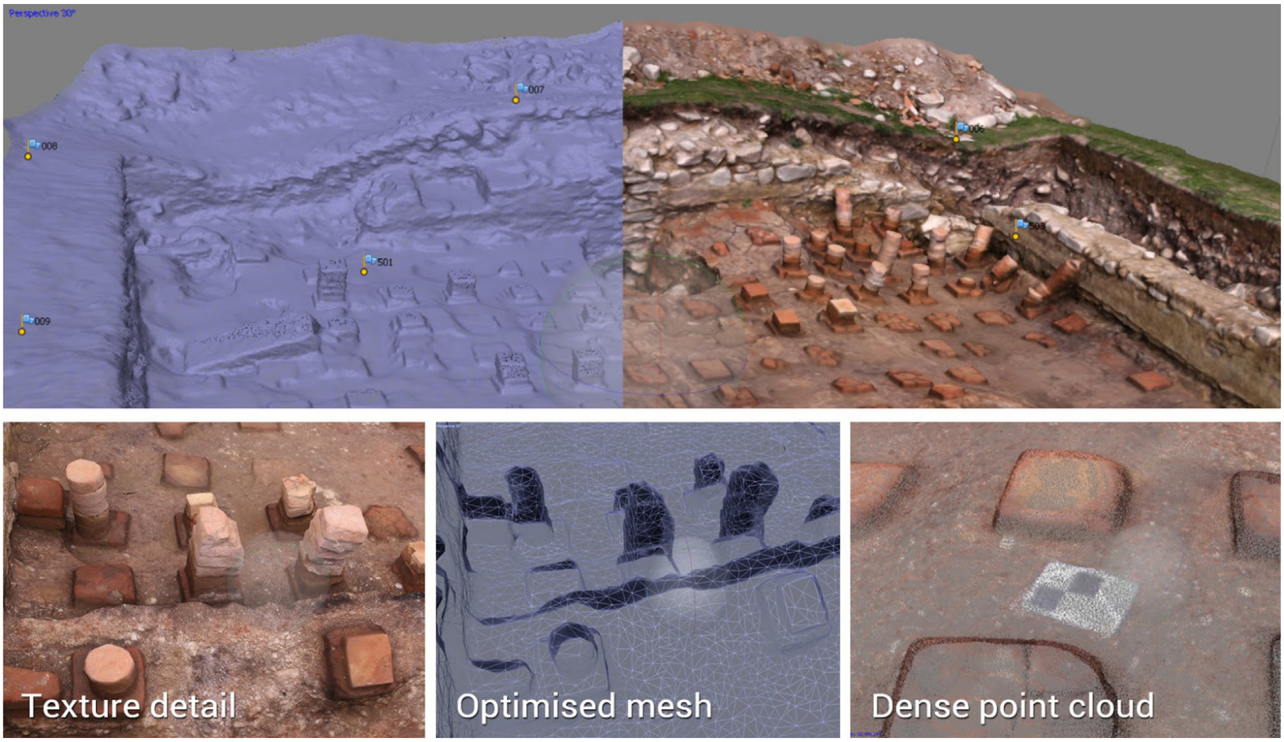


Fig. 6. Post-processing workflow from dense point cloud to textured mesh.

The dense point clouds were treated out of Photoscan within *CloudCompare* 2.08[8] (a 3D point cloud and a triangular mesh processing software). While exporting the dense point clouds, we use the "shift" function which allows to set the value to be subtracted from the respective coordinate value for every vertex in the cloud, providing them with a reasonable position to the origin. This coordinate translation was extremely important for exchanging data and processing them in the 3D processing software. Indeed, these editors usually do not manage geospatial models. In all our clouds we truncated the coordinates values of 6 numbers: x 327,300, y 448,370, z 0. These coordinates approximately correspond to the *locus gromae* (the ancient city centre) of Sarmizegetusa. Thereafter, in order to correct small errors due to matching problems or subsamples (among the others, duplicate vertices and uneven density), we applied the following steps:

- manual cleaning of isolated points;
- uniforming the point density;
- outliers removal filtering;
- de-noise filtering;
- normals computation and reorientation (in case of not properly oriented normals).

The point cloud is in and by itself a usable output to achieve many metrology purposes, inspections, and visualizations.

Polygon mesh building: After the optimization of the dense point cloud, the mesh was calculated using Poisson Surface Reconstruction [46]. The mesh reconstruction was first performed at the highest level of detail and subsequently was reshaped (closing small holes, elimination of non-manifold edges, spikes, self-intersection and double faces). The polygon mesh was finally optimized with the use of re-meshing filters which allow to reduce the number of polygons, thus preserving the level of detail of the parts with a more complex geometry and architectural details (boundary and shapes). This method allows the models to be simplified facilitating the rendering performance, transmission bandwidth, and storage capacities.

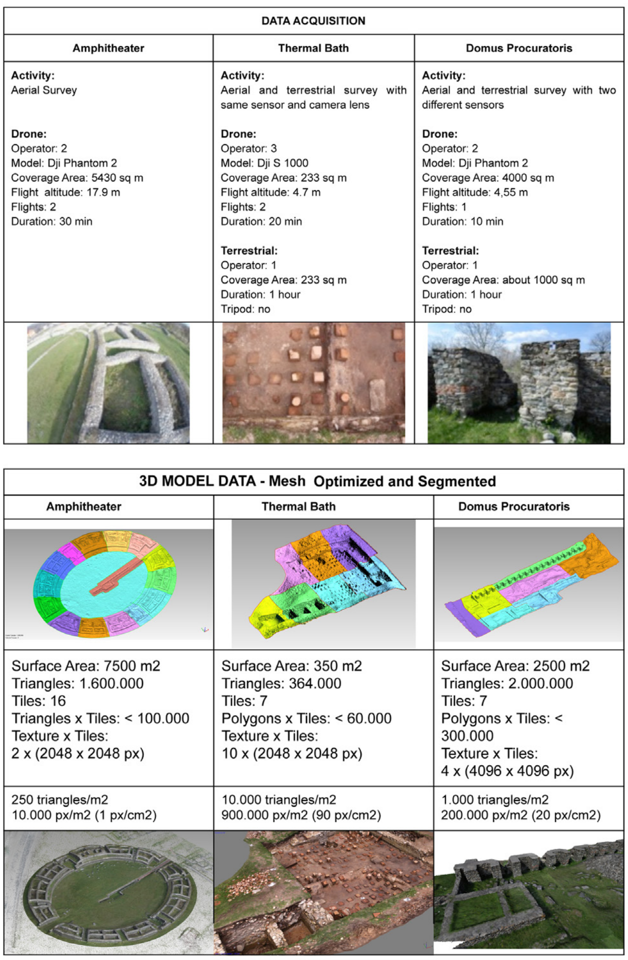
Finally, the models were segmented in order to perform the first steps towards the creation of 3D assets ready for realtime exploration. This procedure can be managed automatically in Photoscan but we preferred to do it manually using cutting tools for several reasons:

- to better control the position of the cutting line and to separate structures from terrains;
- to better control the subsequent texturing step (*see* next paragraph);
- in view of the future integration of the city scale model in realtime rendering engines and web viewers.

Texture mapping: Once the modelling tasks were terminated, we returned the mesh to Photoscan for the parametrization of the model and the generation of high resolution textures. During these import steps, we added the earlier subtracted "shift" numbers in order to assign again the geospatial information. Before using texture building algorithms, we made a first selection of the images for the computation in order to get the best visual quality possible of the final model. We disabled images with evident low resolution in the area of interest and images with strong light contrasts as well. Then, as texture generation parameters, "Blending model" was selected to combine the images, and "Average" was used to select the way how pixels are combined in the atlas texture (it uses the weighted average value of all the pixels from individual images).

Case studies: A schematic description of three context cases (*see* Fig. 7(a)) surveyed using different sensors (*see* Fig. 7(b)) will follow in order to show the result achieved according to different situations. We have experimented with different resolutions and contexts trying to figure out if they fit within the main outputs:

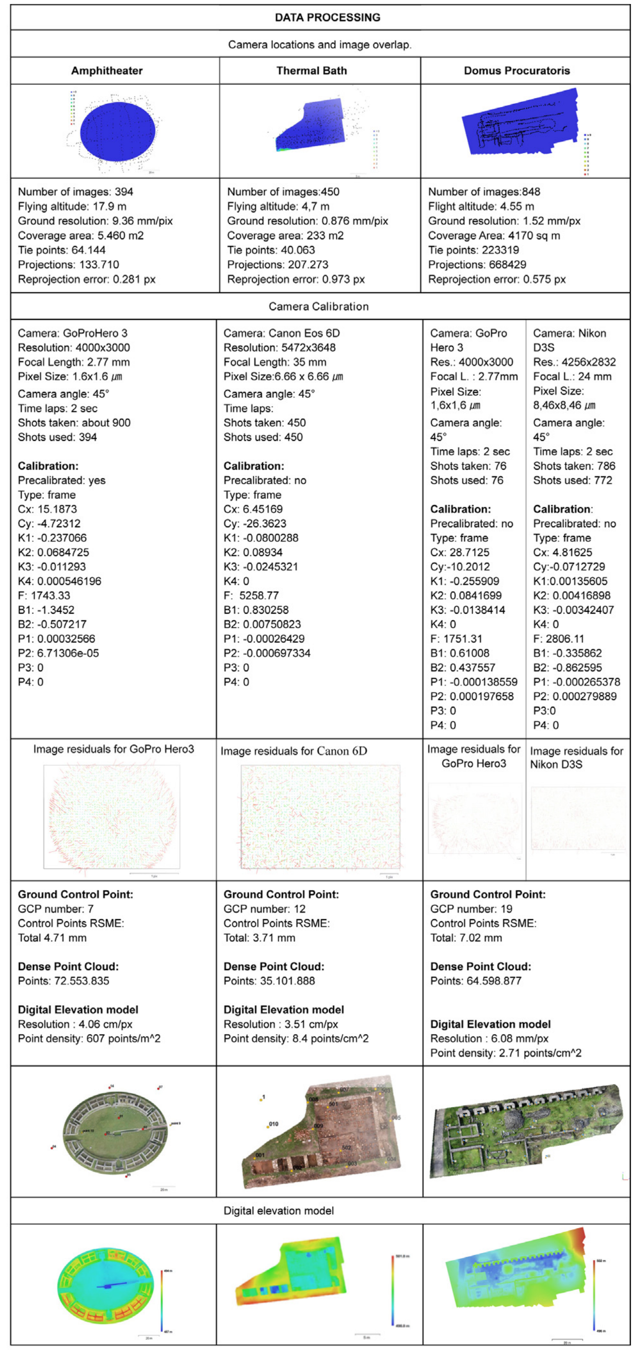
[8] http://www.cloudcompare.org/.



DATA ACQUISITION		
Amphitheater	**Thermal Bath**	**Domus Procuratoris**
Activity: Aerial Survey **Drone:** Operator: 2 Model: Dji Phantom 2 Coverage Area: 5430 sq m Flight altitude: 17.9 m Flights: 2 Duration: 30 min	**Activity:** Aerial and terrestrial survey with same sensor and camera lens **Drone:** Operator: 3 Model: Dji S 1000 Coverage Area: 233 sq m Flight altitude: 4.7 m Flights: 2 Duration: 20 min **Terrestrial:** Operator: 1 Coverage Area: 233 sq m Duration: 1 hour Tripod: no	**Activity:** Aerial and terrestrial survey with two different sensors **Drone:** Operator: 2 Model: Dji Phantom 2 Coverage Area: 4000 sq m Flight altitude: 4,55 m Flights: 1 Duration: 10 min **Terrestrial:** Operator: 1 Coverage Area: about 1000 sq m Duration: 1 hour Tripod: no

3D MODEL DATA - Mesh Optimized and Segmented		
Amphitheater	**Thermal Bath**	**Domus Procuratoris**
Surface Area: 7500 m2 Triangles: 1.600.000 Tiles: 16 Triangles x Tiles: < 100.000 Texture x Tiles: 2 x (2048 x 2048 px)	Surface Area: 350 m2 Triangles: 364.000 Tiles: 7 Polygons x Tiles: < 60.000 Texture x Tiles: 10 x (2048 x 2048 px)	Surface Area: 2500 m2 Triangles: 2.000.000 Tiles: 7 Polygons x Tiles: < 300.000 Texture x Tiles: 4 x (4096 x 4096 px)
250 triangles/m2 10.000 px/m2 (1 px/cm2)	10.000 triangles/m2 900.000 px/m2 (90 px/cm2)	1.000 triangles/m2 200.000 px/m2 (20 px/cm2)

(a)



DATA PROCESSING			
Camera locations and image overlap.			
Amphitheater	**Thermal Bath**	**Domus Procuratoris**	
Number of images: 394 Flying altitude: 17.9 m Ground resolution: 9.36 mm/pix Coverage area: 5.460 m2 Tie points: 64.144 Projections: 133.710 Reprojection error: 0.281 px	Number of images:450 Flying altitude: 4,7 m Ground resolution: 0.876 mm/pix Coverage area: 233 m2 Tie points: 40.063 Projections: 207.273 Reprojection error: 0.973 px	Number of images:848 Flight altitude: 4.55 m Ground resolution: 1.52 mm/px Coverage Area: 4170 sq m Tie points: 223319 Projections: 668429 Reprojection error: 0.575 px	
Camera Calibration			
Camera: GoProHero 3 Resolution: 4000x3000 Focal Length: 2.77 mm Pixel Size: 1.6x1.6 µm Camera angle: 45° Time laps: 2 sec Shots taken: about 900 Shots used: 394 **Calibration:** Precalibrated: yes Type: frame Cx: 15.1873 Cy: -4.72312 K1: -0.237066 K2: 0.0684725 K3: -0.011293 K4: 0.000546196 F: 1743.33 B1: -1.3452 B2: -0.507217 P1: 0.00032566 P2: 6.71306e-05 P3: 0 P4: 0	Camera: Canon Eos 6D Resolution: 5472x3648 Focal Length: 35 mm Pixel Size:6.66 x 6.66 µm Camera angle: 45° Time laps: Shots taken: 450 Shots used: 450 **Calibration:** Precalibrated: no Type: frame Cx: 6.45169 Cy: -26.3623 K1: -0.0800288 K2: 0.08934 K3: -0.0245321 K4: 0 F: 5258.77 B1: 0.830258 B2: 0.00750823 P1: -0.00026429 P2: -0.000697334 P3: 0 P4: 0	Camera: GoPro Hero 3 Res.: 4000x3000 Focal L. : 2.77mm Pixel Size: 1,6x1,6 µm Camera angle: 45° Time laps: 2 sec Shots taken: 76 Shots used: 76 **Calibration:** Precalibrated: no Type: frame Cx: 28.7125 Cy:-10.2012 K1: -0.255909 K2: 0.0841699 K3: -0.0138414 K4: 0 F: 1751.31 B1: 0.61008 B2: 0.437557 P1: -0.000138559 P2: 0.000197658 P3: 0 P4: 0	Camera: Nikon D3S Res.: 4256x2832 Focal L.: 24 mm Pixel Size: 8,46x8,46 µm Camera angle: 45° Time laps: 2 sec Shots taken: 786 Shots used: 772 **Calibration**: Precalibrated: no Type: frame Cx: 4.81625 Cy:-0.0712729 K1:0.00135605 K2: 0.00416898 K3: -0.00342407 K4: 0 F: 2806.11 B1: -0.335862 B2: -0.862595 P1: -0.000265378 P2: 0.000279889 P3:0 P4: 0
Image residuals for GoPro Hero3	Image residuals for Canon 6D	Image residuals for GoPro Hero3	Image residuals for Nikon D3S
Ground Control Point: GCP number: 7 Control Points RSME: Total 4.71 mm **Dense Point Cloud:** Points: 72.553.835 **Digital Elevation model** Resolution : 4.06 cm/px Point density: 607 points/m^2	**Ground Control Point:** GCP number: 12 Control Points RSME: Total: 3.71 mm **Dense Point Cloud:** Points: 35.101.888 **Digital Elevation model** Resolution : 3.51 cm/px Point density: 8.4 points/cm^2	**Ground Control Point:** GCP number: 19 Control Points RSME: Total: 7.02 mm **Dense Point Cloud:** Points: 64.598.877 **Digital Elevation model** Resolution : 6.08 mm/px Point density: 2.71 points/cm^2	
Digital elevation model			

(b)

Fig. 7. Data acquisition (a) and data processing (b) comparison between three different datasets (Amphitheatre, "*Termae*", *Horreum*) including 3D model data output (a).

representation of 1:50 architectural and realistic[9] visualization through virtual reality devices. For all the acquired datasets we have verified the possibility of obtaining 2D drawings in 1:50 scale. For the Amphitheatre, only the dataset acquired by a Phantom drone at a flight altitude of 15 m and equipped with a GoPro Hero 3 camera was used. The geometry is suitable to produce 2D drawings in scale 1:50 but the textures have a density of about 1 px/1 cm^2, and it is not sufficient to satisfy the criterion of credible visualization through virtual reality devices.

The quality of the geometric data and the texture are obviously improved using reduced flight altitude, better quality of the sensors, reduced FOV (Field Of View) and integrating terrestrial photos in the dataset. In the second case, in fact, in addition to a more precise geometric data we have a considerable jump resolution of the textures, about 1 px/1 mm^2. For large areas the phase of acquisition by drone was privileged, then a terrestrial photographic campaign was carried out to reach the parts that had not been photographed. The extension of the area to be acquired plays a decisive role for the timing, but it is not a directly proportional relation. The complexity of

[9] The term "realistic" means that an environment is coherent with the visual expectation of the human eye as defined in the lighting and rendering guidelines used in the CG domain [74].

the structures and the visibility from the drone have a huge impact to the timing acquisition.

In general, acquisition times are considerably reduced if a topographic support network is already present and if the targets have already been positioned on the site. The photogrammetric processing data timing is a tricky issue, since there is a big difference of timing among the different work-stations. The most time-consuming operations are the manual operations like the point cloud editing and the mesh optimization.

Technical drawings: As first outcome of the post-processing procedure, we produced high resolution 3D models useful for obtaining archaeological and architectural technical documentation. We will not deepen this aspect since we prefer to focus the attention on other innovative results in the next section. however, here it follows a list of the technical documentation derived from 3D models:

- high-quality aerial georeferenced photographs of the area to be used in GIS software;
- Digital Surface Model (DSM) for landscape analysis;
- projected orthophotos of the buildings;
- blueprints of the buildings;
- sections of the buildings.

4.2.2. HDRI post-processing

In order to process the images of the mirrored ball to create panoramic HDRI, we used HDRShop v.1 software. Using this tool, we assembled HDRI from the image sequence taken on the field at different intensity levels. HDRShop calculated the relative and absolute stops and scales for every image in the sequence using the EXIF metadata resulting in a single image with a greater dynamic range. As mentioned in Section 4.1.2, we shot two image sequences from two different POVs taken 90° apart from each other. As a matter of fact, the mirror sphere used to capture the panoramic image also recorded the reflection of the photographer and of the tripod. Shooting the same panorama from different positions allowed regions of interference to be recorded in different locations in the image sequences, so that they can be removed in the software. We proceeded as follows: once obtained the two HDRI of the mirrored sphere, we cropped the resulting images to the edge of the sphere and we aligned them in a semi-automatic way using corresponding points. This process allows the software to un-warp and rotate the two HDRI to match each other. Once matched, we covered up the interferences by using a mask and merged the two images in the resulting light probe (angular map). Eventually, the mirrored ball image was also re-sampled into an equirectangular HDRI panorama, another panoramic image format that displays 360° along the horizon, 90° up and 90° down, in a single image with an aspect ratio of 2:1. This HDRI format is usually supported by the majority of the rendering engines.

As described in the next section, panoramic HDRI were used in the virtual environment, taking advantage of the global illumination rendering algorithms [72] to light the 3D models of the monuments in the realtime application, thus obtaining photo-realistic results. Indeed, standard images with low dynamic range like.jpg, have a small range of brightness, from 0 to 255 and should not be used as light emitter in virtual environments. Using a.jpg to light a 3D scene, the details are lost in the brighter parts, thus resulting in a faded rendering which is poor of contrast. The advantage of using HDRI is that the maximum brightness is practically infinite, and this ensures an accurate and realistic lighting and truthful colours and reflections. Furthermore, producing our own HDRI as environment map we could also simulate the real background of the site improving the sense of immersion [75].

4.3. Computer graphics

The models produced through geomatic methods and techniques have been imported inside Blender,[10] a free and open source 3D creation suite.[11] In this project computer graphics techniques have been operated using "3D Survey Collection" (3DSC), an open source add-on,[12] based on python 3 and developed *ad hoc* for the fast editing, cleaning, and optimization of meshes and textures according to the technical requirements of a realtime output. In other words, the 3DSC helps the researchers to create consistent assets to be used in digital replicas using models that come from a photogrammetric workflow. In order to avoid undesirable cropping in the numerical precision of the coordinates, the models are shifted from the geographic coordinate system (Dealul Piscului 1970/Stereo 70 EPSG:31700) imposing an arbitrary local center of the 3D scene near the *locus gromae* of the city. The 3DSC tool has several sections: an importer, an exporter, quick utils, a colour correction tool, photogrammetry tools and a LOD generator.

After importing, further optimizations on the textured models are performed in order to fix texture issues, such as un-sampled areas, texture blending fails, and seam lines problems depending on different exposure among the atlas textures. Some small corrections are done using the internal 3D painting system and the 3D clone tool, while bigger issues are amended with the *photogrammetric tool*: this instrument allows to import and manage the cameras coming from a photogrammetric software, it associates each camera with its corresponding image. Thus, it let the user better adjust the camera calibration and it makes it possible to re-project the selected image over the model. Optionally, it opens a runtime instance of an image editing software (i.e. Adobe Photoshop, Krita, or Gimp) to allow the user to refine the colour and/or the image border adjustment before he re-projects the image on the model. In the case of colour differences between two adjacent meshes due to varying lighting conditions (as well as different moment of the day/year, datasets, or white calibrations) the *colour correction tool* allows a responsive realtime editing of dozens materials from all the selected objects at once through the RGB colour curve, hue-saturation-value, and bright-contrast interactive tools (once the colour of the shadows/lights and tone of the textures are balanced (for the general criteria *see infra* footnote 9), the new colour configuration is baked on a new set of textures and applied to the model). Once the models are correct and the continuity between the different datasets is visually consistent, the LOD generator tool allows to create levels of detail targeting realtime visualization. All the tools mentioned above have a verbose output in the Blender system console that provides information on the running tasks and related time statistics.

3D asset modelling: Landscape and ecosystems representation improves significantly the realism of a virtual world and the sense of presence in an interactive application. In order to replicate the local natural environment which incorporates the archaeological site, an organic procedural generator software (Xfrog[13]) was used. This software permitted to create a library of organic models of local vegetation (trees and bushes) with multi-level branching structures to give them a realistic look. The photos of barks and leaves captured during the field sampling were masked by detecting the edging of every leaf. Thanks to the chromakey backer board, setup during the shootings, this kind of selection was done

[10] Using obj/mtl mesh/materials and png images as interchange formats.
[11] https://www.blender.org/.
[12] E.Demetrescu, Blender 3D Survey Collection Addon (3DSC), 2018, https://github.com/zalmoxes-laran/3D-survey-collection (Blender 2.80). The add-on uses the Blender internal API to call C++ functions.
[13] https://xfrog.com/.

(a)

(b)

Fig. 8. Screenshots from Unreal Engine 4 with the **realtime** digital replica model illuminated using an High Dynamic Range image acquired on the site: (a) Termae, (b) Domus Procuratoris.

in a semi-automatic way using colour range selection tool. Once selected, we easily removed the background obtaining.png texture of the leaves. After few steps of colour correction, the obtained textures were used for mapping the digital models of the trees enhancing their photorealism. This way we could produce a digital library of 3D assets ready-to-use to be arranged and/or instanced in the virtual scene.

Concerning other man-made assets, like sheafs or fences, we adopted a mixed approach. Firstly, we processed dataset of photos using the same image-based modelling workflow mentioned above (*see* Section 4.2.1 at page 11) which allows to get 3D models from imagery, and then the models obtained were imported in Blender. The geometry was here optimized using the sculpting mode option which permits to modify the surface of the models with additive or subtractive effects, using different brushes (instead of editing individually vertices, edges, or faces). Each of these brushes were used with the Dyntopo option activated. This option permits a dynamic re-topology of the surfaces to be carried out altering the mesh topology while sculpting. Thus, lowering the detail size of the triangles that compose the mesh, it was possible to operate manually performing a selective decimation of the polygons, reducing redundant geometry only where needed. Using the texture bake tool, original textures of the acquired models produced in Photoscan were re-projected onto the low-resolution meshes. During this process, geometric details of high-resolution meshes were baked onto normal maps in order to accurately simulate lighting using low-resolution meshes created in Blender.

4.4. Visualization tools and output

When dealing with interactive visualization of large environments, segmentations of 3D assets and hierarchical out-of-core organizations for multi-resolution are commonly employed [76,77]. When properly organized and fine-tuned, under certain circumstances, such approaches theoretically allow the resolution of "limitless" environments at runtime. Creating an interactive experience for a great capital of the ancient world (33 ha) fits exactly in this scenario. All the assets have been optimized (both geometries and textures) using a multi-resolution approach (creation of 3 LODs) and according to a given spatial and hierarchical structure designed on the top of the blueprint of the ancient city. The models have been divided into two main groups:

- reality based models (unique models from photogrammetry);

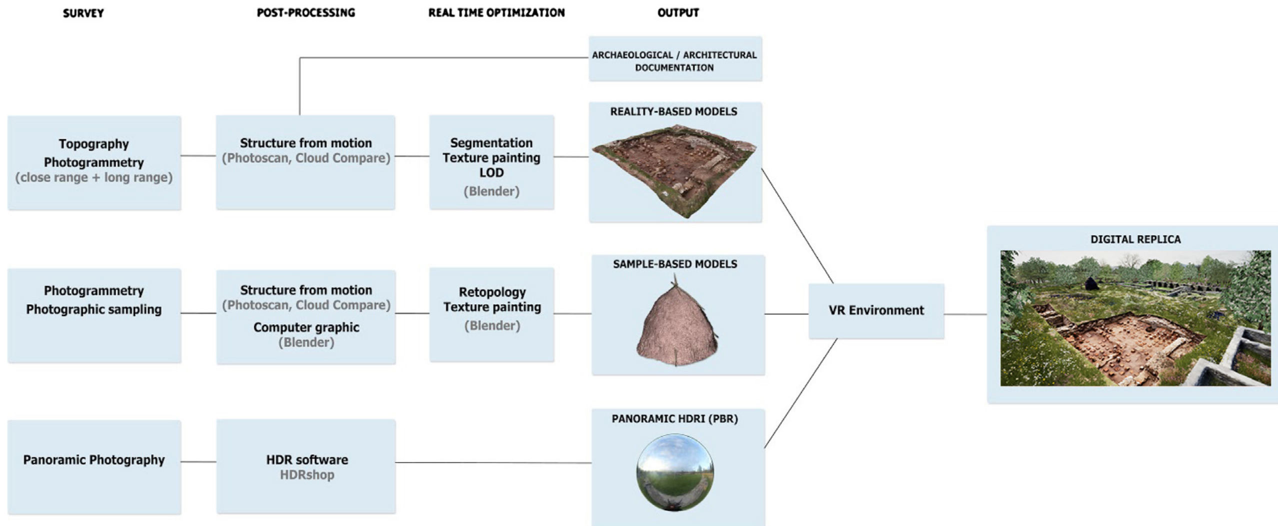


Fig. 9. Digital replica workflow.

Fig. 10. Monuments (a) and sites (b) surveyed and their outputs: technical blueprints/sections (c) and models optimized through a LOD approach (d).

- sample-based models (reusable assets as instanced elements with parametric rules) such as trees, rocks, and sheafs.

5. Results

A first result of our research is the creation of a digital replica of a unique archaeological site experimenting a new approach to document, communicate, and perceive cultural heritage of an emerging European country. Up to now nine contexts are integrated within the digital replica of Sarmizegetusa (Fig. 10).

The workflow described in the last sections and summarized in Fig. 9, was adopted for the first time to develop realtime applications conceived for public usage inside museums. They allowed users to explore the digital replica of present site and search for artefacts discovered during excavations. The main installation, which integrated some of the mentioned scenarios collected on the ancient Roman city (*Domus Procuratoris*, thermal bath and the temples), was deployed within the temporary exhibition in collaboration with MNIT (Muzeul National de Istorie a Transilvaniei) "Turn on the History" in 2016[14] [51].

The adopted workflow allowed also two additional output segments for the produced hierarchical paged assets: (a) immersive VR and (b) web-based presentation and dissemination. The objective of (a) was to offer immersive experiences of the site through the use of VR HMDs, including a full sense of presence inside a large, high-detailed, and complex virtual environment. Regarding (b) output, the ATON 1.0 front-end (HTML5/WebGL)[15] was employed to offer multi-touch inspection of selected items on smart-phones and tablets through the use of qr-codes inside the exhibition. The same front-end was employed to present on desktop browsers (Firefox 55, Chrome 58) the final or iterative results of the processed datasets, also enriched with the built-in annotation system offered by the system itself. Such features were employed to present rich and spatialized multimedia annotations (among others, images, audio, and videos) that fit well in the on-line presentation requirements. In this context, multi-language audios and texts (English and Romanian) as well as reference photos of the original items located in the museum, were also included.

6. Conclusions

Our approach was aimed not only to maintain the data as close as possible to reality, but also to record and include the "experience" that can be gained on the field while walking around the archaeological site (crops, pastures, areas with monuments, ethnographic elements such as sheaves of straw made by hand). In other words, we wanted to keep together the data collected from real world and their photo-realistic visualization. We believe that this approach could allow a better understanding of the site: it offers a synoptic view of the data and it makes it possible for the user to undergo a subjective experimentation, within certain limits and, consequently, to make some analyses that are generally only possible through an "autopsic" visit. The subjective experimentation of the context allows the final user to extract further data and evaluations from the context itself, according to his knowledge, and elements that are not foreseen by us in our grid. An example of this *a posteriori* data generation is the planning of possible further relevant activities taking into account the location of the data already present and the evaluation of areas still to be investigated (the visualization tool becomes an instrument for further analysis in the hands of the researcher who uses the digital replica).

New technologies like UAV systems, Dense Image Matching, computer graphics tools and methods, PBR and Virtual Reality were mixed and used in order to design a flexible workflow to create digital replicas, suitable both for documentation and visualization purposes.

The visualization of city scale archaeological contexts led to a workflow involving the use of scene-graph based frameworks and applied out-of-core techniques to deliver high performance visualization even on low-end machines and mobile devices. The desktop 3D software leveraged on the OpenSceneGraph framework, employing its paging level-of-detail mechanics to offer smooth and fluid experiences to the visitors while maintaining a small memory footprint even on low-end machines. Besides geometrical details and out-of-core techniques, additional care was dedicated to graphics resources management at runtime:

1. texture compression through DDS format (S3TC), offering fast decompression on modern GPUs;
2. minimization of OpenGL state switching, by employing progressive texture merging for upper level-of-details.

6.1. Current directions

Previous results and the realism required by the modern approaches in interactive 3D fruition, led us to consider game engines such as Unreal Engine 4, in order to deliver an improved, multi-layered digital replica of the site – *see* Fig. 8(a) and (b). Current efforts are specifically focused on the novel workflow, including ingestion, processing, scene dressing and automation targeting interactive 3D applications. Nowadays, more content makers are including realtime engines in the assembly line for an interactive visualization as it is demonstrated by the active development of solutions to integrate technical workflows (among the others, engineers, architects) and reality-based contents as in the case of the Unreal Studio[16] which provides a fast conversion tool from CAD software to Unreal Engine (Unreal Datasmith).

About the instancing techniques for vegetation assets employed in the previous section, an Unreal plug-in[17] (already developed within the VHLab) is being used, preserving the familiar workflow with the 3D modelling tools. The plug-in offers common ASCII file loading with parsing options, procedural rules (among the others, randomizers, modifiers), cascading processing and more.

6.2. Limits of current digital replica workflow

Although the *digital replica approach* resulted to be homogeneous and well applicable to the case study of Sarmizegetusa, there are various aspects of the *digital replica workflow* that still need to be addressed. The representation of 3D assets requires minimum resolutions in terms of geometry and texture resolution to make it possible to use them in order to do not loose significant information as well as the embodiment experience. Despite the effort made in the Sarmizegetusa project to create guidelines that regulate the number of polygons and the quantity of texture-pixels per square-meter, we decided for a more structured treatment of the subject in a next paper. Another aspect that remains incomplete is the use of the colorimeter in photographs taken by drones: the color management, in this case, has been limited to manual techniques through the color correction module of the open source plugin 3DSC for Blender.

7. Future works

The research is currently under active development to complete the processing of the collected datasets.

Next steps of the research will be:

- addressing the limitations described at Section 6.2;
- the acquisition of the remaining areas of the city using a BVLOS (UAV flight Beyond Visual Line Of Sight) approach;
- the digitization of elements that concern ethnographic aspects (life style and objects of the Romanian peasant);
- making reconstruction hypotheses for the main monuments of the city;

[14] http://www.mnit.ro/3d-roma-sarmizegetusa-turn-on-the-history/.
[15] http://osiris.itabc.cnr.it/scenebaker/index.php/projects/aton/.
[16] https://www.unrealengine.com/en-US/studio.
[17] http://osiris.itabc.cnr.it/scenebaker/index.php/resources/unreal-engine-4/proceduralutils-plugin/.

- adding soundscape acquisition to the digital replica workflow. Especially for HMD (Head Mounted Dysplay) a 3D audio technology improves the feeling of presence (through omnidirectional microphones);
- extending the outputs of the digital replica through experiments with immersive VR;
- publishing the entire dataset following an open access mechanism (online repository).

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References

[1] J. Jokilehto, Definition of cultural heritage: references to documents in history, in: ICCROM Working Group, Heritage and Society, 2005, pp. 4–8.
[2] S. Pannell, Reconciling nature and culture in a global context, in: Lessons from the World Heritage List, Cooperative Research Centre for Tropical Rainforest Ecology and Management, Rainforest CRC, Cairns, Australia, 2006.
[3] UNESCO, Convention Concerning the Protection of the World Cultural and Natural Heritage, 1972 http://whc.unesco.org/en/conventiontext.
[4] UNESCO, Convention for the Safeguarding of the Intangible Cultural Heritage, UNESCO meeting in Paris, 2003 https://unesdoc.unesco.org/ark:/48223/pf0000132540.locale=en (17.10.03).
[5] Council of Europe, Recommendation No. R (95) 9 on the Integrated Conservation of Cultural Landscapes Areas as Part of Landscape Policies. (Adopted by the Committee of Ministers on 11 September 1995 at the 543rd Meeting of the Ministers' Deputies), 1995.
[6] C. Urbani, Codice dei beni culturali e del paesaggio. DECRETO LEGISLATIVO 22 gennaio 2004, n. 42, 2004 www.gazzettaufficiale.it/eli/id/2004/02/24/004G0066/sg.
[7] I. Colomina, P. Molina, Unmanned aerial systems for photogrammetry and remote sensing: a review, ISPRS J. Photogramm. Remote Sens. 92 (2014) 79–97, http://dx.doi.org/10.1016/j.isprsjprs.2014.02.013.
[8] K.G. Nikolakopoulos, K. Soura, I.K. Koukouvelas, N.G. Argyropoulos, UAV vs classical aerial photogrammetry for archaeological studies, J. Archaeol. Sci.: Rep. 14 (2017) 758–773, http://dx.doi.org/10.1016/j.jasrep.2016.09.004.
[9] S. Green, A. Bevan, M. Shapland, A comparative assessment of structure from motion methods for archaeological research, J. Archaeol. Sci. 46 (2014) 173–181, http://dx.doi.org/10.1016/j.jas.2014.02.030.
[10] I. Aicardi, F. Chiabrando, A.M. Lingua, F. Noardo, Recent trends in cultural heritage 3d survey: the photogrammetric computer vision approach, J. Cult. Herit. (2018), http://dx.doi.org/10.1016/j.culher.2017.11.006.
[11] A. Jalandoni, I. Domingo, P.S.C. Taçon, Testing the value of low-cost Structure-from-Motion (SfM) photogrammetry for metric and visual analysis of rock art, J. Archaeol. Sci.: Rep. 17 (2018) 605–616, http://dx.doi.org/10.1016/j.jasrep.2017.12.020.
[12] G. Fangi, The Multi-Image Spherical Panoramas as a Tool for Architectural Survey. CIPA HERITAGE DOCUMENTATION, 2011, pp. 21.
[13] G. Kyriakaki, A. Doulamis, N. Doulamis, M. Ioannides, K. Makantasis, E. Protopapadakis, A. Hadjiprocopis, K. Wenzel, D. Fritsch, M. Klein, G. Weinlinger, 4d reconstruction of tangible cultural heritage objects from web-retrieved images, Int. J. Herit. Digit. Era 3 (2014) 431–451, http://dx.doi.org/10.1260/2047-4970.3.2.431.
[14] R. Pierdicca, Mapping Chimu's settlements for conservation purposes using UAV and close range photogrammetry. The virtual reconstruction of Palacio Tschudi, Chan Chan, Peru, in: Digital Applications in Archaeology and Cultural Heritage, 2017, http://dx.doi.org/10.1016/j.daach.2017.11.004.
[15] H. Thomas, A methodology for combining terrestrial and aerial photographs to create high resolution photogrammetric models of large-scale archaeological sites: a case study for Methone, Greece, J. Archaeol. Sci.: Rep. 16 (2017) 27–33, http://dx.doi.org/10.1016/j.jasrep.2017.09.015.
[16] D. Fritsch, M. Klein, 3d preservation of buildings – reconstructing the past, Multimed. Tools Appl. 77 (2018) 9153–9170, http://dx.doi.org/10.1007/s11042-017-4654-5.
[17] F. Chiabrando, F. Nex, D. Piatti, F. Rinaudo, UAV and RPV systems for photogrammetric surveys in archaelogical areas: two tests in the Piedmont region (Italy), J. Archaeol. Sci. 38 (2011) 697–710, http://dx.doi.org/10.1016/j.jas.2010.10.022.
[18] A.T. Mozas-Calvache, J.L. Pérez-García, F.J. Cardenal-Escarcena, E. Mata-Castro, J. Delgado-García, Method for photogrammetric surveying of archaeological sites with light aerial platforms, J. Archaeol. Sci. 39 (2012) 521–530, http://dx.doi.org/10.1016/j.jas.2011.10.007.
[19] M. Dubbini, L.I. Curzio, A. Campedelli, Digital elevation models from unmanned aerial vehicle surveys for archaeological interpretation of terrain anomalies: case study of the Roman castrum of Burnum (Croatia), J. Archaeol. Sci.: Rep. 8 (2016) 121–134, http://dx.doi.org/10.1016/j.jasrep.2016.05.054.
[20] J. Fernández-Lozano, G. Gutiérrez-Alonso, Improving archaeological prospection using localized UAVs assisted photogrammetry: an example from the Roman Gold District of the Eria River Valley (NW Spain), J. Archaeol. Sci.: Rep. 5 (2016) 509–520, http://dx.doi.org/10.1016/j.jasrep.2016.01.007.
[21] F. Remondino, S. Campana, 3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and Best Practices, BAR/International series, Archaeopress, 2014.
[22] C. Corsi, M. Klein, G. Weinlinger, The Roman town of Ammaia (Portugal): from total survey to 3d reconstruction, in: Proceedings of the 16th International Conference on Cultural Heritage and New Technologies, Vienna, 2012, pp. 59–73.
[23] F. Fiorillo, B.J. Fernández-Palacios, F. Remondino, S. Barba, 3d surveying and modelling of the archaeological area of Paestum, Italy, Virtual Archaeol. Rev. 4 (2013) 55–60, http://dx.doi.org/10.4995/var.2013.4306.
[24] V.A. Ziparo, F. Cottefoglie, D. Calisi, F. Giannone, G. Grisetti, B. Leibe, M. Proesmans, P. Salonia, L. Van Gool, C. Ventura, et al., A new approach to digitalization and data management of cultural heritage sites, in: Digital Heritage, 2015, IEEE, 2015, pp. 143–146.
[25] K. Themistocleous, The use of UAVs to monitor archeological sites: the case study of Choirokoitia within the PROTHEGO project, in: Fifth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2017), International Society for Optics and Photonics, 2017, p. 104441I.
[26] G. Guidi, G. Tucci, J.A. Beraldin, S. Ciofi, D. Ostuni, F. Costantini, S. El-Hakim, Multiscale Archaeological Survey Based on the Integration of 3d Scanning and Photogrammetry, 2002.
[27] S.F. El-Hakim, J.A. Beraldin, M. Picard, G. Godin, Detailed 3d reconstruction of large-scale heritage sites with integrated techniques, IEEE Comput. Graphics Appl. 24 (2004) 21–29.
[28] S. El-Hakim, J.A. Beraldin, M. Picard, L. Cournoyer, Surface reconstruction of large complex structures from mixed range data – the erechtheion experience, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 37 Part B5 (in the proceedings of this Congress), Citeseer, 2008.
[29] G. Guidi, F. Remondino, M. Russo, F. Menna, A. Rizzi, 3d modeling of large and complex site using multi-sensor integration and multi-resolution data, in: VAST, 2008, pp. 85–92.
[30] G. Guidi, M. Russo, S. Ercoli, F. Remondino, A. Rizzi, F. Menna, A multi-resolution methodology for the 3d modeling of large and complex archeological areas, Int. J. Archit. Comput. 7 (2009) 39–55.
[31] F. Vermeulen, C. Corsi, M. De Dapper, Surveying the townscape of Roman Ammaia in Portugal: an integrated geoarchaeological investigation of the forum area, Geoarchaeology 27 (2012) 123–139.
[32] J. De Reu, G. Plets, G. Verhoeven, P. De Smedt, M. Bats, B. Cherretté, W. De Maeyer, J. Deconynck, D. Herremans, P. Laloo, et al., Towards a three-dimensional cost-effective registration of the archaeological heritage, J. Archaeol. Sci. 40 (2013) 1108–1121.
[33] A. Mouget, G. Lucet, Photogrammetric archaeological survey with UAV, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 2 (2014) 251.
[34] H. Rua, P. Alvito, Living the past: 3d models, virtual reality and game engines as tools for supporting archaeology and the reconstruction of cultural heritage – the case-study of the Roman villa of Casal de Freiria, J. Archaeol. Sci. 38 (2011) 3296–3308.
[35] G. Guidi, M. Russo, D. Angheleddu, 3d survey and virtual reconstruction of archeological sites, Digit. Appl. Archaeol. Cult. Herit. 1 (2014) 55–69.
[36] G. Landeschi, N. Dell'Unto, K. Lundqvist, D. Ferdani, D.M. Campanaro, A.M.L. Touati, 3d-GIS as a platform for visual analysis: investigating a Pompeian house, J. Archaeol. Sci. 65 (2016) 103–113.
[37] G. Agugiaro, F. Remondino, G. Girardi, J. von SCHWERIN, H. Richards-Rissetto, R. de Amicis, QueryArch3d: querying and visualising 3d models of a maya archaeological site in a web-based interface, Geoinform. FCE CTU 6 (2011) 10–17.
[38] D. Borra, La valle degli Imperatori: la villa di Traiano, in: MIMOS – Il Decennale, atti del convegno, Roma, 2012, pp. 167–177.
[39] C. Meghini, R. Scopigno, J. Richards, H. Wright, G. Geser, S. Cuy, J. Fihn, B. Fanini, H. Hollander, F. Niccolucci, et al., ARIADNE: a research infrastructure for archaeology, J. Comput. Cult. Herit. (JOCCH) 10 (2017) 18.
[40] M. Seymour, EPIC's Unreal Engine Open World: Behind the Scenes, 2015 https://www.fxguide.com/featured/epics-unreal-engine-open-world-behind-the-scenes/.
[41] F. Antoine, Creating the Open World Kite Real-Time Demo in UE4 GDC 2015 Event Coverage Unreal Engine, 2015, youtu.be/clakekAHQx0.
[42] Unreal, A Boy and His Kite: An Animated Short, 2015 https://vimeo.com/121146483.
[43] IGN, Assassin's Creed Unity: Real Life vs. In-Game Paris. youtu.be/yTTvkD, R6euk, 2014.
[44] SJMTech, Virtual Archaeology: Ancient Megalithic Walls – First Person Exploration, 2016 https://www.youtube.com/watch?v=8N3nxOKsh78.
[45] G. Lock, Using Computers in Archaeology, Towards Virtual Pasts, London and New York, 2003.
[46] M. Kazhdan, M. Bolitho, H. Hoppe, Poisson surface reconstruction, in: Proceedings of the Fourth Eurographics Symposium on Geometry Processing, 2006.

[47] J.A. Barceló, M. Forte, D.H. Sanders, Virtual Reality in Archaeology, Archaeopress Oxford, 2000.
[48] O. Floca, Muzeul de arheologie Ulpia Traiana, Sarmizegetusa. Muzeul Regional Hunedoara, 1967.
[49] D. Alicu, C. Pop, V. Wollmann, Figured Monuments from Ulpia Traiana Sarmizegetusa, vol. 55, British Archaeological Reports, 1979.
[50] C. Ciongradi, Grabmonument und sozialer Status in Oberdakien, Mega-Verlag, 2007.
[51] A. Antal, E. Bota, C. Ciongradi, E. D'Annibale, E. Demetrescu, C. Dima, B. Fanini, D. Ferdani, A complete workflow from the data collection on the field to the deployment of a virtual museum: the case of virtual Sarmizegetusa, in: C.E. Catalano, L.D. Luca (Eds.), Eurographics Workshop on Graphics and Cultural Heritage, The Eurographics Association, 2016, http://dx.doi.org/10.2312/gch.20161386.
[52] A. Adami, I. Cerato, E. d'Annibale, E. Demetrescu, D. Ferdani, Different photogrammetric approaches to 3d survey of the Mausoleum of Romulus in Rome, in: GCH, 2014, pp. 19–28.
[53] F. Remondino, S. El-Hakim, Image-based 3d modelling: a review, Photogramm. Rec. 21 (2006) 269–291.
[54] G. Pavlidis, A. Koutsoudis, F. Arnaoutoglou, V. Tsioukas, C. Chamzas, Methods for 3d digitization of cultural heritage, J. Cult. Herit. 8 (2007) 93–98.
[55] R. Szeliski, Computer Vision: Algorithms and Applications, Springer Science & Business Media, 2010.
[56] G. Verhoeven, Taking computer vision aloft-archaeological three-dimensional reconstructions from aerial photographs with photoscan, Archaeol. Prospect. 18 (2011) 67–73.
[57] M. Dellepiane, N. Dell'Unto, M. Callieri, S. Lindgren, R. Scopigno, Archeological excavation monitoring using dense stereo matching techniques, J. Cult. Herit. 14 (2013) 201–210.
[58] A. Koutsoudis, B. Vidmar, G. Ioannakis, F. Arnaoutoglou, G. Pavlidis, C. Chamzas, Multi-image 3d reconstruction data evaluation, J. Cult. Herit. 15 (2014) 73–79.
[59] C. Dostal, K. Yamafune, Photogrammetric texture mapping: a method for increasing the Fidelity of 3d models of cultural heritage materials, J. Archaeol. Sci.: Rep. 18 (2018) 430–436, http://dx.doi.org/10.1016/j.jasrep.2018.01.024.
[60] L.D. Vito, C. Lubritto, Editorial of the special issue on the 1st international conference on metrology for archaeology: Measurement science for archaeology and cultural heritage, Measurement 114 (2018) 492, http://dx.doi.org/10.1016/j.measurement.2017.06.012.
[61] M. Balzani, N. Santopuoli, A. Grieco, N. Zaltron, Laser scanner 3d survey in archaeological field: the forum of Pompeii, in: International Conference on Remote Sensing Archaeology, Beijing, 2004, pp. 169–175.
[62] M. Doneus, W. Neubauer, 3d laser scanners on archaeological excavations, in: Proceedings of the XXth International Symposium CIPA, Torino, 2005, pp. 226–231.
[63] S. Gonizzi Barsanti, F. Remondino, D. Visintini, D surveying and modeling of archaeological sites – some critical issues, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. (2013) 145–150, http://dx.doi.org/10.5194/isprsannals-II-5-W1-145-2013.
[64] F. Galeazzi, Towards the definition of best 3d practices in archaeology: assessing 3d documentation techniques for intra-site data recording, J. Cult. Herit. 17 (2016) 159–169.
[65] J.A. Beraldin, Integration of laser scanning and close-range photogrammetry – the last decade and beyond, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 35 (2004) 972–983.
[66] R. Kadobayashi, N. Kochi, H. Otani, R. Furukawa, Comparison and evaluation of laser scanning and photogrammetry and their combined use for digital recording of cultural heritage, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 35 (2004) 401–406.
[67] A. Abdelhafiz, B. Riedel, W. Niemeier, Towards a 3d true colored space by the fusion of laser scanner point cloud and digital photos, in: Proceedings of the ISPRS. Working Group V/4 Workshop (3D-ARCH, Citeseer, 2005.
[68] J.L. Lerma, S. Navarro, M. Cabrelles, V. Villaverde, Terrestrial laser scanning and close range photogrammetry for 3d archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study, J. Archaeol. Sci. 37 (2010) 499–507.
[69] F. Galeazzi, H. Moyes, M. Aldenderfer, Defining best 3d practices in archaeology: comparing laser scanning and dense stereo matching techniques for 3d intrasite data recording, Adv. Archaeol. Pract. 2 (2014) 353–365.
[70] S. Hajisharif, Real-Time Image Based Lighting With Streaming HDR-light Probe Sequences, 2012.
[71] P.E. Debevec, J. Malik, Recovering high dynamic range radiance maps from photographs, in: Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques, ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 1997, pp. 369–378, http://dx.doi.org/10.1145/258734.258884.
[72] P. Debevec, Rendering synthetic objects into real scenes: bridging traditional and image-based graphics with global illumination and high dynamic range photography, in: ACM SIGGRAPH 2008 Classes, ACM, 2008, p. 32.
[73] J. Stumpfel, C. Tchou, A. Jones, T. Hawkins, A. Wenger, P. Debevec, Direct HDR capture of the sun and sky, in: Proceedings of the 3rd International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, ACM, 2004, pp. 145–149.
[74] J. Birne, Digital Lighting & Rendering, 2013.
[75] E. Reinhard, W. Heidrich, P. Debevec, S. Pattanaik, G. Ward, K. Myszkowski, High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting, Morgan Kaufmann, 2010.
[76] P. Lindstrom, Out-of-core simplification of large polygonal models, in: Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques, ACM Press/Addison-Wesley Publishing Co., 2000, pp. 259–262.
[77] P. Lindstrom, V. Pascucci, Terrain simplification simplified: a general framework for view-dependent out-of-core visualization, IEEE Trans. Vis. Comput. Graphics 8 (2002) 239–254.