Integrated information system for 3D interactive reconstruction of an archaeological site

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Archaeological recording is intended to preserve as much information as possible about the finds. However, once the pieces are removed from the site, there is information regarding the original positioning of these pieces that may be lost or not accurately recorded, and can be relevant for further studies. This spatial arrangement can also be crucial for subsequent piece restoration or to understand certain aspects of ancient cultures.

In this paper, we describe a software prototype and a methodology to virtually reconstruct an archaeological site for posterity, once it has been excavated. The system is implemented with a client-server architecture. In the server, a spatial database stores and manages the 3D models of the finds, as well as several 3D site ground surface models acquired at different times during the excavation process. On the client side, a graphical interface allows the user to manipulate the find models in order to recreate and virtually reconstruct the original spatial arrangement of the archaeological site. Topological relationships among the finds are stored in the database to provide further spatial analysis. The result is an integrated information system that goes beyond 3D visualization, making the site last for posterity after its excavation, and allowing further spatial analysis.

CCS Concepts: • **Applied computing** → **Arts and humanities**; • **Information systems** → *Geographic information systems*; Digital libraries and archives.

Additional Key Words and Phrases: Virtual reconstruction, 3D Interaction, Archaeological recording

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1 INTRODUCTION

Documenting is one of the most important tasks both during archaeological excavation and once the finds have been collected and are under study in the lab. In any case, these meticulous processes have to be paired with an accurate methodology to record all the relevant data about the finds, gathering information such as the material they are made of, or their dating. However, there are additional aspects such as their position on the site, or even the arrangement of the pieces on a given location, which can be also crucial for further analysis. Starting from the premise that excavation is destruction, the ever-present objective of recording is preventing any loss of information that might be missed in the future.

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Traditional recording methods, mainly manual, have been gradually enriched with digital tools that allow feeding an archaeological database. The nature of the data provided by these tools is often dissimilar. The textual information of the records is frequently complemented with digital pictures, handmade sketches, etcetera. Although these 2D inputs are very enriching, they imply a level of abstraction by representing a three-dimensional reality in a two-dimensional way.

This drawback has been partly solved nowadays by means of techniques based on 3D capturing. Some of them are based on photogrammetry, laser-scanning or LiDAR. 3D modeling offers numerous advantages, mainly in terms of visualization, but also for collaborative analysis and data exchange. These technologies can also solve the lack of geometric accuracy that planes and sections might have, or the morphology correctness of the pieces. Definitely, 3D documentation is able to reflect the features of archaeological vestiges in a more natural way.

However, fully integrating 3D information with the records of a traditional database is still challenging. 3D recording must go beyond mere three dimensional visualization. The shape, appearance and position of the virtual objects in the resulting scene should reproduce as closely as possible the reality they are representing. This entails a new approach that generates advanced knowledge compared to classic recording methods.

We propose in this paper a methodology for 3D documenting archaeological sites that additionally allows generating a 3D model of the site before completing the extraction of the pieces. In short, we aim at (1) recreating the moment of the discovery for experts who were not present at the time and place of the discovery, (2) preserve some informational elements that are lost after the excavation, namely the spatial layout of the finds and (3) allowing experts to observe and access the virtual recreation of the site from anywhere.

Our proposal provides the necessary mechanisms to establish an accurate correlation between real finds or structural elements with their virtual representation. The result is a synthetic scene with 3D models of the vestiges placed at their original position and orientation in which the soil has been removed. For that purpose, we first acquire a 3D model of the archaeological site during the excavation and before the finds are removed. Different techniques for this 3D capture have been tested. Then, the pieces are cleaned and processed with a 3D scanner. Finally, the resulting models are placed at their original locations using the model of the archaeological site as a reference. For that purpose, the user is provided with an interface to manipulate the virtual elements, allowing them to translate and rotate each model. The interactive tool is supported by a database that allows to store and retrieve information of different nature. In addition, the information in the database is updated according to the changes made to the 3D scene by the users with the interactive tool. The system architecture allows final users to visit the virtual reconstruction of the archaeological site from a computer connected to the Internet by means of an application implemented in the Unity game engine. The result is an intuitive and user-friendly interface not only for archaeological recording purposes, but also for consultation and analysis.

The rest of the paper is structured as follows. Section 2 reviews the state of the art. Section 3 describes the main features of our proposal, including the system architecture. Section 4 details how the data is acquired and processed before being stored in the spatial database. Section 5 describes the process to virtually reconstruct the archaeological site as well as the spatial analysis that can be performed on the virtual site. Section 6 discusses some results and Section 7 presents our conclusions and plans for future work.

2 STATE OF THE ART

Archaeological documentation techniques are currently evolving towards a multi-faceted approach. The primary objective is to save for posterity all the knowledge that disappears when the finds are extracted during excavation [25]. For that purpose, traditional archaeological recording methods are being improved by adding some of the following features:

- Information of the records is digitized, and additional data of different nature is now part of these records. As a result, 2D images or heavy 3D models of the finds are increasingly present in the documentation of archaeological sites [12, 15].
- There is a trend towards sharing information with the scientific community through web platforms, or client server architectures [19]. This groupware provides experts from any part of the world an efficient and comprehensive access to the records, and allows them to participate in the analysis process through a computer connected to the Internet [29].
- All stages involved in the archaeological process, from capture and documentation to analysis and dissemination, are desirable to be part of an integrated information system [28]. This means that even the capture process made in situ feeds the same database, which inevitably implies the use of ubiquitous devices during the excavation [4]. This pipeline could include even the virtual reconstruction of the site in ancient times [14].
- The interfaces to access this complex information should be as user-friendly as possible, since collaborative systems can be accessed by experts with different levels of knowledge about the archaeological recording process [30]. In this regard, 3D models representing the finds and the archaeological site itself provide a better understanding [9].

In order not to destroy the context, all the features described above are desirable to recreate the original archaeological site. This way, the assertion "excavation is destruction" is replaced by "excavation is digital reconstruction". Thus, an expert who did not participate in the excavation could reliably know the details of the archaeological site as if they were there.

Nowadays many possibilities to capture the details of sites and finds in 3D are at our disposal. Laser scanners [26], LiDAR [32] or structure from motion (SfM) photogrammetry [17] are widely used techniques in Archaeology [2, 18]. Their capabilities can be used to observe the features of a piece in order to determine its material, its dating, the presence of possible inscriptions or for examining in detail its deterioration. However, one additional aim is also capturing the underlying spatial information in an archaeological site. The original position of the pieces and their disposition regarding the surrounding environment, including other vestiges, is necessary for virtually reproducing the site [16]. For example, obtaining a collection of topologically connected fragments from a site provides a good starting point for later reconstruction of pottery [1, 15]. As another example, the way in which the remains were deposited in human burial sites can provide relevant clues to understand religious customs or social relationships in a human settlement.

Compared to a 2D pictorial representation, 3D virtualization enriches the experience of archaeologists [23]. Most 3D models are thought for a better user experience in visualization, for example using Augmented Reality [5, 6, 33]. In addition, greater geometric precision is achieved when compared to the drawings [21]. Photographs shot during excavations have limitations because they are taken from a specific angle, allowing to visualize only one side of the objects, and those parts of them that are still buried are not displayed. In our framework, the inclusion of 3D models, both of the environment and of the pieces, allows us to overcome this drawback. In a 3D scene of an archaeological site, given the appropriate GUI (Graphical User Interface), the user can move freely i.e. the camera can be located at any position around the scene to allow observing it from any point of view. In addition, the soil can also be removed if necessary (for example, if the user wants to view the scene from below).

However, 3D virtualization of an archaeological site still has significant shortcomings to address. On the one hand, a 3D scan of the site can produce very heavy models, with millions of points, that are difficult to handle by standard computer hardware. Frequently, the software capable of visualizing these models is decoupled from the database manager. Therefore, the 3D model is usually complementary information that lies outside the information system. Something similar happens with models that are scanned individually once they are removed from the site. They are stored outside the database, or the database just stores a link to their file location. In the few cases in which they are integrated in the system, 3D models are used only for visualization and analysis, but detached from the place of discovery [34], or conceived just for later dissemination [31]. Thus, they do not include its original position and the spatial relationships with the surrounding finds. In short, in the literature we find a dissociation between these 3D models and the rest of the information system [20]. This way, it is difficult to establish the actual spatial relationships between the pieces and their environment. This can be solved by adding topological relationships to enable this spatial analysis. Adding topological operators allows archaeologists to recover crucial information that disappears after excavation [3, 39].

One solution to add spatial information to the archaeological record comes from Geographical Information Systems (GIS), which integrate data management and visualization [8, 37]. 3D GIS outperform traditional 2D systems by incorporating spatial data with three-dimensional models under the same framework [22, 24]. There are, however, some problems underlying these tools. They provide generic solutions with a high level of abstraction, that is away from archaeological methodology [32]. 3D GIS are still in early stages of development, with limited capabilities in terms of 3D model integration, friendly interfaces or ubiquity. This is usually the reason why in many research projects, like GRAVITATE, the choice is to develop their own software tools [9].

In this paper we introduce a methodology that makes possible the virtual reproduction of an archaeological site with a wide functionality. The prototype system has been designed not only for visualization [19]. This allows improving the integration between the spatial database and the graphical interface representing the site. Our system allows reproducing the original spatial distribution of the pieces as they were found [36]. In order to achieve this objective, we have designed a 3D GUI which facilitates the process of placing the individual 3D scanned models at their correct positions. This process is conducted by the archaeologist using well known 3D manipulators for translating and rotating the models (scale is set in advance). For that purpose, the site ground surface is digitized during the excavation process, that is, while pieces are still embedded in the ground but partially out and their shapes are distinguishable. Given a find model, once its scale is adjusted to match the one of the site ground surface model, the user translates and rotates it to match the part of its geometry that is visible from the site ground surface model. The process is easy to perform and no experience is needed to do it, since the visual reference of the site ground surface model helps to achieve the desired precision.

Some other techniques could also be taken into consideration to perform this adjustment automatically. In particular, the Iterative Closest Point (ICP) algorithm [7] has been already applied in Archaeology [38]. This method iterates trying to approximate positions between a floating model A (the find model) and a fixed one B (the site ground surface model). In each ICP iteration, the best geometric transformation that aligns A and B is calculated. This is done by minimizing the squared error (MSE), computed as the sum of the squared distances between the points in A and the closest points to them in B. In each iteration, a combination of a translation and a rotation of the floating model is computed. However, proper results are only obtained when one model is a subset of the other [35]. Regarding our proposal, the differences between the models can be too significant for applying this algorithm, as the site ground surface model covers much more space; moreover, it only contains the parts of the finds that have been already uncovered, and these can still have remains of materials stuck; on the other hand, the find models are acquired in the lab, once the pieces have been cleaned, and the resolution of the meshes will be typically higher. Many different modifications to the algorithm have been proposed in the literature for better accuracy [27], including genetic algorithms [35]. However, all of them work with the models when they have already been extracted, not facing the problem of alignment with ground semi-embedded objects.

On the contrary, our method can be considered agile, as it gives the expert the opportunity to manipulate each object individually. Additionally, the use of mobile devices or smartphones, which are able to create 3D models of the site in a few minutes [13, 40], makes this procedure very useful in Archaeology. To achieve such an objective, we have implemented a client-server architecture prototype. On the client-side, an expert can manage and interact with the virtual finds using the user-friendly interface provided by Unity, a video-game engine. In contrast with other solutions developed for dissemination or the general public [10], not only the user interacts

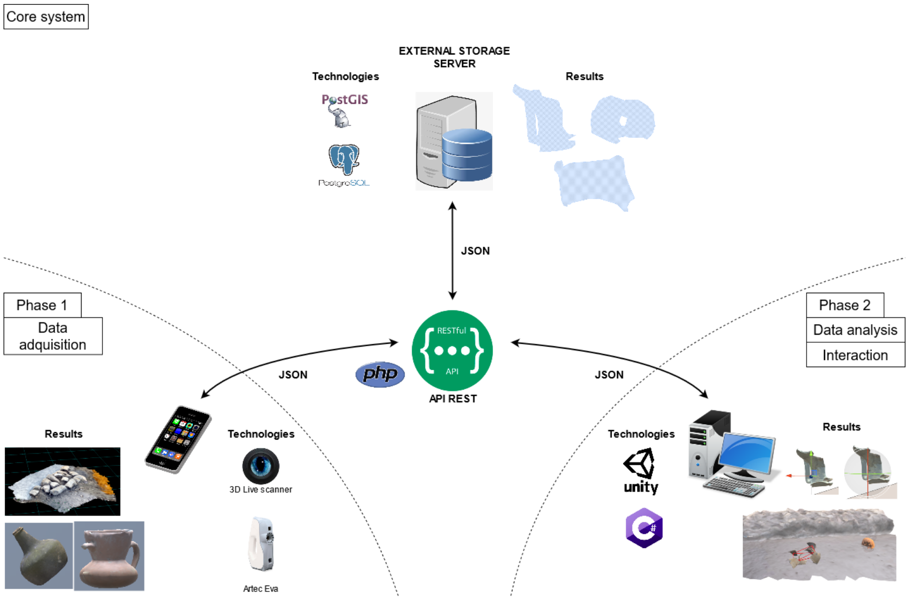

Fig. 1. General system architecture

and manipulates the 3D models through the GUI and updates their spatial disposition on the screen, but also updates the database to save the new spatial configuration. Therefore, the resulting three-dimensional interface is not a separate module of the system. Instead, it is connected to the database, allowing full interaction and feedback between both. These and similar features are considered the challenges to conform the new Digital Cultural Heritage [23].

3 PROPOSAL OF A 3D ARCHAEOLOGICAL RECORDING SYSTEM

Our system aims at providing archaeologists with a simple and intuitive interface for creating virtual reconstructions of the sites under study that can help improve the results of the archaeological analysis. In order to achieve this goal, the architecture of the system is as follows (Figure 1):

- First of all, a spatial database implemented in the well-known system PostGIS allows us not only to store the typical archaeological record information (texts, dates, quantities…), but also locations. Combining this information with the powerful spatial queries implemented by PostGIS allows us to provide the users with spatial analysis features.
- A REST API implemented in PHP acts as a middleware that allows accessing the information stored in the database in a uniform and simplified way.
- Finally, a graphical user interface implemented on top of the Unity game engine allows the users to easily browse through the stored information, as well as interact with it.

Even though Unity is a general purpose video game engine, its development environment (using C# as scripting language) covers all the requirements for developing a tool for archaeological site recreation. Unity core provides standard functionality for creating virtual scenarios with 3D models which can be created, edited or imported. It also includes lighting, animation, physics, artificial intelligence or sound. We have taken advantage of this tool to create a virtual 3D environment which (1) enables free navigation and interaction using the mouse and

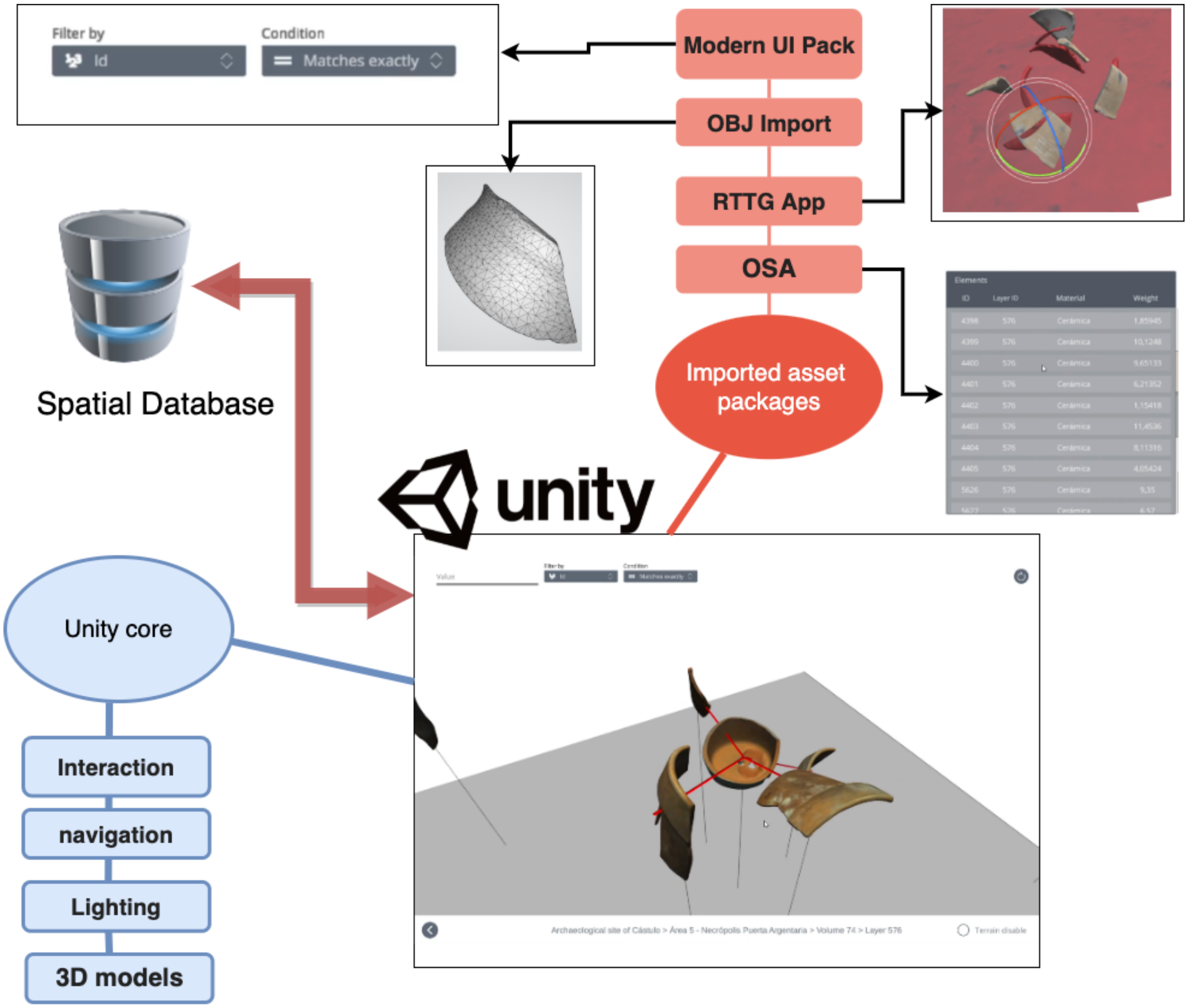

Fig. 2. Use of the Unity game engine to provide the graphical interface

keyboard; (2) is also capable of importing 3D models and (3) uses standard protocols to communicate with an external database. Additional functionality that is not directly included in Unity core was added to the system through third-party asset packages.

The diagram in Figure 2 represents how all the aforementioned elements are combined in the graphical interface of our system. Both standard and external functionality are shown. We use four asset packages to provide advanced capabilities. In particular the package (1) *Modern UI Pack* is used to improve the appearance and behavior of the graphical interface; (2) the *OBJ Import* pack is used for loading OBJ files in runtime; (3) the *Runtime Transform Guizmos (RTTG App)* pack provides runtime gizmos for modeling operations (translation, rotation and scaling), as well as camera behaviors; (4) and finally, the scripts from the *Optimized ScrollView Adapter (OSA)* pack allows optimizing the use of lists, making them more efficient.

In order to get the most from this system proposal, we propose the following three-stages workflow:

1. The first stage is carried out on the archaeological site. It consists of acquiring 3D models of the relevant excavation locations whenever interesting objects are found, and before these objects are completely removed from their original locations. Modern 3D scanners allow doing this task in a few minutes, as described below. Therefore this activity can be easily integrated into the regular excavation process. This task is very important in order to allow the virtual reconstruction of the site, as well as the creation of a timeline of the excavation. Together with the spatial coordinates inherent to the 3D capture, UTM coordinates of these relevant finds are also recorded.
2. Once the finds (like ceramics, tools, bones, or any other material) are removed from the site and taken to the laboratory for cleaning and classification, one of the tasks that is becoming more and more frequent nowadays is the acquisition of a 3D model of the more relevant pieces. It is possible to get these models with high accuracy in a few minutes thanks to accessories like automated turntables.
3. Both types of captures (on the site and in the lab) are fed into our system, together with the standard record information, and stored in a spatial database. Then, our system provides a software interface that allows the users to easily and intuitively integrate the high resolution models obtained in the laboratory with the excavation models acquired on the archaeological site. This way, it is not only possible to study the detailed 3D models of the finds in isolation, but also integrated in the context they were obtained. The position and orientation of the piece models that are set by the user with the graphical interface are stored in the database for further use.

The virtual site model obtained allows accessing the database information through 3D interaction instead of standard SQL queries or textual or numerical data filters. This results in a much more intuitive tool that also allows browsing through the timeline of the excavation, providing a much more complete perspective of the recorded data.

4 DATA ACQUISITION AND STORAGE

As stated in Sections 1 and 2, technology for obtaining 3D models of both the archaeological site and the pieces found on it is becoming increasingly cheaper and more agile. This makes it possible to speed up the recording methodology, since it may take only a few seconds to obtain a detailed representation of the work field and the finds. However, this acquisition process alone is not so useful if its results cannot be integrated into an information system. In fact, repeating the work field scanning at regular times during the excavation process would be very desirable in order to feed a 4D data model. This 3D representation is used not only for further visual representation but as a structural frame to virtually rebuild the site with all its finds at their original positions.

In our tests, we have carried out the acquisition process on the testing site used by Archaeology students of our university. Despite not being a real archaeological site, the students follow the extraction process in a traditional way and the methods they use can be compared with those of the methodology proposed in this paper.

4.1 Acquisition techniques

We have tested several techniques and devices for obtaining 3D models of both the archaeological site and the individual pieces in order to determine the ones with the best balance between accuracy and speed, while trying to keep the costs as low as possible.

For on-site 3D scanning, outdoors lighting conditions can make the use of handheld laser scanners useless, as this kind of device can not be used under direct sunlight. Therefore, it is necessary to wait for a cloudy day, or to cover the site with a tent, for example. We tried the Artec Eva scanner, from the Artec 3D company[1] with a point

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[1] https://www.artec3d.com

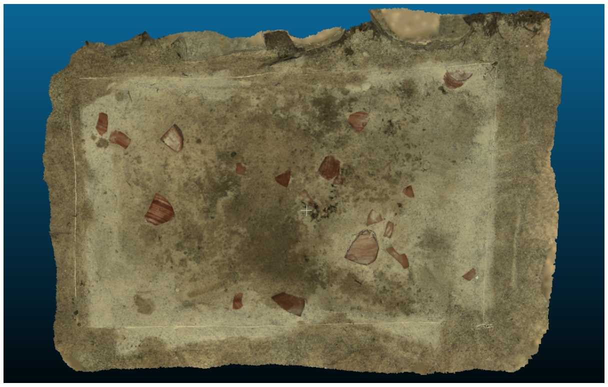

Fig. 3. 3D model acquired using the Artec Eva 3D scanner

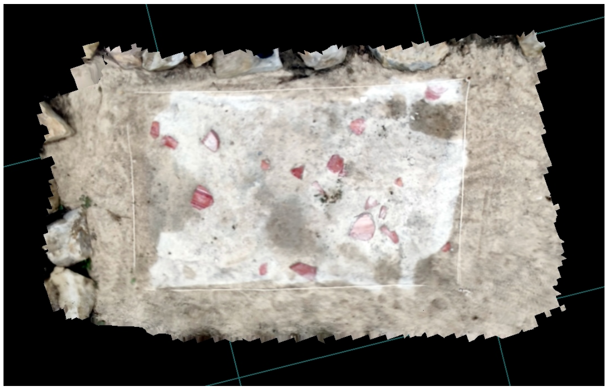

Fig. 4. Result of scanning with the "3D Live Scanner" application using the ToF technology. The result includes both geometry and image texture

accuracy down to 0.1mm and resolution up to 0.2mm. This scanner also provides high accuracy textures, and requires to be connected to a laptop computer during the capture process. Post-processing of the data using its proprietary software is necessary to obtain the final model. Figure 3 shows an example.

The rest of the on site tests were made using smartphones, which are lighter and do not require carrying a laptop in the process. Photogrammetry-based applications provide excellent results, but at the expense of a post-processing time to generate the whole model. We finally opted to take advantage of the ToF (Time of Flight) camera sensor that is becoming increasingly common among the smartphones already available in the market (for example: the Huawei P30 and the Honor View 20 models). This device measures distances by means of a modulated light source similar to a laser and a sensor that captures the reflection of this light from the objects. The 3D model is obtained in only a few seconds for scanning a surface of about $2m^2$. The final model is obtained instantly, and no post-processing is necessary. Mobile applications like "3D Live Scanner" allow acquiring 3D models using this technology, including both geometry and texture. Figure 4 shows an example of a model captured with this application.

One of the main advantages of using the ToF sensor is that it can be used outdoors with different lighting conditions. The only problem detected is that this technology does not perform so well with very small objects.

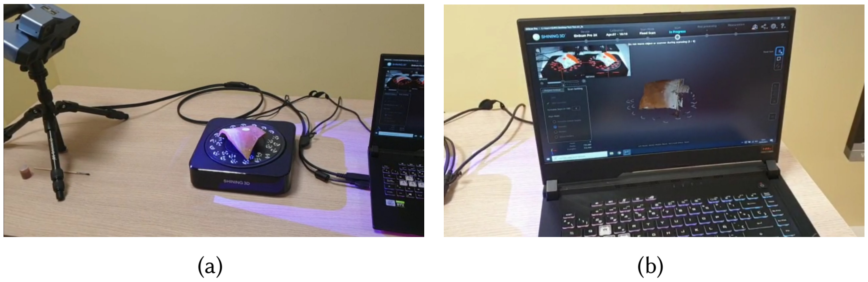
(a) (b)

Fig. 5. Scanning a piece with a rotating platform

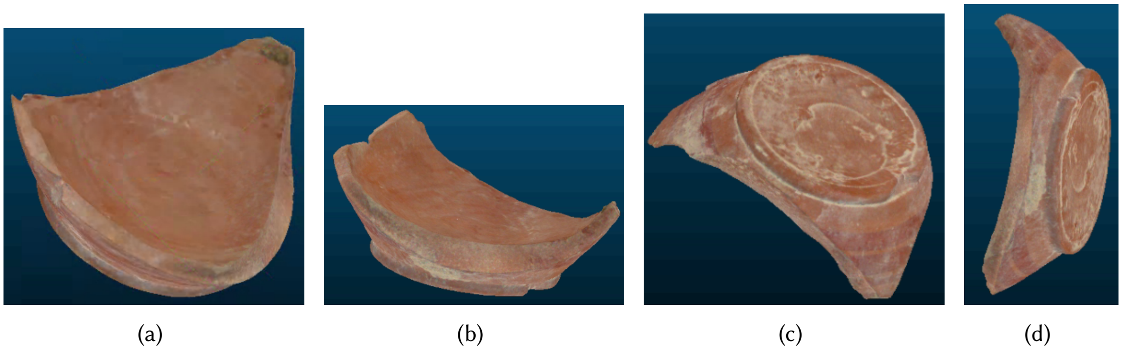
(a) (b) (c) (d)

Fig. 6. Some views of a scanned piece (A)

However, this tool is easy, agile and very affordable to keep track of the excavation process. The model obtained can be directly uploaded to the information system on site with the same smartphone used for scanning, provided that it is connected to the Internet.

Sometimes it is necessary to acquire more detailed models of those finds that are especially relevant. This process is usually done in the laboratory, once the pieces have been cleaned and registered. Depending on the specific piece, the 3D model can be acquired using a handheld scanner or a fixed scanner with the aid of an auxiliary device such as a rotating platform. In our tests, we have used an EinScan Pro 2X scanner manufactured by Shining 3D[2]. This device has an accuracy of up to 0.04mm and a scanning speed of up to 30 fps. Scanning each piece individually is a slower process compared with the on site scanning using ToF sensors, and it is usually necessary to do more than one capture, changing the position of the piece on the platform. The scanner uses proprietary software to manage the process and scanning a piece may take about 4 or 5 minutes. Then, the 3D model can be used as necessary. Figure 5 shows images obtained during the scanning of sample pieces, and Figures 6 and 7 show some results.

4.2 Treating model geometry

While site models obtained with the ToF technology can be directly handled by any application, find models obtained with the EinScan Pro 2X scanner (or any similar device) are too detailed to be used in spatial analysis supported by PostGIS spatial operations. Therefore, we decided to keep two versions of each piece model (Figure

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[2] https://www.einscan.com

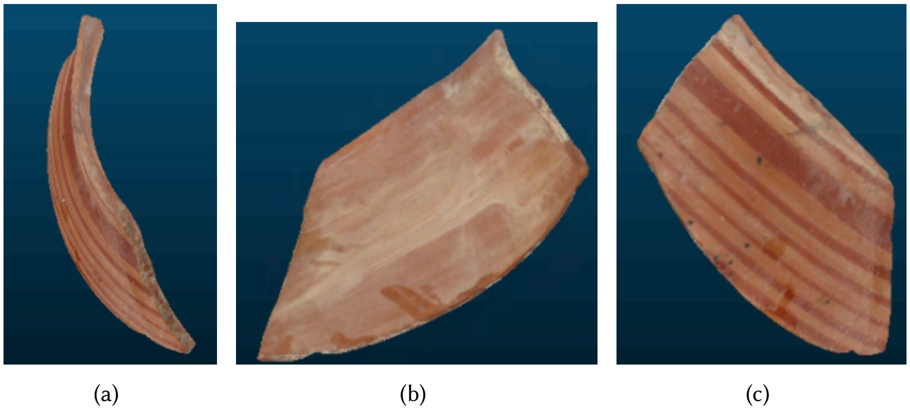

(a) (b) (c)

Fig. 7. Some views of a scanned piece (B)

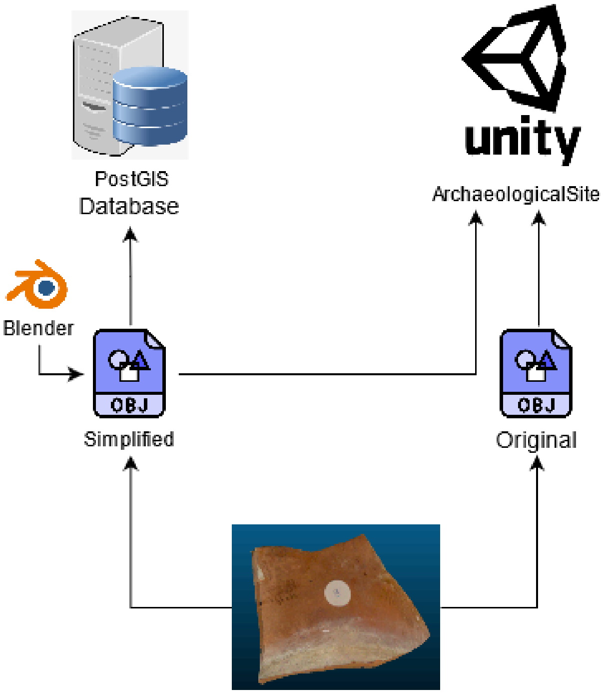


Fig. 8. Two versions of each model are stored in our system

8): on the one hand, the original mesh is only used in the interactive environment whenever the expert user wants to study a piece in full detail; on the other hand, a decimated version of the mesh is directly stored in the database, in order to be used for the aforementioned spatial operations, as well as for interactive navigation through the virtual reconstruction of the site.

Any standard mesh decimation algorithm can be used for this model simplification. In our case, we have applied the decimation algorithm implemented in the well-known Blender modeling software to reduce the number of polygons in the mesh, while keeping enough detail for the spatial analysis process. Blender allows to decimate meshes not only through its interface, but also using scripting languages like Python and Bash, making it easy to automatically process a group of models.

Finally, and before adding the piece models to the system, it is necessary to assure that the scale of the models is correct. One of the standard excavation procedures is taking measurements of the excavation site (using tools as traditional as measurement tape and surveying rods, or as modern as total stations), as well as of the individual pieces (this can be done on site or in the lab, using the appropriate measuring tools, depending on the size of each piece). Knowing the proportion between these two measurements, it is easy to scale the 3D models of the individual pieces to match the same ratio with respect to the site model than in the real world. Computing this ratio is straightforward, and if the same devices are used for all the scanning tasks, the ratio will remain constant for all the scanned pieces. Section 5.2 describes how the models are added to the virtual reconstruction of the archaeological site.

4.3 Data storage

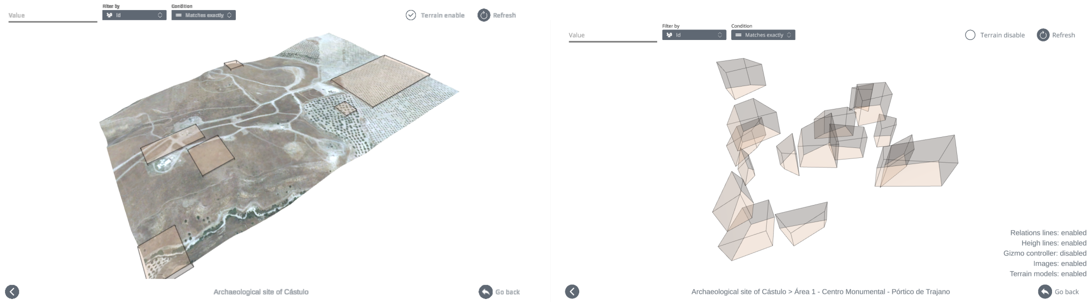
One of the most important components of our proposal is the database. Using a relational database for archaeological recording is nowadays a widespread practice, but taking as a reference the database scheme used in the archaeological site of Castulo (Jaen, Spain), we have developed our own scheme including spatial and topological information. This database is powered by PostGIS, a powerful free software RDBMS that expands PostgreSQL with spatial features. In our design, the archaeological site is divided into *areas* (closed superficial perimeters) that may contain one or several *volumes* (including not only the surface, but also the ground below). Each volume is in turn divided into *layers* (defined by a top and a bottom height). The layer is the minimum spatial division of the system. An *element* is an abstraction that allows us to treat in the same way any type of find, independently of its specific nature. Each element is located in a layer inside our scheme. Figure 9 shows examples of the aforementioned concepts, which are the most relevant in our database design. Figure 10 shows the relationships among these entities.

The database also allows storing the spatial location of each element in the archaeological site (as UTM or WGS84 coordinates), as well as a transformation matrix to orient the 3D model of that piece in the virtual reconstruction of the site. In addition, we also allow storing the 3D simplified model of each relevant piece, as mentioned in Section 4.2.

In order to find and store topological relationships among the elements, the 2D projections of each model onto the XY, ZY and XZ planes are also computed and stored whenever a 3D model is fed into the database. These projections allow computing fast tests to suggest topological relationships among the pieces (for example: fragments that might be parts of the same pottery for later reconstruction). These suggestions, however, need to be confirmed by an expert user. The topological relationships among the pieces are represented in the database by a single 3x3 matrix through the DE-9IM model (Dimensionally Extended 9 Intersection Model) [11], and stored in a separated table.

5 INTERACTIVE VIRTUAL RECONSTRUCTION OF THE ARCHAEOLOGICAL SITE

This section describes the interactive process and mechanisms to virtually reconstruct an archaeological site through a graphical interface in the client device. This way, the interaction with the virtual 3D objects and the environment is the natural way to access the information stored in the database.



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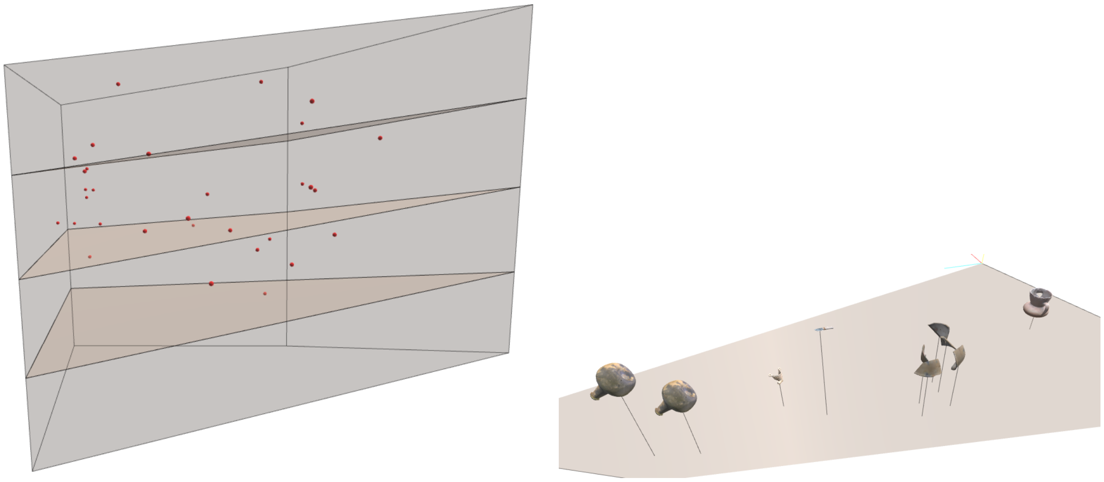
Images: enabled
Terrain models: enabled

(a) Areas in an archaeological site (b) Volumes within an area



(c) Layers within a volume (d) 3D models within a layer

Fig. 9. Hierarchical structure from areas to layers

5.1 Selecting and accessing the layers through the GUI

As explained above, the archaeological site model is conceived in a hierarchical structure: areas, volumes and layers. The graphical user interface of our application prototype allows accessing each of these hierarchy levels using the standard mechanisms of interaction and navigation in a 3D scene (see Figure 9). For example, clicking on one of the highlighted areas from Figure 9a takes us to a view of the volumes in that area (Figure 9b). In the same way, clicking on a specific volume allows us to view the layers in that volume (Figure 9c), and finally, clicking on one of the layers allows us to view that layer in detail. The 3D models of the finds are only shown at this level of detail (Figure 9d).

It is important to note that the interaction with the scene through mouse clicking generates queries to the database transparently to the user. These queries are sent to the database server through the API REST protocol in order to retrieve the required data to be shown. Another very useful interaction mechanism is free navigation. Once the desired level of detail of the virtual site is reached, the user can freely move around the scene by clicking and dragging with the mouse, allowing them to observe the site from any point of view. Compared to the use of

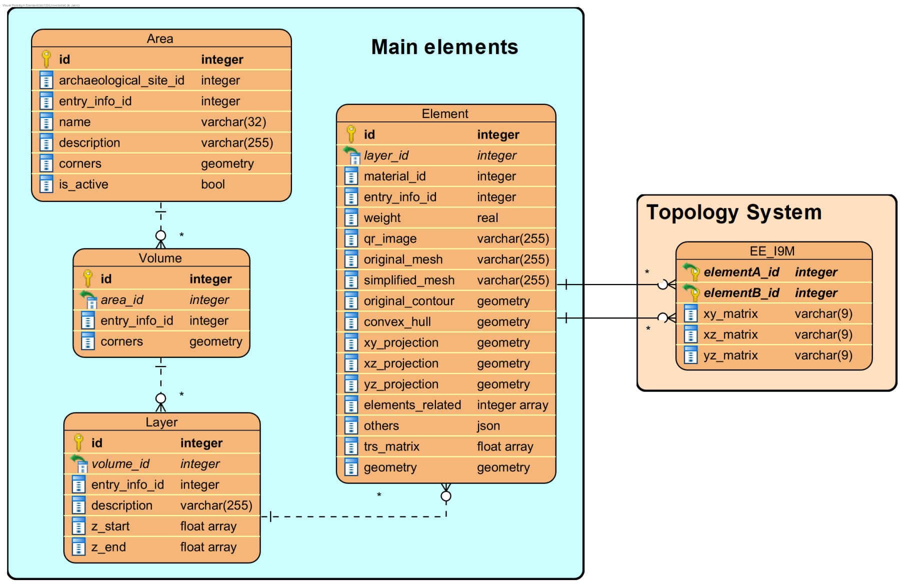


Fig. 10. Most relevant entities in our database model and their relationships

photographs taken from a fixed position, the virtual camera simulates the expert eye on the site itself, with the advantage of allowing the user to activate/deactivate the viewing of the ground surrounding the finds.

Figure 9d shows a layer with the find models placed at their right positions. This allows us to display the 3D models spatially arranged as they were found during the excavation. The following section describes the process followed to achieve this result.

5.2 Find placement procedure

In order to place each find model at its original location in the archaeological site, the series of 3D site ground surface models acquired during the excavation process (Section 4) are of major relevance. In the ground surface models, part of the geometry of the finds is visible, and acts as reference for placing the models of the pieces (Figure 11).

The graphical interface of the application (Figure 11) also provides relevant information stored in the database. For example, the breadcrumb trail at the bottom keeps the user always informed of the hierarchical situation of the layer into the database. Additional controls enable different ways of visualization, like display or hide the terrain, for example.

During the excavation process, the database is fed with the new finds, including the spatial coordinates of each relevant find. Therefore, location is incorporated into the system from the first moment, although some finer position adjustment might be necessary afterwards. Once the 3D models of the finds are obtained in the lab, as described in Section 4.1, they are also fed into the database. As the spatial coordinates are already stored, the editing process that is left is rotating (and maybe fine tune the location of) the model to place it at its original position on the site.

Then, the modus operandi to reproduce a layer begins once the user selects it through the graphical interface. At this point, both the site ground surface model and the find models are retrieved from the database and displayed.

Relations lines: disabled
Heigh lines: disabled
Gizmo controller: disabled
Images: disabled
Terrain models: enabled

Archaeological site of Cástulo > Área 2 - Edificio de los Mosaicos y Edificio Paleocristiano > Volume 28 > Layer 215

Fig. 11. Graphical interface for the archaeological information system

The first time a model is visualized, it is shown with correct scale, position (recorded during the excavation) and default orientation (obtained when the piece was scanned).

Figure 12 shows the stages of this process. Figure 12a shows the find models the first time they are displayed, without the site ground surface model. In Figure 12b we see the same layer, but in this case, one site ground surface model is shown. As can be seen, some find models are below this surface model. Then, a red patina is applied to the site ground surface model to help differentiate it from the find models. In Figures 12c and 12d, the find models, with real textures, appear next to their corresponding partial geometries as contained in the site ground surface model. Figure 12c shows the translation controls, while Figure 12d shows the rotation controls. Both sets of controls allow adjusting the position and orientation of the models in order to match the corresponding partial geometry in the site ground surface model.

Figures 12e and 12f show how the locations and orientations of these pieces have been modified. As a result, the find models are correctly located and oriented with respect to the virtual replica of the archaeological site.

The most interesting feature of this methodology is that the result of this edition process is stored again in the database. This means that the transformation matrix obtained after modifying the position and orientation of each model is captured and associated with the element in the database for posterity. From this moment on, any expert can visualize, interact and navigate with the virtual site, being able to also study the spatial information that disappeared during the excavation process.

5.3 Spatial analysis

This section is devoted to describing a direct application of the information system presented in this paper. Our proposal aims at both recovering the information lost in the excavation and compensating for the loss of the context after the excavation process. In this regard, the size of the whole scene or even of each individual item is important to make up for the lack of reality. This also means understanding how the pieces are related to each other.

Even though experts can take advantage of an accurate 3D representation of the archaeological site, a spatial information system should also provide for further analysis. As mentioned above, a simplification of the 3D model of each significant find is stored in the PostGIS database. Among the functions provided by PostGIS to work on 3D geometric data we can find distances, intersections, bounding volumes or influence buffers. Thus,

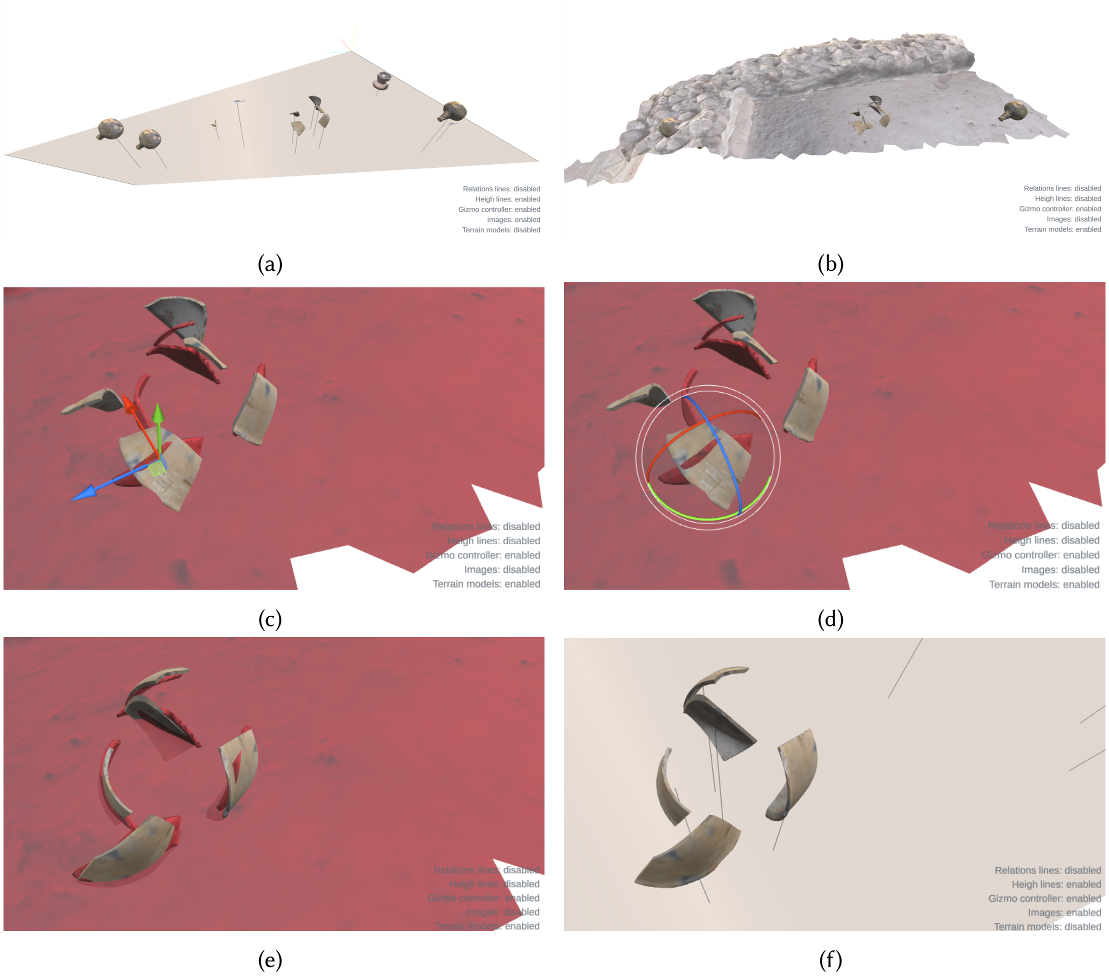


Fig. 12. Stages of the find placement procedure

using these functions it is possible to determine not only which are the surrounding elements of a given one, but also their relative distances, for example.

Sometimes the spatial arrangement of the pieces in an archaeological site can help find relationships between them (fragments of the same vessel, for example). For those cases, our system can suggest possible relationships through the calculation of topological relationships. PostGIS implements the DE-9IM model (Dimensionally Extended 9 Intersection Model) for 2D geometries[11]. This model is a standard 3x3 matrix representation to describe the spatial relationships between two regions. These links are described by the DE-9IM as “Equals”, “Disjoint”, “Intersects”, “Touches”, “Crosses”, “Within”, “Contains” and “Overlaps”. The spatial relationships expressed by the model are invariable to rotation, translation and scaling transformations.

In order to overcome the limitation of this PostGIS feature to 2D geometries and make an extrapolation to 3D models, the projections of the geometry into the three orthogonal planes (XY, XZ and YZ) are computed and stored in the database, as shown in Figure 13. When a new 3D find model is added to the database, its projections

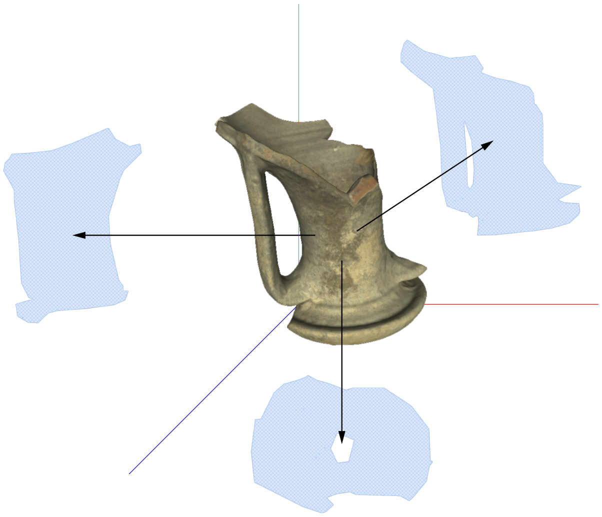


Fig. 13. Projections of a fragment of a vessel into the three orthogonal planes

are computed and, for each find model in the database close enough to the new one (the distance threshold to decide which elements are close enough is a system parameter that can be configured depending on the features of the excavation site; for example, one meter), three DE-9IM matrices are computed using the model projections to determine if there is a possible relationship between those objects. Given two find models A and B, if there are intersections between their projections in the three orthogonal planes, the relationship is labeled as "Touches" in the database. Even though this is not necessarily true, this means that both artifacts are very close to each other. In the case that at least one of the pairs of projections are "Disjoint", the pieces are labeled as separated in 3D in the database. The expert user can then review the potential relationships found in this way, and confirm or discard them as meaningful.

It is obvious that not all the finds in a layer are necessarily related. However, if two pieces are close enough and are made of the same material (ceramic, for example), there is a high probability of them being fragments of the same original object. This information can be directly obtained by computing influence buffers in PostGIS with the 2D geometry of the aforementioned projections (ST_Buffer function in PostGIS). Thus, only pairs of objects inside a given distance are considered as possibly related for further analysis. Finally, distance between fragments previously selected can be computed in 3D by means of the PostGIS function ST_3DDistance. The set of fragments in Figure 14 was processed as described above: (1) the 2D projections of each fragment into the orthogonal planes were computed, (2) for each projection, influence buffers given a radius (1m) were computed to obtain a set of related pairs, and finally, (3) the distances in 3D from the center of each pair of fragments were computed. The distance between two fragments is shown in the same figure; in our application, this value is shown when hovering the mouse over each red connector.

In the database, the Table EE_9IM (see Figure 10) stores for each pair of related elements the three matrices DE-9IM computed by PostGIS.

6 RESULTS

We have tested our system prototype with real data from the archaeological site of Castulo. Castulo was an Iberian-Roman city, one of the ancient capital centers in Southern Spain. From this site we have obtained the

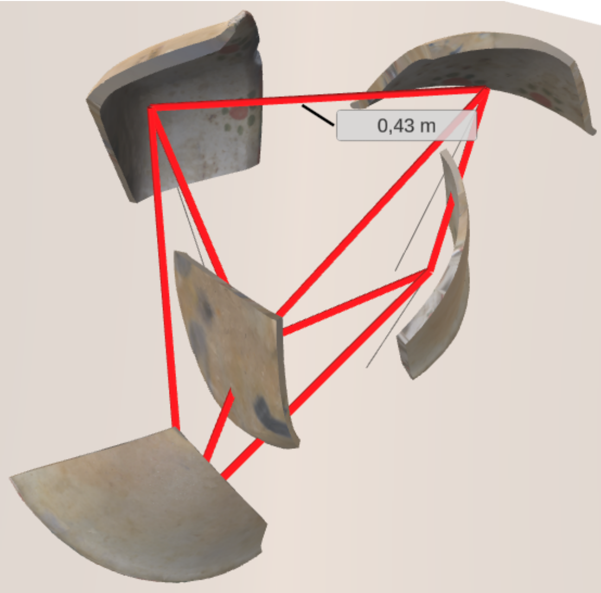


Fig. 14. Distance computation between close pieces

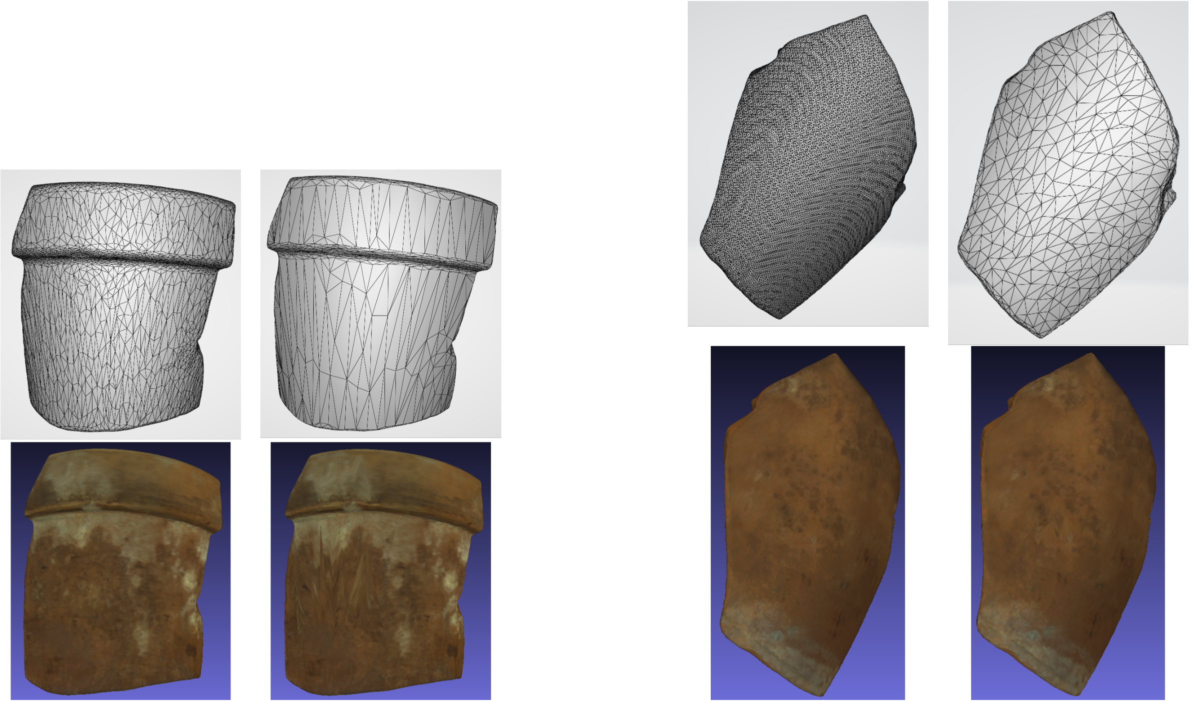
information of areas, volumes and layers. However, due to a series of setbacks in the excavation processes (mainly due to the COVID-19 pandemic), we have not been able to complete our data capture as required. Therefore, we have had to simulate the work on a layer in the following way:

- Several real objects have been scanned and preprocessed to be stored in the database. We have tested the resolution and the loading time of a layer by replicating these models.
- As mentioned in Section 4, we have acquired the 3D site ground surface model from the site used by Archaeology students of our university.

Tests have been carried out on a desktop computer with an Intel Core i7-4790 3.80GHz processor with 16 GB RAM memory DDR3-2400 and a NVIDIA GeForce GTX 970 graphics card with 4GB VRAM. According to Figure 8, each scanned model can be directly displayed in the client-side user application. However, the database only stores simplified versions of these models. Figures 15 and 16 show some of these pieces with different resolutions. The models were acquired with the lowest resolution of the EinScan Pro 2X scanner, and for database storing, the meshes were decimated with Blender to a value between 5% and 30%. However, the visual results are very similar, as can be seen in the figures.

We have measured the time taken for loading the 3D models in a layer (Table 1) considering the number of models (column 1) and the time in seconds to load the full resolution (columns 2 and 3) and the simplified models (columns 4 and 5). In conclusion, we can determine that loading more than four millions of triangles corresponding to 100 virtual models is possible but it requires more than 5 minutes on our test computer. In contrast, if the system loads the simplified models, the number of triangles to be loaded is about two hundred thousand, and the time to have access to the layer is about one minute and a half.

A standard layer with between 20 and 50 full resolution models, and over one million triangles needs about one minute to be loaded. In contrast, the same layer only needs between 12 and 50 seconds when the low resolution models are used. From the point of view of an archaeologist, a full resolution model is not always necessary,



(a) 4774 v.; 9544 t. (b) 1433 v.; 2862 t. (c) 31616 v.; 63228 t. (d) 1266 v.; 2528 t.

Fig. 15. Examples of scanned ceramic pieces and their simplified meshes ("v." stands for vertices, and "t." for triangles)

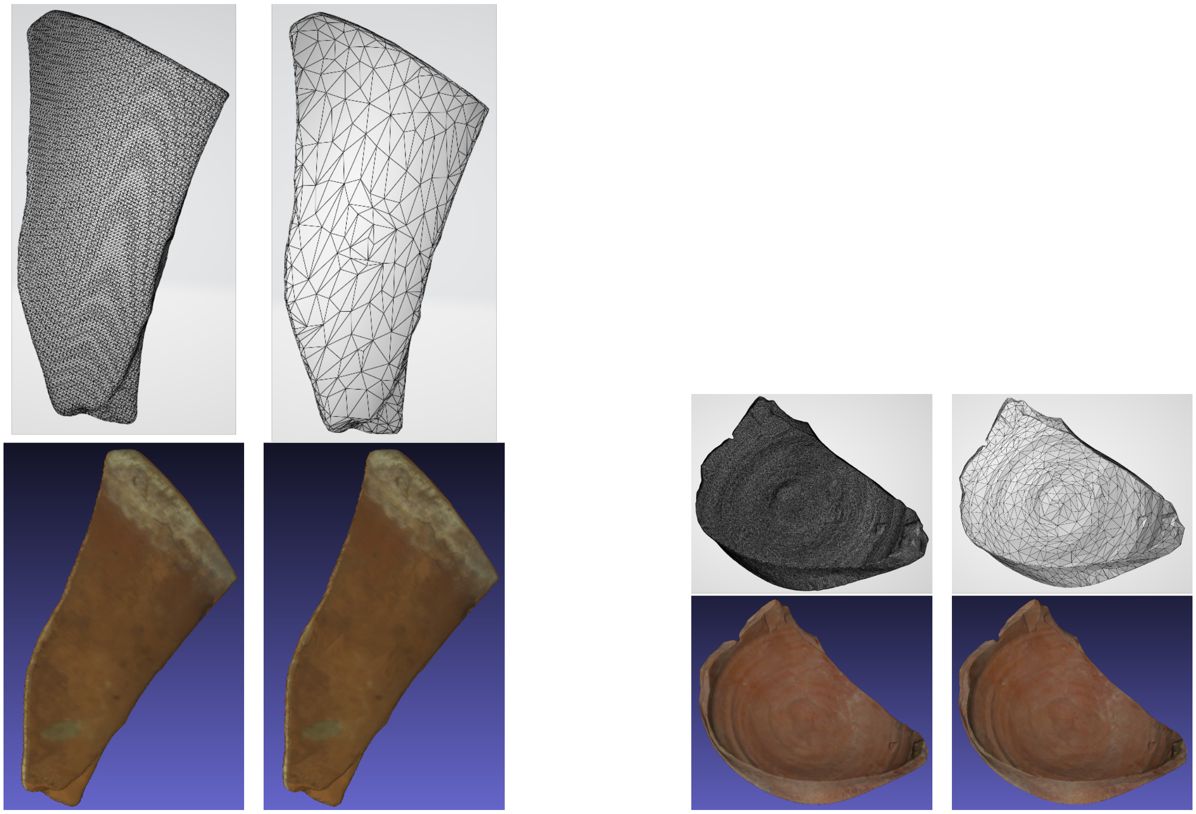
	Original models		Simplified models	
Number of models	Loading time (s)	Triangles (thousands)	Loading time (s)	Triangles (thousands)
5	13.23	224	3.1	12
10	26.72	448	5.9	24
20	53.35	897	12.03	48
50	130.18	2244	50.74	121
100	333.33	4488	90.42	242

Table 1. Times to load the models in a layer

especially when placing the models at their original locations or performing spatial analysis on the virtual site. Thus, the visualization of an entire layer can be done with the simplified models. In contrast, when a specific piece is under thorough scrutiny, the full resolution model should be used.

7 CONCLUSIONS AND FUTURE WORK

In this paper we have described an agile methodology to virtually reconstruct an archaeological site preserving the spatial arrangement of the finds for posterity. This process is implemented as an information system with a client-server architecture. The client runs a Unity application on any device connected to the Internet. It takes advantage of the 3D object manipulation capabilities of this game engine, which makes it possible to easily edit

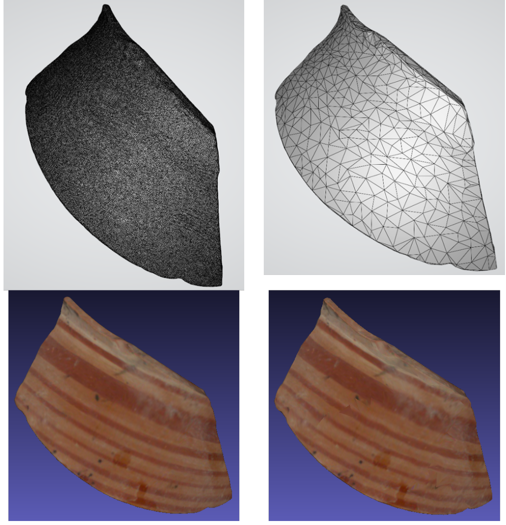


(a) 20483 v.; 40962 t.

(b) 1026 v.; 2048 t.

(c) 193426 v.; 386848 t.

(d) 1452 v.; 2900 t.



(e) 88887 v.; 177770 t.

(f) 1335 v.; 2666 t.

Fig. 16. Examples of scanned ceramic pieces and their simplified meshes ("v." stands for vertices, and "t." for triangles)

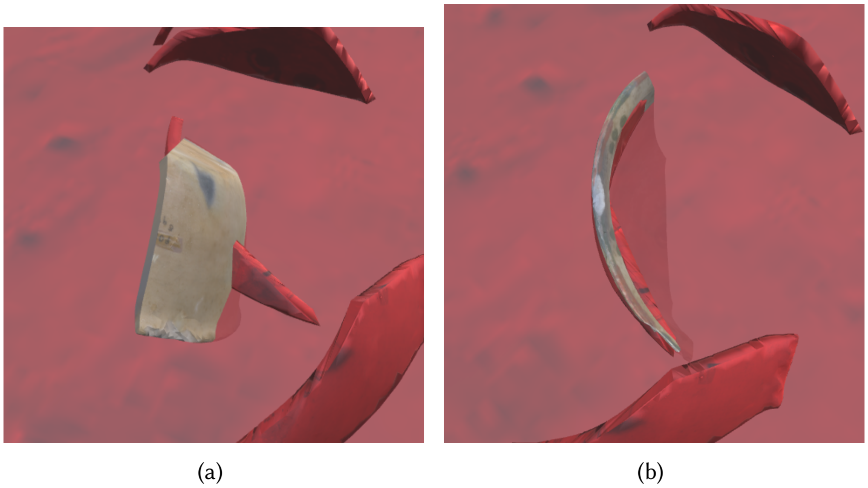

(a) (b)

Fig. 17. 3D model of a piece before (a) and after (b) its placement using the tool

the position and orientation of the find models. We use the 3D site ground surface models acquired during the excavation and before the finds are removed as reference for fine adjusting the position and orientation of the find models. This scanning process can be performed easily in a few seconds by using the ToF technology of current smartphones. With this tool, it is possible to get a visually good result in just a few seconds, and therefore create a realistic replica of the site, as shown in Figure 17.

On the server side, a spatial database stores the classical tables on an archaeological site. In particular, we designed this database based on the entities of the database currently used in the archaeological site of Castulo (Jaén, Spain). Additionally, we include as spatial information for each find its location, its topological relationships with other finds and a low resolution 3D scanned model. The graphical interface in the client allows the user to fine tune the location and orientation of these models, therefore updating the transformation matrix associated with the corresponding element in the database.

Given the 3D models of the finds, the system is able to infer and propose to the user a series of topological relationships, based on the spatial distribution of the models. This process is based on 2D projections of the 3D models into the orthogonal planes XY, YZ and XZ, using the DE-9IM model. Confirming these relationships as really meaningful is up to the expert user.

The procedure can be globally considered as agile, since depending on the number of finds for a given layer, it takes only a few minutes to create the virtual reconstruction once all the pieces have been scanned. In fact, the slowest part of the process is the 3D scanning of each individual piece in the laboratory. An additional result of this process is the achievement of an integrated information system. The graphical interface is linked to the data and makes it possible to navigate and interact with the 3D scene while the information is retrieved from the database transparently to the user. In order to optimize the performance of the interface, the full resolution find models are used only when the expert user requires them for a detailed study. Experts in any part of the world can execute the client application and visit the site virtually, as if they were there. The user interface also allows visualizing the finds without the ground surrounding them. The navigation process provides a perspective from any point of view, and the database is queried by simply clicking the 3D objects.

As future work, we are interested in working with real finds of a layer from the archaeological site of Castulo, since due to the special circumstances caused by the COVID-19 pandemic we have not been able to work with a real excavation. Thus, even though the information related to areas, volumes and layers is from this site, the field work has been simulated by using the facilities used by Archaeology students for their practicum on our university campus.

In addition to working with real data, we want to conduct a thorough study with potential users of the applications (namely researchers and undergraduate students), in order to collect their feedback on the use of the application both with mobile devices and desktop computers, and include their suggestions and comments in future versions of the software. This study will also include aspects related to the time necessary not only for creating the virtual model of the excavation, but also for querying the system. These results will be compared to the procedures currently in use for archaeological recording.

Finally, although initially we ruled out the ICP algorithm because it can not be directly used to compare the 3D find models to the 3D site ground surface model, we are considering the study of different adaptations or modifications of this algorithm to improve the results. Finally, we expect that the SFCGAL extension of PostGIS, which offers advanced 3D functions and volumetric support based on CGAL (Computational Geometry Algorithms Library), provides better spatial analysis features.

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