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ARCube—THE AUGMENTED REALITY CUBE FOR ARCHAEOLOGY*

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Augmented Reality (AR) allows the direct and intuitive access of digital objects visualized in real time on computer screens. AR applications are commonly used in many different areas, such as entertainment, sports and tourism, while their use in archaeology is still limited. When employed, current archaeological AR applications use expensive devices or flat targets, which are insufficient for visualizing complex artefacts. In this paper, we present a low-cost, automated method called the ARCube System, which allows the expansion and enrichment of AR applications focused on archaeological objects. In this paper, the newly developed ARCube System is described by presenting several archaeological examples to show the system's ability to visualize and investigate archaeological finds. The reported tests demonstrate the method's reliability on a variety of objects characterized by different shapes and sizes. The ARCube System allows users to interact with digital 3D models, rotate them through 360° and explore details in high resolution (without any risk of damaging the find). The system renders 1:1 scale between digital and actual object and offers a low-cost flexible system for the interactive visualization of archaeological finds that can be beneficial to public research (e.g., museum exhibits) and education (e.g., the classroom) and may possibly lead to new avenues of archaeological research.

KEYWORDS: AUGMENTED REALITY, COMPLEX 3D MODELS, VISUAL INSPECTION, ARCHAEOLOGY, MULTI-TARGET

INTRODUCTION

Augmented Reality applications offer a live, direct or indirect, view of a physical, real-world environment in which elements are augmented (or modified) by computer-generated sensory inputs such as sound, video, graphics, maps or global navigation satellite system (GNSS) positions (http://www.fondazioneaquileia.it/; Ciolfi and Bannon 2002; Pacheco *et al*. 2014), adding information to real scenes. In contrast to virtual reality, where the real world is replaced by a simulated one, AR is typically in real time and in semantic context with environmental elements (Balog *et al*. 2007). The number of Augmented Reality (AR) applications has been increasing, and now includes gaming, entertainment, education and visualization (http://www.mashable.com; http://www.tripwiremagazine.com). It is a cutting-edge technology that varies from conventional applications, such as visualizing the virtual ball position on TV during sporting events, up to more complex applications, when digital information about objects and their environment is overlaid on to the real world (Fig. 1). While AR has many entertainment uses, it also has possibilities for industry: motor companies such as Toyota, Kia and BMW have developed applications that use AR glasses to assist mechanics in performing automobile maintenance; simulators of robot-assisted

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Figure 1 *(a) Already available AR applications for pop-up books (from http://www.junaio.com), (b) tourist information, (c) educational purposes (from http://www.hitlabnz.org) and (d) commercial applications (from http://goldsealnews.com).*

surgery systems based on AR techniques have been developed for training surgeons (Matu *et al*. 2014). In addition, many companies, such as iPhone, Google and BlackBerry, have developed apps based on AR that superimpose additional real-time information on images acquired by smartphones, such as the location of shops, road information and so on (http://www.junaio.com; http://www.augmented-reality.fr/cest-quoi-la-realite-augmentee/des-exemples-dutilisation-de-la-realite-augmentee/; http://www.augmentedrealitytrends.com/). Last but not least, Google has started some revolutionary projects, such as Project Glass, for the development of an AR head-mounted display (HMD) (http://www.googleglassproject.org/).

The wide range of applications suggests that AR devices could also be very important for investigating archaeological objects. Advanced AR technology can enable archaeologists to edit and interact with digital artefacts in a real-world context. It offers a non-destructive way for archaeologists, art historians and other scholars to examine objects, providing high-resolution detail of objects (depending on the quality of the 3D model) without damaging, dirtying or altering the objects. Researchers located in different locations can simultaneously investigate the same objects, thus facilitating data sharing and collaboration, and ultimately enriching unique experiences for visitors in museums as well as becoming an intuitive device for educational purposes.

AR in archaeology has already been employed in the development of interactive tour guides using smartphones (Wang *et al*. 2011; Niedermair and Ferschin 2012), tablet devices (Vassilios *et al*. 2003) or interactive books (so called AR pop-up books) for very specific applications (Papagiannakis *et al*. 2005; http://www.electricarchaeology.ca). More expensive applications have been developed using special glasses and screens (Benko *et al*. 2004; Zöllner *et al*. 2009).

Many of these archaeological applications tend to focus on entertainment, gaming or tourism (Fig. 1) (Barceló 2000; Vassilios *et al*. 2003; Caarls *et al*. 2009; Noh *et al*. 2009; Garagnani and Manferdini 2011); however, the use of AR for research applications is limited to a few examples (http://www.ucl.ac.uk/museums/petrie/research/research-projects/3dpetrie), because AR is often considered insufficient for scientific use in the visualization of scaled, detailed and metrically correct objects. Then, another shortcoming arises because most applications employ a single coded target tracked by a webcam that does not allow for pivoting of the object, but that allows the visualization of objects only when they are tilted at less than 50° with respect to the webcam. When the tilt angle exceeds 50°, current software cannot correctly set the target in the space. The result is that 3D models are not properly visualized on screen. For archaeology, this problem is particularly relevant because the use of planar targets limits AR visualization to plates or other flat objects, and complex objects (such as figurines, projectile points, statues and jewellery) cannot be easily visualized. As a result, information necessary for research purposes is unavailable (i.e., not visualized).

The ARCube System overcomes some of these limitations: the proposed methodology allows the visualization of complex 3D objects, just by handling a simple cube (the ARCube) and showing the digital replica of the object on the screen. The methodology is based on AR open-source software and low-cost devices; ARCube is flexible for a large number of applications and it prevents the finds from being damaged or soiled, thus becoming a valid instrument for both research and exhibition purposes.

While several free and open-source software programs are available, such as ARSights (http://www.arsights.com), ArToolkit (Woods *et al*. 2003) and BuildAR (http://www.buildar.co.nz), these software toolkits typically employ single flat targets and thus, they cannot be used 'out of the box', but must be adapted to archaeological applications. For these reasons, the new multi-target cube (the ARCube) was developed in order to manage all the possible aspects of complex archaeological 3D models. A 3D Studio Max plug-in was developed to automatically split the 3D model into different overlapping faces and load them in the AR environment for a correct and complete visualization. The presented methodology is a further advancement of an initial work (Jiménez Fernández-Palacios *et al*. 2012), where the potentiality of the approach was shown, but some problems still persisted in the visualization of complex 3D models. In the following sections, the newly developed methodology will be presented and then several tests on reality-based 3D models will be presented to demonstrate the reliability of this methodology for visualizing and accessing archaeological artefacts.

PROCESSING FOR SUB-MODEL GENERATION AND AR VISUALIZATION

The methodology is composed by both hardware and software devices that are concatenated in subsequent steps, as shown in Figure 2. Starting from a 3D model, it is possible to automatically generate a set of sub-models that can be directly loaded in an AR software package. In the following paragraphs, the description of the ARCube and the AR software used is first presented. Then, the methodology to preprocess 3D models for AR applications and the created 3D Studio Max plug-in are reported.

The ARCube device and AR open-source software

The ARCube (Fig. 3 (a)) comprises six targets, one on each face. Each target loads a different part of the 3D model; thus each target must be correctly recognized. Each part of the model has to be

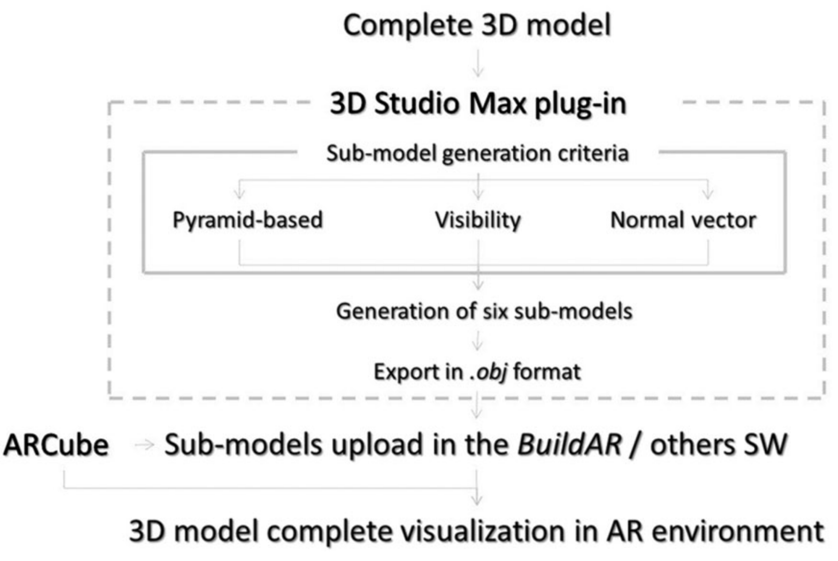

Figure 2 *The presented methodology workflow.*

associated to a defined face of the cube in an unequivocal way to correctly display the object's geometry. For these reasons, several tests were done to identify the best way to split the 3D models and the most appropriate type of target. The distance of the cube from the webcam was varied, the illumination conditions were changed and different alphanumeric characters on the targets were evaluated, to determine which of them were the most suitable and recognizable without any ambiguity. Finally, the letters A, B, C, D, F and G were chosen, as they assured good results in the tests. Each cube face measures 8×8 cm, because: (1) this is the mean value usually suggested by AR software developers; (2) it allows many archaeological artefacts to be visualized at a 1:1 scale or to be rescaled at a suitable scale; (3) it assures a sufficient resolution for target recognition at a distance up to 1.5 m from the webcam (i.e., with a resolution of 2 megapixels and a focal length of 3.7 mm); and (4) the white edges bound the area where the cube can be handled without preventing the target recognition. For the visualization, the BuildAR software (free version) was used, because it is able to simultaneously manage several models of thousands of triangles and it can work with different file formats.

As for the ARCube, each of its six targets has a reference system that is independent from the others, and the link between the faces and the model tiles must respect the criteria used in their generation, in order to build the correct geometry of the object. Because of this, a rototranslation is applied to each model tile to fit the corresponding ARCube target; each tile of the 3D model is loaded separately into the software and associated to a different target (with the same name). The developed 3D Studio Max plug-in generates models that can be visualized on screen without the need of any further transformation (Fig. 3 (b)). In this way, a key advantage for archaeologists consists of the streamlined and automated AR visualization: the user just has to show the ARCube on the webcam and the model will be visualized on the screen.

ARCube methodology—pre-processing of 3D models

The pre-processing procedure consists of dividing a complete 3D model (normally produced using techniques such as laser scanning, photogrammetry, CG modelling etc.) into six

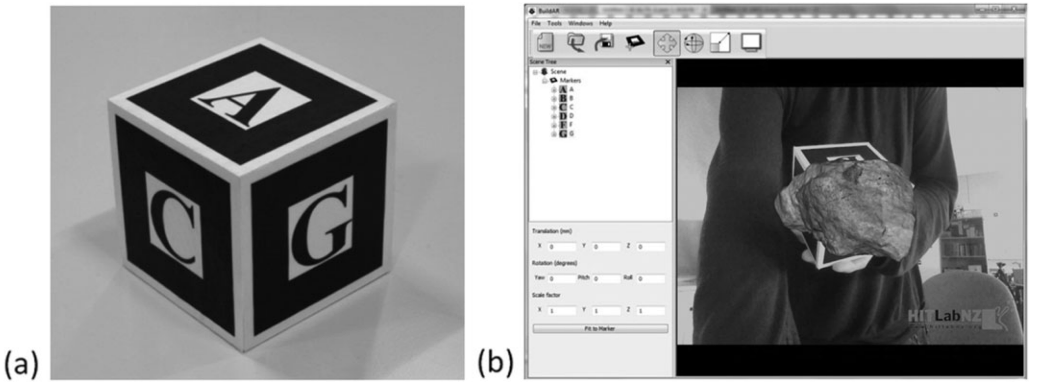

Figure 3 *(a) The ARCube device and (b) a screenshot of the employed open-source BuildAR software for the visualization of archaeological artefacts.*

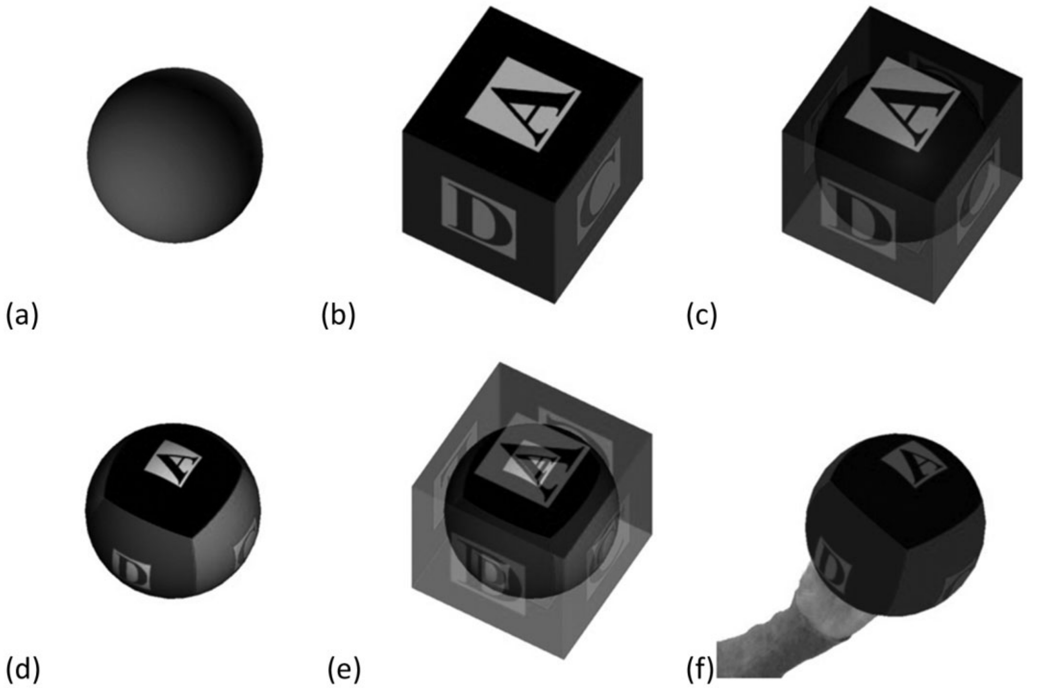

Figure 4 *The steps of the methodology: (a) starting from a 3D model (i.e., a sphere), the virtual replica of the ARCube (b) envelopes the considered 3D model (c); the used 3D model (sphere) is divided into six sub 3D models (d), each corresponding to a side of the cube (e); the 3D model is finally visualized in an AR scene.*

sub-models that can be directly loaded into the AR software. The pre-processing methodology is split into a series of steps, and for simplicity's sake, a sphere, rather than an actual artefact, is used to explain the methodology (Fig. 4 (a)) in the following.

The ARCube, which is concentric with the sphere, is reproduced virtually and each side of the virtual cube is then named in the same way as the real one, in order to define an unequivocal association between them and the real cube (Fig. 4 (b)). The virtual cube is initially sized to envelop the test model, in order to approximate its shape and dimension (Fig. 4 (c)).

Then, the test model is divided into six parts (Fig. 4 (d)). To allow sub-models to be loaded and visualized in the AR software, each sub-model is associated with a face on the virtual cube (Fig. 4 (e)) and then to its corresponding target using a letter (A, B, C, D, F or G) (Fig. 4 (f)).

The six sub-models can be generated by intersecting the model with six pyramids, with the vertex in the barycentre of the model (Jiménez Fernández-Palacios *et al*. 2012). This approach needs some additional manual intervention (i.e., translations from the geometric barycentre of the model) to allow a correct automated splitting of objects with complex convex and concave shapes. For this reason, two additional methods for sub-model generation have been implemented. The first method performs a visibility analysis from different points of view, while the second method segments the object according to the values of the local normal vectors to the model surface. In the following sections, the process of subdividing a complex 3D model (a skull model) is shown in order to explain these three methods (pyramid generation, front face visibility and normal vectors) that have been implemented. The pictures shown in Figure 5 refer to the generation of the sub-model that is associated to target A of the cube.

Sub-model generation criteria As already mentioned, the methods are as follows:

(1) *The pyramid method* (Jiménez Fernández-Palacios *et al*. 2012). This method starts with the generation of six pyramids. Each generated pyramid has its base in correspondence with one side (the base of the pyramid and the cube's face are equal) while the top of the pyramid is in the barycentre's cube. The same process is repeated for each side of the cube in order to obtain the six pyramids. The test model is intersected by the pyramids and is divided into six independent sub-models (Fig. 5 (a)).

(2) *The front face visibility method*. Six points of view, each one corresponding to a different face of the virtual ARCube, are defined. Then, all the front face polygons of the model with respect to a defined point of view are selected (Fig. 5 (b)). In this way, each face of the cube is associated to the visible part of the model.

(3) *The normal vector method*. In this method, six different directions are defined, each one perpendicular to a different face of the cube. Then, the values of the normal vector for each polygon of the model are computed and are compared to the normal directions of the faces of the cube. For each face of the cube, the polygons with normal vectors close to the corresponding direction are selected: polygons with normal vector directions that differ by less than 30–40° from the cube face direction are usually selected (Fig. 5 (c)).

These methods can be implemented together in order to assure a complete visualization of the model in every condition. The points selected by at least one of the above-described methods are considered in the sub-model generation of the corresponding face of the cube. If the model is completely concave, the normal vector and the front face methods will provide very similar results: on the other hand, the normal vector method will also allow the loading of hidden and occluded parts with similar normal directions corresponding to convex parts of the model.

For not just a slice (i.e., the newly generated sub-models) but the complete 3D model to be visualized in the AR scene, a smooth transition between each sub-model and its adjacent sub-models must be guaranteed, especially when the cube is rotated. For this reason, overlapping sub-models are usually generated using overlapping pyramids or higher difference values in the normal vector method, as will be described in the 'Case study' section.

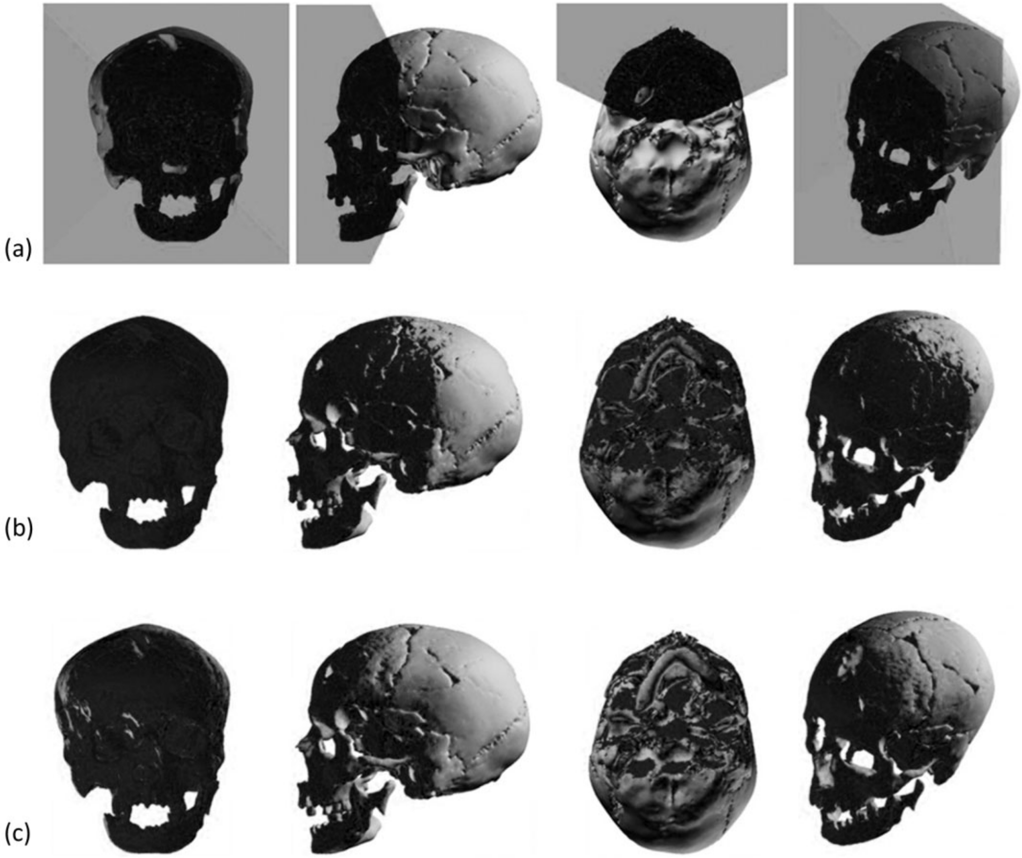

Figure 5 *The sub-model generation criteria: (a) the generation of a sub-model using the pyramid method; (b) the generation of a sub-model using the front face visibility method; and (c) the generation of a sub-model using the normal vector method.*

The ARCube plug-in for 3D Studio Max

Based on the pre-processing described above, an automatic procedure has been developed in order to obtain a split 3D model that can be directly imported into an AR software program (i.e., BuildAR). 3D Studio Max was chosen because it is commonly used by architects, archaeologists and other professionals for 3D modelling and it permits a straightforward workflow. A number of open-source software programs (e.g., Blender) would have been suitable for this task too.

The MaxScript language, which is natively available in order to customize 3DS Max Design 2011, was used to create the ARCube plug-in (Fig. 6): the script allows users to create personal windows, buttons and dialogue messages to facilitate the user's experience and completely automate the process. Initially, the 3D model is loaded and the export folder is defined in the plug-in window. The barycentre of the object is automatically defined to translate the system coordinate origin on to it; a scaling value can be defined if necessary, to scale the object. The shape and the minimum and maximum dimensions are automatically evaluated by the software in order to generate a virtual box sufficient to envelop the whole model and generate the sub-models in the correct way.

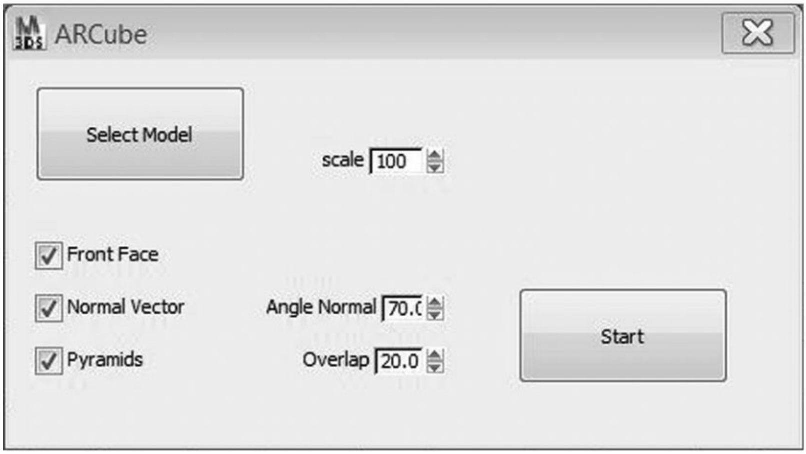

Figure 6 *The ARCube plug-in.*

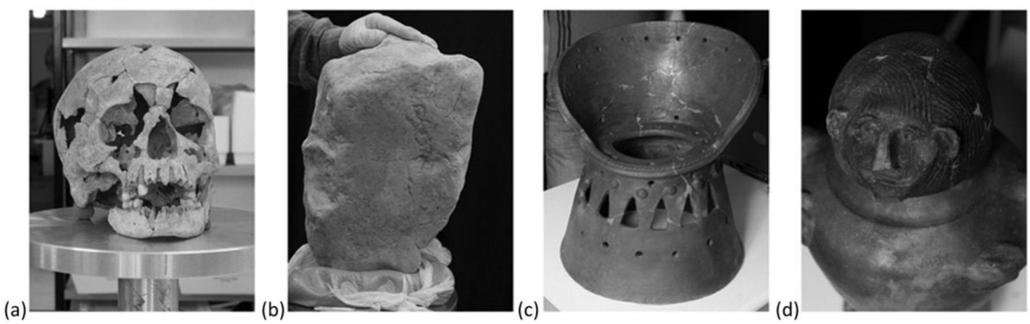

Figure 7 *Test artefacts: (a) the Mezzocorona skull; (b) Dalmeri's Stone; (c) the funeral throne of Chianciano Terme; and (d) the monkey's head.*

In the pyramid method, the dimensions of the pyramid depend on the overlap value defined as the input: the vertex is in the centre of the system coordinates (0,0,0) and the bases are parallel to one side of the box. When the overlap is set to zero, each side of the adjacent pyramid is coincident with the sides of the adjacent pyramid. However, when the overlap is greater, the base of each pyramid will be proportionally bigger than the side of the corresponding box. The normal vector method can be set defining the threshold angle for the process of aggregation of polygons. When this method is selected, the maximum difference angle between the normal vector direction and the face direction can be defined: high values imply that a greater part of model is selected. Finally, the front face method does not need any parameter setting.

After the parameters have been set, the plug-in is started and it automatically generates tiles for the models. Each face of the cube has an independent X,Y,Z reference system, which requires that each tile is rotated and translated from the 3D model into the new target reference system. The plug-in perfoms these functions automatically and the tiles are finally exported in .obj format.

CASE STUDY: APPLYING AR TO ARCHAEOLOGICAL ARTEFACTS

This section presents four practical cases. They are (a) the Mezzocorona skull, (b) Dalmeri's Stone, (c) the funeral throne of Chianciano Terme and (d) a monkey's head (Fig. 7). These four

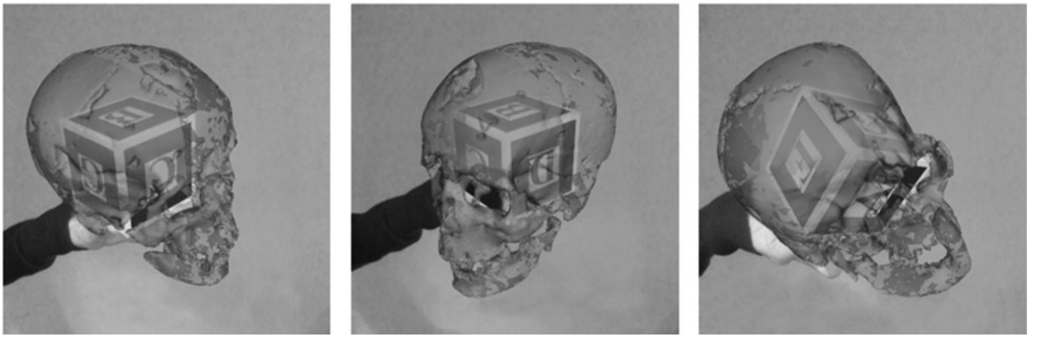

Figure 8 *An AR visualization of the woman's skull from the archaeological area in Mezzocorona, Trento, Italy.*

artefacts were selected because they represent a range of physical characteristics, including different shapes, materials, colours and dimensions, that can be used to evaluate the performance, suitability and quality of AR visualization. The cube can visualize 3D models with dimensions sufficient to 'include' the cube during on-screen visualization (the lower dimension is higher than the cube side). The 3D models were acquired using triangulation-based laser scanners. Each test model has a sub-millimeter resolution (0.3 mm) to guarantee good quality in its visualization: in this way, details such as incisions or fractures necessary for highly accurate measurements during research or conservation studies were correctly captured. The models were textured with high-resolution digital images acquired using a Nikon D3X camera, in order to create photo-realistic 3D models that can assist in archaeological analysis.

The Mezzocorona skull

This test was performed using the 3D model of a woman's skull of the ancient Bronze Age (Fig. 7 (a)). The skull was discovered in the funeral area of Mezzocorona (Tomb no. 10), in the 'Borgo Nuovo' area, an archaeological site located in the Trentino region (Italy). The artefact is preserved at the 'Soprintendenza per i Beni Librari Archivistici e Archeologici' in Trento (Italy) and it was surveyed in order to achieve a physical replica at a 1:1 scale for the reproduction of a prehistoric woman. The artefact is about 200 mm wide and 160 mm high. The 3D model was acquired by using the ShapeGrabber triangulation-based laser scanner and the complete model consists of approximately 1 800 000 triangles.

Due to its complex geometry, this archaeological object was chosen to show the different methods used to generate sub-models. The original 3D model was simplified to 500 000 polygons in order to reduce the size of the model and the time needed for the sub-model generation.

The pyramid and visibility methods were chosen in order to guarantee the visibility of the whole model. The final 3D model is shown in Figure 8 in semi-transparent mode, which also allows us to see the ARCube behind the digital model.

Dalmeri's Stone

Dalmeri's Stone (RD_211) (Fig. 7 (b)), an anthropomorphic figure with a hat (Dalmeri and Neri 2008), was excavated at the archaeological site of 'Riparo Dalmeri' in the Trentino region (Italy). This irregularly shaped granite stone was painted about 6000 years ago and remnants

Figure 9 *An AR visualization of the painted stone (RD_211) belonging to the Palaeolithic 'Riparo Dalmeri' archaeological site (Trento, Italy).*

of ochre are still visible on its surface. The ShapeGrabber triangulation-based laser scanner was used to acquire the 3D data. The artefact is approximately 310 mm high and 140 mm wide and the AR visualization was done at a 1:1 scale; the final model contains ~372 000 triangles. The pyramid method was demonstrated to be ideal to visualize this artefact, which is characterized by regular geometry. An overlap of about 20% between adjacent tiles was used in order to guarantee a smooth transition between models when the cube is rotated. In Figure 9, different views of the virtual artefact illustrate the complete visualization of the find provided by the ARCube.

The model looks well defined on the screen due to the high density of polygons in the geometric data and the very high resolution of the images used in the model texture.

The funeral throne of Chianciano Terme

The third test is a throne (Fig. 7 (c)) that was part of an Etruscan funeral urn (seventh century BC), which was discovered in an Etruscan tomb. Today, the artefact is housed in the Archaeological Etruscan Museum of Chianciano Terme, Italy.

The artefact is cylindrical and the diameter varies from 250 mm in the centre to 380 mm at the bottom and its height is approximately 440 mm. The 3D data were collected using the ShapeGrabber triangulation-based laser scanner and the 3D model comprises about 3 million triangles. The results of this test were previously presented in Jiménez Fernández-Palacios *et al*. (2012). In that paper, the problems in complete visualization of the model arising from the artefact's elongated and convex shape were described. To overcome these problems, the new methodology for generation of sub-models has been applied. In particular, the pyramids were set with a large overlap value, to guarantee reconstruction of the complete model. On the other hand, a different threshold of 40° was used in the normal vector estimation. In comparison to the original test (based solely on the pyramid method), the visualized 3D model is complete, indicating that the integration of the normal vectors method can achieve better results (Fig. 10).

The monkey's head

The last test was performed on a monkey's head (Fig. 7 (d)) that formed part of an Etruscan funeral urn found in an Etruscan tomb (seventh century BC). This artefact is now located in the

Figure 10 *An AR visualization of an Etruscan throne (part of a funeral urn).*

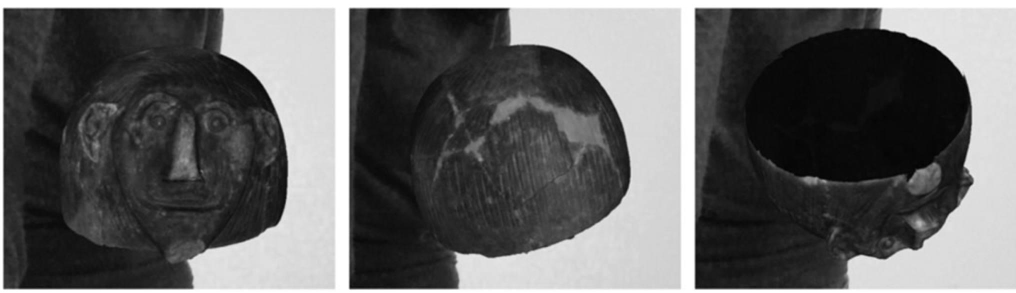

Figure 11 *An AR visualization of the monkey's head found in an Etruscan tomb.*

Archaeological Etruscan Museum of Chianciano Terme, Italy. The produced 3D model of the artefact was generated by the NextEngine scanner and comprises about 575 000 triangles.

The height of the artefact is similar to the width dimensions (about 180 mm × 160 mm), but this artefact is also convex, as in the previous test. For this reason, the strategy to achieve a complete 3D visualization is the same, using both the pyramids method and the normal vector method. In order to guarantee a smooth transition between sub-models, an overlap of 20% between adjacent tiles is used. As shown in Figure 11, the visualized 3D model looks complete both in its external and internal aspects.

DISCUSSION

The paper has presented a new methodology for the visualization and management of archaeological artefacts in AR environment. Compared to Kinect and 3D glasses, ARCube takes an opposite approach: Kinect and 3D glasses assume that observers move around the inspected object, while ARCube allows them to be inspected by rotating and moving the small cube only; in this way, the presented approach has proved to be particularly suitable for small artefacts.

Several tests have been presented, using laser scanner generated textured 3D models to evaluate the reliability of the method under challenging operational conditions. The developed plug-in splits the 3D models into six different sub-models, oriented in a common reference system, to reproduce the complete object geometry. Only the visible parts of the object are loaded on the screen managing high-resolution models. The object can be moved interactively by the operator and it is visualized on the screen in real time. The sub-model generation is performed using three different methods: pyramid generation, front face visibility and normal vector estimation. Good results can be achieved using standard values in most cases. In any event, simply by modifying few parameters, a complete visualization can also be guaranteed with complex geometries. The performed tests have shown the reliability of the methodology on a large variety of objects characterized by different shapes and sizes. The front face visibility and normal vector estimation allowed us to optimize the visualization in the funeral throne model, overcoming the limits of the former implementations. The tracking of the target still suffers from the illumination conditions and therefore homogeneous illumination is suggested for a reliable visualization.

The software correctly tracks targets, allowing an efficient visualization of the model as shown in the following video: http://youtu.be/BxhX8DzHL2w. The visibility of the complete artefact is always assured by the faces of more than one active cube at any time and by using overlapping models. The textural quality of the 3D models partly depends on the illumination and contrast on the screen and on the possibility of interactively changing these values in the model. In any event, the high geometric and textural quality of the tested models allowed sharp and well-defined shapes and colours in the AR scene, providing a realistic visualization of the objects.

In general, the better the hardware (the PC and webcam) performs, the better is the definition. Various different PCs and different model resolutions were considered: the tracking and the visualization processes proved to be effective in most cases. BuildAR (the free version) has shown its reliability and handiness, but it does not allow programming and customizations. Other open-source toolkits will be tested and customized to add some features, such as the interactive variation in the model illumination to increase the visualization quality and highlight different details on its surface. The developed MaxScript will be converted and tested in other programming languages to process the data using open-source software only.

CONCLUSIONS

In this paper, a new application using Augmented Reality (AR) tools was described and applied to interactively visualize archaeological finds. Although a huge number of software programs devoted to AR applications have been developed, the ARCube System exploits a 3D target instead of 2D targets, as proposed in the already existing applications. The 2D targets are useful to visualize one side of the artefacts only: the tracking process is guaranteed when rotations between the target and the webcam do not exceed 50° and back-face visualization of the model is not allowed. The complete visualization of artefacts on the screen can be guaranteed by the ARCube System, as it exploits six 2D targets integrated together. The improvements and the optimization of Jiménez Fernández-Palacios *et al*. (2012) were presented. The ARCube is an automated, turnkey and low-cost solution that could be successfully applied both for reseach and educational purposes by enabling 360° interaction with fully reconstructed 3D archaeological artefacts in real-world contexts. Compared to other devices (such as 3D glasses and Kinect), it represents a low-cost solution, which is easy to use and does not require any additional energy supply, making it particularly suitable for the visualization of small artefacts.

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