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Heritage pieces integration in autonomous augmented reality systems: key problems and solutions

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Abstract

Nowadays virtual reality users and professionals demand a growing quality and a higher degree of realism in development and applications. Among these technologies augmented reality systems stand out due to their complexity and possibilities, having open current problems from the digitalization process to the accurate insertion of digital information in the reality. This paper is addressed to present solutions to key problems that arise in these environments which the 3D Computer Vision and Robotics (UCLM) group has been working on over the last two years. The final objective is to extend and complete the real visual information perceived by the user superimposing three-dimensional information synthesized with a high degree of realism. Our research is focused on two aspects that converge towards the same objective. The first objective is to carry out a reverse engineering process on valuable heritage pieces with the aim of obtaining complete and realistic models. This is a field where current technology itself is not capable of yielding a complete and satisfactory answer. Here we present solutions to two of the most important issues which many researchers continue working on: automatic filling holes in 3D meshes and color integration in the geometrical model through view fusion techniques. The second objective concerns the problem of the insertion of virtual models in the image captured by one or more cameras. Current display as well as positioning devices solves most of the AR problems in controlled environments. Nevertheless, a more interesting matter, on which notable research efforts are being carried out, are focused on the positioning aspects in external and non controlled environments. In this paper, we describe an efficient solution with low computational cost that allows us to carry out autonomous augmented reality sessions in free environments.

Categories and Subject Descriptors (according to ACM CCS): I.4 [Image processing and computer vision]: Digitization and Image Capture I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism-Virtual Reality

1. Current problems in A.R. systems

Cultural heritage is currently accessible to the people in a virtual way thanks to the technology developed over the last two decades. Within the new technologies, augmented or mixed reality systems allow an interaction with the real world in a natural way, by adding synthetic objects over the live image of the scene. So, in the last years a special effort has been made to develop methods and systems [IHEM06].

Autonomous augmented reality systems (AARS) add a significant enhancement and a growth complexity not always successfully solved. In fact, although there are hardware devices which provide the image of the scene (monocular or stereo cameras), the user position (inertial devices, vision based methods, etc) and the real/fiction visualization (integrated displays), augmented reality immersion can be disappointing and sometimes is of low quality. For example, low quality synthetic objects superimposed on the image or inaccurate virtual object insertion are due to the fact that some key steps, even previous to the process of the mix real/virtual, have not been correctly solved.

Four significant phases arise in a virtual reconstruction process: views alignment, geometric integration, mesh processing and color integration.

View registering and geometric integration are problems which have been solved years ago. Despite research progress in the 3D field, the filling holes task is a nontrivial problem which does not have a general solution yet (Problem 1). Color processing plays a key role in the whole process where several researchers have only introduced partial solutions. Most of them are based on global approaches, where the complete image is processed (and therefore, modified) or local strategies, where only the colors of some points of the image vary. Consequently, obtaining accurate whole models (geometry+color) is an unsolved and important problem on which researchers and partitioners are currently working [BB06] (Problem 2).

Regarding the insertion of synthesized models over the live image, most of the steps are solved with current devices. As we know, the augmented reality process has three basic components. First, an image capture module (camera) to provide images from the real environment. Second, a visualization module (stereo projection systems or augmented reality glasses) solves the problem of making up and displaying the augmented real world with unreal information. The third component, not always solved by the technology, must provide position and orientation of the user in the real environment. Although there are positioning and tracking systems, all of them can be effective in controlled environments. However, for autonomous systems, positioning must be solved with new solutions. Consequently, this issue continues to be an open research field, where more innovative solutions are suggested every year (Problem 3).

In this paper we present solutions to the noted problems (Section 2): detection and automatic hole filling in mesh structures, color integration in the model by means of view fusion techniques and an original and computational efficient solution which allows the user to navigate in autonomous augmented reality environments. Finally section 3 presents the integration of solutions in the whole system.

2. Realistic virtual models in augmented reality systems

2.1. Problem 1: Filling holes in 3D meshes

Hole filling is one of the most important and not completely solved problems that remain in the digital reconstruction area. Moreover it is a tedious and less autonomous task in mesh processing. There are two facts that lead to the appearance of holes in a mesh. One is due to an incorrect redefinition or loss of data in the register and/or integration process. The second is the loss of geometric information, for example, during the acquisition process. In this case, the holes are greater and the neighbouring area must be used to fill them. Figure 1 shows a mesh with several great holes.

There are two main approaches for filling holes in 3D surfaces. Firstly, there exist methods in which the hole filling is an implicit task in the generation of the 3D model. The input for the first kind of method is the 3D coordinates of the surface with no topological information associated. From this data a representation with no holes (mesh, Bezier, implicit function...) is created. More information about techniques that follow this strategy can be found in [Del99], [HK06]. In the second approach the hole filling task is a post process of the 3D mesh generation. This second strategy is more common than the first one. That is because with these algorithms, the 3D mesh modeling process becomes independent of the hole filling procedure, which allows the use of more flexible mesh restoration methods. Interesting works in this line can be reviewed in [NT03], [DMGL02], [WO07].

All the methods cited above have a common feature: they have no general validity, that is, they can offer good solutions for some kinds of holes, but not for all cases. To solve this problem we have decided to test image restoration algorithms to the reparation of surfaces, as they provide very good results for a large variety of situations.

Our filling holes technique has been developed modifying two image restoration algorithms in order to adapt them to three dimensional topologies. The first technique, proposed by Roth and Black [RB05], extends traditional Markov Random Field (MRF) models by learning potential functions over extended pixel neighbourhood. The second algorithm is the one's by Criminisi et al. [CPT04] and combines the advantages of two approaches: "texture synthesis" algorithms for generating large image regions from sample textures, and "inpainting" techniques for filling in small image gaps. Therefore the developed method for filling holes in 3D surfaces are based on image restoration algorithms. In order to measure the suitability of our method we generated artificial holes and compared the repaired and original meshes. The main stages of our approach are as follows:

1. Creation of artificial holes in a mesh.
2. 3D-2D transformation to obtain an image associated to a mesh.
3. Application of the restoration image algorithm.
4. After a 2D-3D transformation, merging of the filled hole and the mesh obtained in stage 1.
5. Comparison between nodes built in stage 4 and those that belong to the original mesh.

Figure 1 illustrates this procedure. The original mesh, labelled M, is subjected to a process of hole creation to provide M_h. In the next step a range image, I_h, is generated by projecting every point of the 3D mesh onto a plane and associating a depth value to every pixel of the projection. Range image I_h is the input data for the restoration image algorithms proposed in [RB05], [CPT04]. The filled image is denoted I_f . Fourth stage consists of the 3D transformation of the repaired patches in I_f to get M_f , which is merged with M_h to provide the resulting mesh M'. Finally, M' is compared with M to validate the applied algorithm.

As we said above the verification of this method has been carried out by comparing the data of the original mesh, M, with the data of the repaired one, M'. The comparison is based on the measurement of the Euclidean distance between the nodes belonging to M' and their related nodes of M. We have applied the method over 20 partial views of

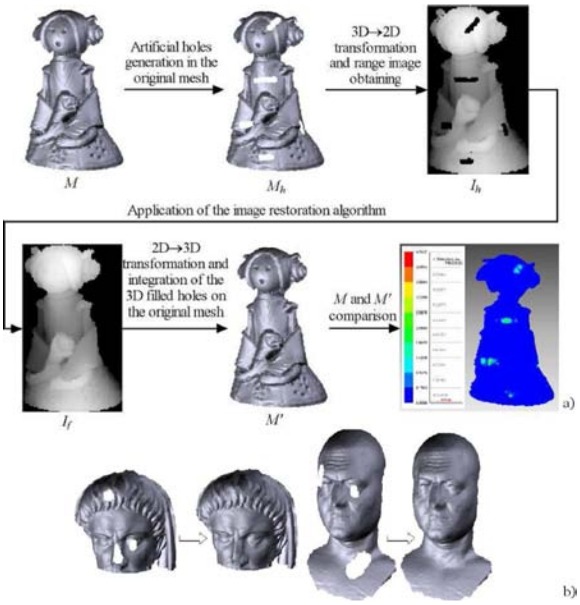

Figure 1: *a) Procedure for 3D surface filling holes and evaluation of image restoration algorithms. b) Original and repaired meshes*

freeform objects sensed with a Minolta VI-300 scanner. The meshes have been damaged with a number of holes, from 2 up to 6, all with significant sizes and different kinds of surfaces (smooth surfaces, surfaces with sharp edges, flat surfaces, etc.). Figure 1 shows restorations performed on several meshes from the sculptural collection of the National Museum of Roman Art in Spain, using the expounded method and algorithm.

In order to prove the usefulness degree we have compared our method with another commercial software packet that includes filling holes solutions. Thus, the same holes have also been filled using this commercial software. Figure 2 illustrates the obtained errors with our algorithm and the commercial software for 32 meshes. Also the average values of both two series are calculated yielding values $Av = 0.65$ and $AvComSoft = 0.71$, which confirms the good performance of our approach. A complete report of this work can be found in [PSA*08].

2.2. Problem 2: Color processing

As mentioned before one of the faults of the current conventional 3D sensor devices is that they are unable to make a realistic color fusion between overlapped samples Thus, integration of the different colors acquired from different views is still an open problem [BB06]. The aim of this section is to present an overview of an efficient technique that allows us to obtain realistic colors of an object which is viewed from a set of viewpoints.

In the virtual reconstruction process, color processing plays a key role where several researchers have introduced partial solutions. Most of them are based on global approaches, where the complete image is processed (and therefore, modified) or local strategies, where only the colors of some points of the image vary. Works which deal with 3D meshes and information obtained from range sensors can be found in references [BFA07], [WG03], [CCRS03], [PGSQ05]. We have designed a method that improves previous solutions by introducing a new merging texture approach that integrates global and local corrections. As a consequence of this, color changes due to lighting conditions and camera positions as well as local color discontinuities between adjacent views are corrected achieving a realistic and complete color map. The general idea is to perform a precise color mapping over the nodes (or vertices) of the complete geometric model and then to accomplish a sequential correction based on surface attributes.

Here we assume that the whole geometrical model has been built in advance following a sequential process which integrates all views. Thus, the geometrical model grows as a new partial mesh is integrated with the whole geometrical model M being the final result. For n views, we also store: the point coordinates of each view at a common world reference system $\{P_1{}^*, P_2{}^*, P_3{}^*, \ldots P_n{}^*\}$; the set of transformations that aligns the views $\{T_{11}, T_{21}, T_{31}, T_{41}, \ldots_{n1}\}$ and the merged partial meshes $\{M_1, M_{12}, M_{123}, \ldots M_{123\ldots n}\}$, which are obtained as a new registration is made.

Let P be the set of vertices of M. We can associate a partial texture to P, called $I(P)_{V_i}$, which comes from the view V_i. Extending this mapping to all views we have n partial images mapped onto $P, \{I(P)_{V_1}, I(P)_{V_2}, \ldots I(P)_{V_n}\}$ (see Figure 3 above).

The goal is to obtain a realistic and single color image $I(P)$ after integrating the set of partial images

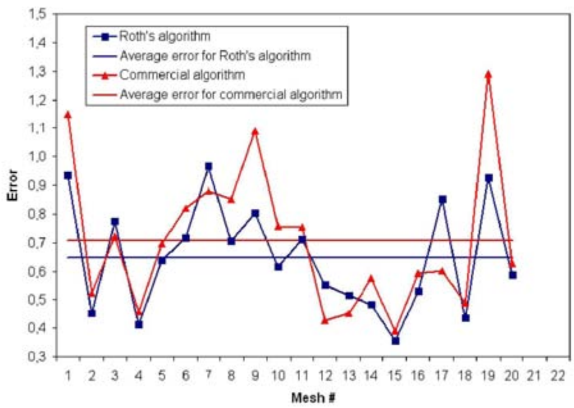

Figure 2: *Error vs. mesh number for the Roth's (in blue) and commercial (in red) algorithms.*

$\{I(P)_{V_1}, I(P)_{V_2}, \ldots I(P)_{V_n}\}$. Then, each vertex of the whole geometrical model $p^k \in P$ will have its assigned color $I(p^k)$.

To perform the total texture integration, two options can be chosen: fusing all partial images in a single step or carrying out a sequential integration. In our case we have adopted the second strategy for several reasons. Firstly, a sequential procedure allows us to control the color merging and to check the result as a new view is added. Secondly, algorithmic and computational requirements are far minor than in a parallel strategy. Figure 3 presents an explicatory diagram of the sequential integration.

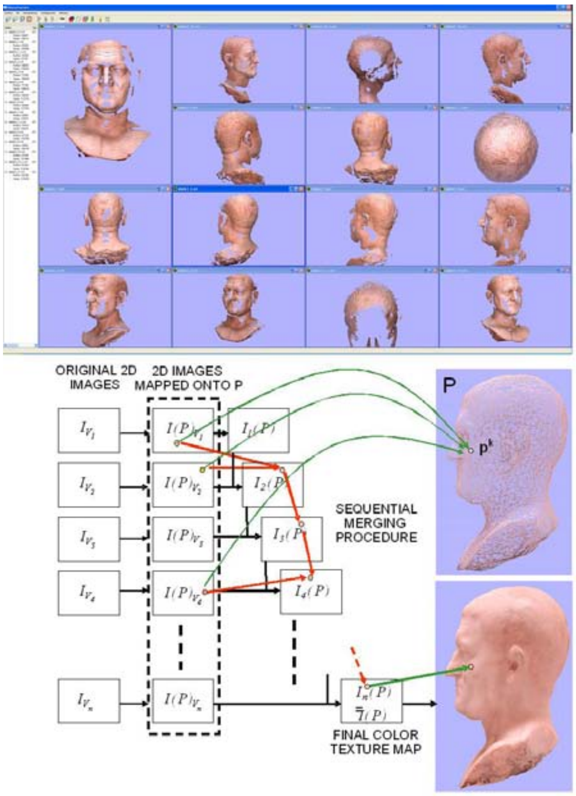

Figure 3: *Set of partial meshes of a male portrait (first century A.D.)and overview of the method.*

In this process, $I_{t-1}(P)$ is the color image assigned to the model M after $t-1$ views have been integrated, $I(P)_{V_q}$ is the image corresponding to the next view V_q to be merged and $I_t(P)$ is the image after merging. The merging process is carried out following three stages: global processing, local processing and filtering. A brief explanation of these follows.

In the global correction phase the image of the following view to be merged is corrected before merging it with the current image $I_{t-1}(P)$. Since we use objects with smooth color changes (marble pieces), the relationship between the colors corresponding to the points that are in the intersection $I(P)_{V_q} \cap I_{t-1}(P)$ is established by means of a linear transformation. This transformation is applied over $I(P)_{V_q}$ obtaining a corrected image.

In the local processing, the corrected image in the last stage is merged with the current whole image $I_{t-1}(P)$ calculating a weighted mean of the RGB components of the overlapped points in both color images. The weight is calculated taking into account the angle θ between the normal at the point p and the vector $\overrightarrow{pO}$, O being the position of the camera.

Finally, color discontinuities corresponding to typical seam or edge points arise after the local correction. The solution to such types of color discontinuities is addressed here by means of a linear smoothing filter in a 3D environment. Filtering process is carried out at the same time over the three seam-points belonging to the triangular patch. We have applied a 3D discrete Gaussian filter over the three color components. Figure 4 above illustrates seam-patches in green, the points that fall into the Gaussian mask in blue and the final result after the smoothing stage.

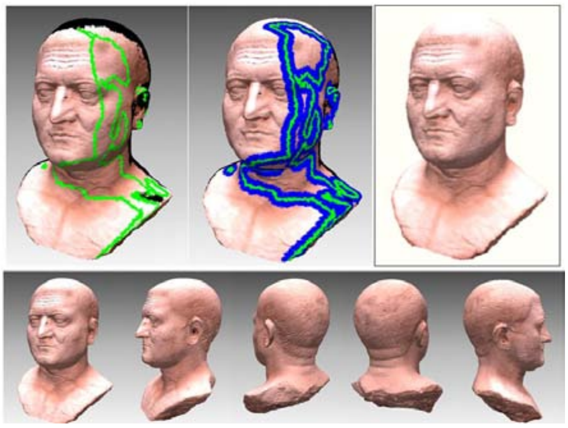

Figure 4: *Above: Detection of seam points (left) Filter windows superimposed onto the model (middle) and final correction (right). Below: Complete model.*

We used a Minolta VIVID 910 laser scanner to take the range images and a 17mm color camera to capture the RGB image of the scene. Acquisition is performed with a very simple light setting consisting of three halogen light sources located in front of the scene. The average surface scanned is around 150cm^2 per sample, handling pieces with up to 200 overlapped samples and meshes with millions of points [ADC*08].

2.3. Problem 3: Inserting virtual models in reality. The observer pose problem

As we have pointed out in the first section, to insert virtual models in AR autonomous systems, the main problem is to obtain an accurate camera pose. In other words, the position and orientation of the observer with respect to the world coordinate system must be calculated as accurately as possible.

Systems with external positioning devices (GPS, compass, etc) provide a coarse pose, so they can only be used for applications that require a low quality. Otherwise, the most efficient and autonomous solutions are suitable for the computer vision field by using artificial [KKR*97] and natural [VLP*03] landmarks.

The movement of the observer involves a variation of the reference system in a short time. The problem of re-calculating the new spatial transformations is faced through tracking techniques by superimposing virtual information on the real scene in real time. This is a complex process in which many solutions have been proposed over the last years. The authors of [ZSM06] present a tracking method that works with several cameras and that allows us to reconstruct and project rigid objects onto the image. Mooser et al [MWYN08] propose a system based on incremental key-point matching that yields good results in complex scenes and for real-time requirements. A tracking solution specially suitable for RA applications based on natural features can be found in [CCP02]. Their approach is based on computing the relative motion of the camera taking into account a set of pre-captured reference frames of the scene. Meanwhile, Cho et. al [CLN99] propose a solution suitable in changing light environments, which means an advantage in non controlled light environments. Finally, Vacchetti et al [VLP*03] present an AR system to blend real scenes with complex objects by carrying out a tracking of natural features of the image, which implies a notable contribution in the AR area.

We introduce a user localization technique from a single landmark using a single frame of the scene. Thus, the user pose problem (position + orientation) is solved through the information extracted from a single image of a specific landmark. These approaches are included in monocular perspective projection techniques. Here we just give an introduction to this method and show how it is used to make mixed reality. An extended explanation of the method can be found in [AM08].

We have designed an original landmark consisting of eight colored spots corresponding to the vertices of an octahedron and one more double-size spot located at the centre of the octahedron. This landmark defines the world reference system, S_0, which is centred at the center-point, lying the rest of spots on plane X_0Z_0. The pose procedure is based on the fact that for any view of the pattern the eight external points belong to an ellipse E which changes its parameters as the camera (or the observer) moves. Through a geometric analysis of E and the location of the points on it, we are able to extract the angular parameters *swing* (ψ), *tilt* (ϕ), *pan* (θ) as well as the distance D' between the origin of S_0 and the camera. Consequently positioning of the user is calculated and digital information (in our case 3D models) can be placed in the real environment captured by the camera. Figure 5 shows images of the landmark viewed from different positions and the ellipse that fits those.

The centres of the nine spots are labelled as $\{P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9\}$. Points P_1 to P_8 come from colored spots whereas P_9 is the centre of a double-size black spot. Note that in the pattern, P_1 *(first point)* is on the Z_0 axis and P_9 and O_0 are coincident.

When the observer moves, a different aspect of the pattern is viewed. Next we will explain what is the consequence of the variation of parameters ψ, ϕ, θ and D' over the ellipse that adjusts the external points P_1 to P_8:

- Parameter ψ gives the rotation of the major axis of the ellipse in the image.
- Parameter ϕ. If $\phi = 0$, $\{P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8\}$ belong to a circle whereas if $\phi \neq 0$ they belong to an ellipse.
- Parameter θ. When $\theta \neq 0$, $\{P_1, P_3, P_5, P_7\}$ are outside the minor and major axis of the ellipse.
- Parameter D' is the distance between O_e and O_0 and maintains a quasi-lineal relationship with major axis of the ellipse.

It is important to point out that the positioning area is not only restricted to the landmark surrounding but it is extended to a wider area like a building. This is possible since we have introduced a color code in the landmark and can easily identify it. Thus the complete location of the user who carries the augmented reality device can be extracted.

The performance and accuracy of this pose method was initially tested on a Pioneer I multisensor mobile robot using a SONY EVI D-31 color camera with controlled azimut/latitude and auto-focus controlled zoom on board yielding promising results. Position error average was below 5cm (e(D)=2.14 cm, e(X)=2.80cm, e(Y)=4.10, e(D)=2.92). After that, the approach was implemented in an autonomous augmented reality system which consists of a Trivisio ARvision-3D HMD binocular head-mounted display with two color cameras and a Quantum3D Thermite portable computer.

As said before we define the world coordinate system in the landmark. When an AR session starts, the observer can see the live scene through the cameras inserted in the HMD device. Then he finds and centres the landmark in the image. Next, an on board computer processes the image and extracts the self position in this system. Finally the 3D to 2D reverse transformation is calculated and the 3D virtual objects can be projected onto the frame. The resulting composite video image is displayed back to both eyes of the user.

The final goal of this work is to carry out different AR sessions where the user can explore cultural heritage pieces, which have been digitalized with quality requirement, inserted in the reality. Of course, the user can move freely around the scene looking at the synthetic model overlapped onto the image. Figure 6 shows several AR experiments that have been carried out inserting valuable pieces reconstructed

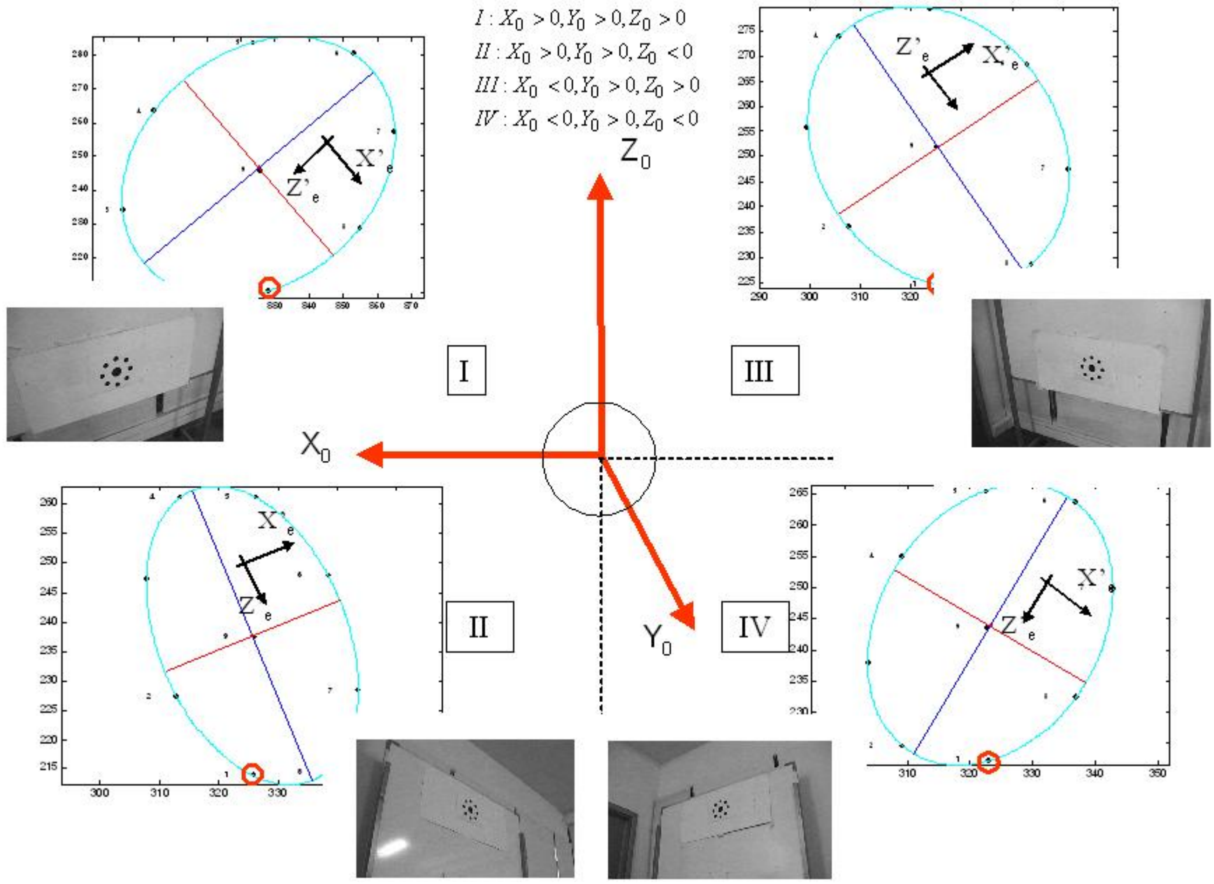

Figure 5: *Aspect of the fitted ellipse depending on the quadrant in which the camera captures the image.*

in our lab. Note that the observer can explore the piece from any viewpoint.

3. Integrated solutions in AARS

In this section we integrate the solutions proposed in this paper into our autonomous augmented reality system. Figure 7 shows a global diagram of the system and the required steps for top-quality results. The solutions presented in this paper (filling holes, color integration and camera pose) have been pointed out on it. This is a long process from the obtaining information problem to the visualization of mixed reality. To integrate the synthetic model into the reality we distinguish between two main blocks: virtual digitalization process of the piece and augmented reality process. In the following paragraphs a discussion about both aspects is given.

Concerning the process of obtaining realistic models through reverse engineering, we have used a Minolta VIVID 910 laser scanner which supplies us geometric and color information of a single view of the scene. Then, we accomplish for all views the alignment and merging processes generating a single mesh. After that, the filling holes procedure is applied and the color integration is later carried out. A complete and unique color-model is obtained using all range images and partial color images taken from different viewpoints. Now, the complete model is ready to be inserted in a graphics system. In the augmented reality part, the user wears a HMD device with two cameras. The user captures the real scene maintaining the landmark into the camera field and the camera position with respect to the landmark is calculated through the algorithm proposed in section 2.3. Then, synthetic model can be virtually inserted in the real image using the graphics resources. Finally, the user perceives the coexistence of real and virtual information at the same space and same time.

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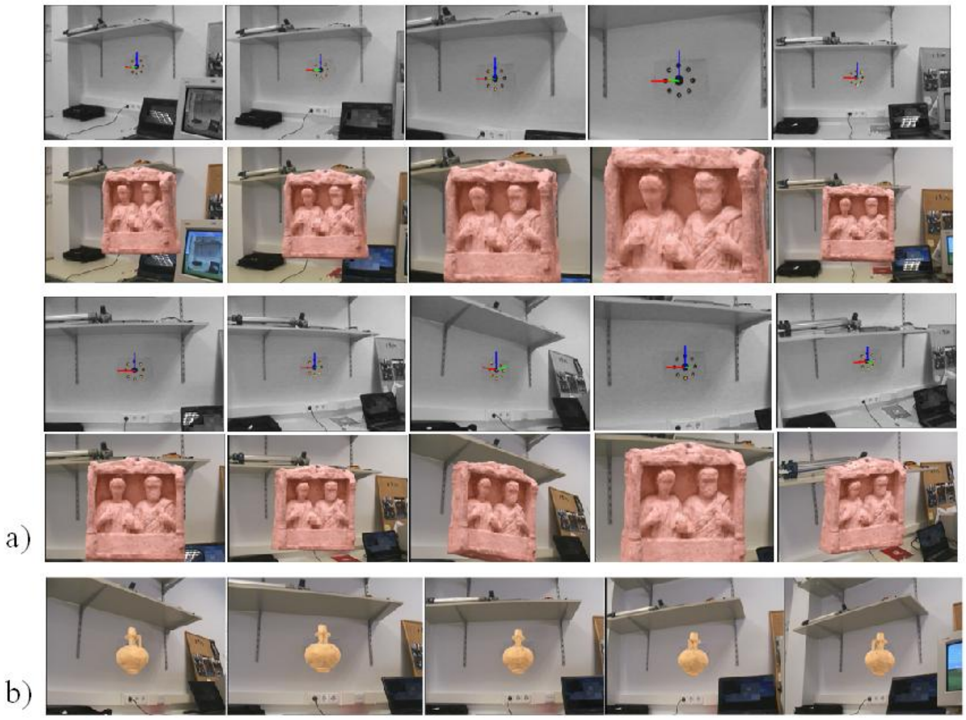

Figure 6: *Inserting virtual models in reality. a) First row: recognition of the landmark and observer pose calculation; Second row: Insertion of the piece in the image (Funeral altar, second century A.D.) b) Insertion of an almohade jar (twelfth century) in several frames.*

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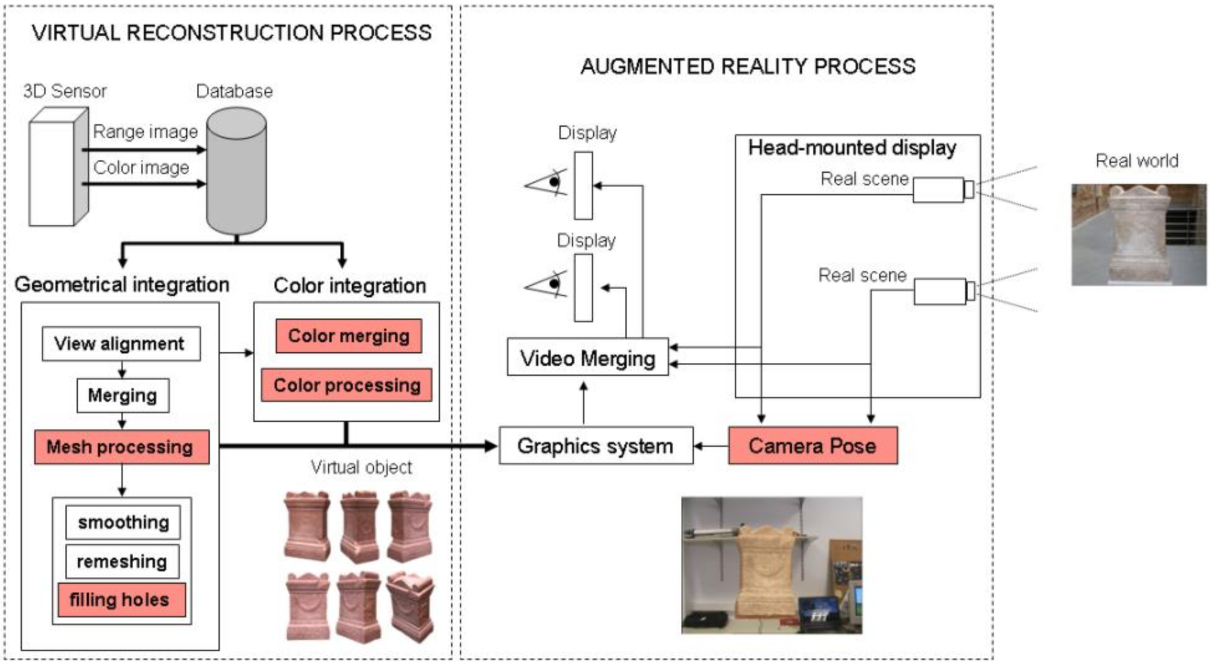

Figure 7: *Virtual reconstruction and integration in the autonomous augmented reality systems*

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