ArcheoTUI - Tangible interaction with foot pedal declutching for the virtual reassembly of fractured archeological objects

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ArcheoTUI is a new tangible user interface for the efficient assembly of the 3D scanned fragments of fractured archeological objects. An efficient user interaction for the complex task to orientate or position two 3D objects relative to each other is essential, eventually in addition to automatic matching techniques.

Our key idea is to use tangible props for the manipulation of the virtual fragments. In each hand, the user manipulates an electromagnetically tracked prop, and the translations and rotations are directly mapped to the corresponding virtual fragments on the display.

For each hand, a corresponding foot pedal is used to clutch the movements of the hands. Hence, the user's hands can be repositioned, or the user can be switched. The software of ArcheoTUI is designed to easily change assembly hypotheses, beyond classical undo/redo, by using a scene graph.

We designed ArcheoTUI on the demand of archeaologists and in a direct collaboration with them, and we conducted two user studies on site at their workplace. The first user study revealed that the interface, and especially the foot pedal, was accepted, and that all the users managed to solve simple assembly tasks. In a second user study, we compare a different clutching mechanism with buttons on the props to the foot pedal mechanism. This second user study revealed that the movement of the hands is more similar to real-world assembly scenarios when using the foot pedals, and that the users can keep on concentrating on the actual assembly task.

Finally, we show how the virtual assembly is used for a fractured archeological finding.

Categories and Subject Descriptors: I.3.1 [**Computer Graphics**]: Input devices; I.3.6 [**Computer Graphics**]: Interaction Techniques; H.5.2 [**User Interfaces**]: Input devices and strategies

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1. INTRODUCTION

Cultural objects of archeological findings are often broken and fractured into an innumerable amount of fragments. A common tedious and time-consuming task for archeologists is to reassemble the fractured objects. So to speak, large 3D puzzles have to be solved. This task is sometimes made even more difficult because some of the fragments are either deteriorated by erosion, weathering, or impact damages, and are sometimes even missing. Moreover, in the case of stoned statues, the fragments can be heavy and must be manipulated carefully, because each move risks damage. Sometimes restorers even build external frames to hold fragments in position while other pieces are fitted, and there is always concern that parts are in the right place when the time comes to glue them together. Even worse, some very big and heavy fragments cannot be moved and assembled at all! Think of, for example, fragments that are underwater.

In recent years, 3D scanners have become ubiquitous for the acquisition of 3D models, and various researchers proposed to scan the fragments in order to use the ever increasing computing power for a virtual computer-aided assembly. Once figured out how the virtual fragments fit together, the information can be used as a blueprint to reconstruct the real-world object.

On the one hand, the reassembly can be done manually by interacting with some standard 3D modelling software. On the other hand, a variety of techniques have been proposed to automatically reassemble the fractured objects recently. Most of these automatic techniques are based on pair wise geometric matching, see e.g. the stunning results of [Huang et al. 2006].

Since all the automatic methods rely on pair wise matching propagated bottom-up to reconstruct the fractured object, they fail when entire fragments are missing, or when the fragments are strongly deteriorated by, for example, erosion, weathering, or impact damages.

We are convinced that in archeology, the long-year work experience of the archeologists is crucial to solving the 3D assembly puzzle. The archeologists reason not only bottom-up by pair wise matching, but also top-down, by considering the assembly problem as a whole, and by taking into account the archeological context. Even though automatic methods assist the user to partly solve the assembly task by classifying and matching the fragments, they cannot fully replace a manual user interaction. Nevertheless, automatic techniques should always be integrated, either before the manual assembly for classification and matching, or after the assembly for precise alignment.

We observed that the user interaction techniques involved in classical existing 3D modelling software hinder the efficient virtual assembly of 3D objects, because the two 3D objects have to be positioned and oriented relative to each other. Since the archeologists are often unexperienced in the user interaction with 3D models by using the 2D metaphor of the mouse, in some laboratories the virtual assembly is somehow slowed down or even completely abandoned. Note that it is already difficult to position and orientate *one* 3D object by a 2D metaphor such as the trackball metaphor. Consequently, positioning and orientating *two* relative to each other is even harder, especially for non 3D experts.

In this paper, we present ArcheoTUI, a new tangible user interface for the efficient assembly of the 3D scanned fragments of fractured archeological objects. The key idea of the ArcheoTUI system is to use props as physical representation and control for the scanned virtual fragments. In each hand, the user manipulates an electromagnetically tracked prop, and the translations and rotations are directly mapped to the corresponding virtual fragments on the display. For each hand, a corresponding foot pedal is used to clutch the movements of the hands. Hence, the user's hands can be repositioned, or the user can be switched.

The software of ArcheoTUI is designed to easily change assembly hypotheses, beyond classical undo/redo, by using a scene graph. This is important because the reassembly of archeological findings is a lengthy trial-and-error task.

ArcheoTUI was initiated by the demand of archeologists to improve the user interaction for the assembly task. We designed ArcheoTUI in a direct collaboration with a team of archeologists, and we show its efficiency in a virtual assembly of one of their fractured archeological findings.

This paper is organized as follows. In Section 2, we review some related work on tangible user interfaces for the automatic assembly of virtual objects, and we recall some automatic assembly techniques. In Section 3, we present the set-up of our ArcheoTUI system. In Section 4 we describe the involved software. In Section 5 and 6 we present two user studies, before we conclude and show directions for future work in Section 7.

2. STATE OF THE ART

2.1 Overview

We structure the related work into two categories. On the one hand, we recall some related interaction techniques, and on the other hand, we discuss some automatic assembly methods that can be used in addition to the manual interaction that we propose.

2.2 Related interaction techniques

When assembling two fragments, the user has to manipulate two times 6DOF at a time, and classical user interfaces such as the 2D mouse or the keyboard are impractical for this assembly task. Our work is inspired by the seminal work of [Hinckley et al. 1994] where passive real-world interface props are used for neurosurgical visualization. In our ArcheoTUI interface, the user manipulates a prop in each hand, and the translations and rotations are directly mapped to the corresponding virtual objects on the display. Note that each of these props can be regarded as 6 degrees of freedom flying mice (e.g. [Ware and Jessome 1988; Fröhlich and Plate 2000]). We consider our user interface to be a tangible user interfaces (TUI): the tangible part, two wooden blocks, can be moved and rotated, and the visualization provides visual feedback. Even though the TUI concept was known before, as passive props ([Hinckley et al. 1994]), or as graspable user interface ([Fitzmaurice et al. 1995]), the term TUI was first defined by [Ishii and Ullmer 1997] as user interfaces that "augment the real physical world by coupling digital information to everyday physical objects and environments". In order to unify the various different definitions and categorizations of TUI, [Fishkin 2004] proposed two axis: the *metaphor axis* classifies the TUI in the way how the system effect of a user action is analogous to the real-world effect of similar actions. The *embodiment axis* qualifies the TUI about how closely the input focus is tied to the output focus.

Using TUIs for assembly is not a new idea. The assembly of numerous Lego-like blocks as props was already done with the ActiveCubes ([Kitamura et al. 2001]). Our work limits the number of props to two, one for each hand, resulting in a bimanual interaction technique ([Buxton and Myers 1986; Kabbash et al. 1994]). Based on the conceptual framework of [Guiard 1987], two-handed manipulation techniques were developed, see for example [Hinckley et al. 1994; Pierce et al. 1999; Llamas et al. 2003], and a part of their success can be attributed to their cognitive benefits ([Leganchuk et al. 1998]).

In the ArcheoTUI user interface, two foot pedals are used. They have to be hold down to clutch the movements of the hands to the movements of the virtual objects. This declutching mechanism was already used by [Hinckley et al. 1994] with only one unique foot pedal, and we extended this metaphor to two foot pedals: the left pedal for the user's left foot is associated to user's left hand actions, and the right pedal for the right hand's action, respectively. Foot pedals for two feet were also used by [Balakrishnan et al. 1999], however, in contrast to our foot pedals, the role for each foot is not similar in their work.

2.3 Automatic assembly methods

The automatic assembly of fractured 3D objects is a groundbreaking idea, and recently, a significant progress has been made, see for example [Huang et al. 2006] and the references therein. An exhaustive review of all existing automatic assembly methods is clearly out of the scope of this paper. Nevertheless, we state that the automatic techniques are generally based on pair wise matching of either geometric or photometric features. Geometric pair wise matching has been proposed by [Papaioannou et al. 2001] by estimating the curvature, and by [Huang et al. 2006] by using a feature-based approach in combination with a non-penetrating iterative closest point algorithm (ICP; [Besl and McKay 1992]). Other pair wise matching approaches for shards of pottery surfaces estimate axis/profile curves ([Willis et al. 2003; Kampel and Sablatnig 2004]), but they are limited to surfaces of revolution. Photometric pair wise matching has been proposed by [Sagiroglu and Eril 2005] by estimating the photographic affinity between neighbouring fragments: the texture outside the border of the fragments is predicted using texture synthesis.

To our knowledge, all the automatic methods rely on pair wise matching that is propagated bottom-up to reconstruct the fractured object. Consequently, they fail when entire fragments are missing, or when the fragments are strongly deteriorated by, for example, erosion, weathering, or impact damages.

However, we are convinced that the automatic assembly methods are essential and should be used in combination with manual user interaction. The automatic assembly methods solve partial or entire assemblies, and they are able to classify the fragments into different categories and identify potential candidates for matching. The results of the automatic methods can be used as an input for the manual user interaction that we propose. And even more, after a user has manually pro-

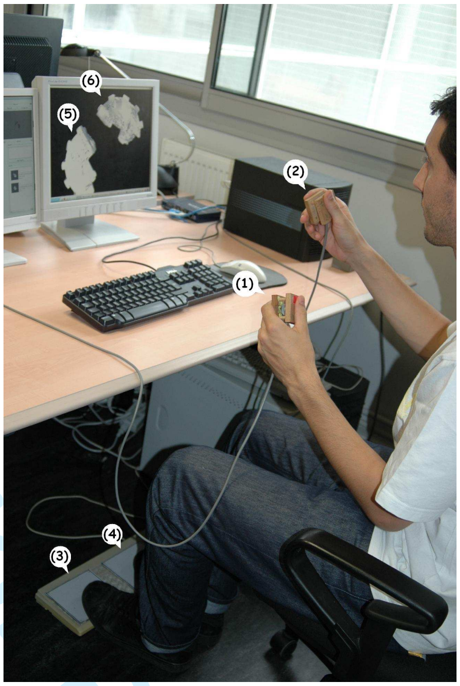


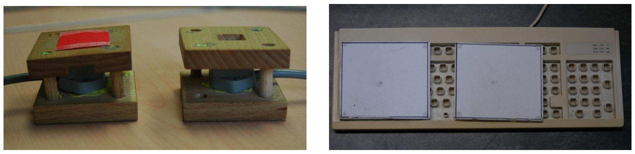
Fig. 1. The ArcheoTUI user interface.

posed a new assembly hypothesis, automatic methods, such as the ICP algorithm, help to precisely align the fragments and can deliver a confidence value about the correspondence of the fragments.

3. THE DESIGN OF ARCHEOTUI

3.1 Overview

The key idea of the ArcheoTUI system is to use props as physical representation and control for the scanned virtual fragments. For an illustration, consider the 6 items of the set-up of the ArcheoTUI system in Figure 1. In each hand, the user manipulates a prop (items 1 and 2). The props can be freely positioned and oriented in space. For each prop, there is a corresponding foot pedal (items 3 and 4). Only when the corresponding foot pedal is pressed down, the translations and rotations are directly mapped to the corresponding virtual fragment on the display (items 5 and 6). Consequently, the user gets a sort of passive haptic feedback when manipulating the props. Once the foot pedal is released, the movement of the corresponding prop is dissociated from the virtual fragment. Consequently, the position and orientation of the virtual fragment is fixed, and the hands of the user can be repositioned. This is especially useful when the user feels uncomfortable about his arm positions, or when the physical props collide with each other. Thanks to this declutching mechanism, the user can also be switched while the virtual fragments stay in position, and thus another user can propose new assembly hypothesis.



(a) The props. (b) The foot pedals.

Fig. 2. The props and the associated foot pedals.

3.2 Technical concerns

Let us now have a closer look on some design decisions for our first prototype. The props are wooden blocks as illustrated in Figure 2(a). We chose the dimensions of $5cm \times 5cm \times 3cm$ for the simple ergonomic consideration that the prop can be easily grasped. In the center of each wooden block, there is a sensor that is tracked electromagnetically by the Polhemus Liberty system with a precision of 0.08cm and a latency time of 3.5ms. Of course, it would be better to use a wireless tracking system such as the Polhemus Latus. Maybe we should remark at this point that at the beginning of the project, we tried wireless optical tracking with one camera and the ARToolkit. However, we quickly abondoned this idea due to occlusion problems.

Concerning the pedals, we used an additional keyboard and simply fixed two classical CD covers on the left and right CTRL keys (Figure 2(b)). Of course, this in an intermediate solution that works quite well, and future prototypes will integrate a more ergonomic solution with a better design. Note that initially, we preferred the foot pedals compared to simple buttons on the props, because the props are rotated all the time and differently grasped by the users, thus the buttons are not always well accessible. However, in our second comparative user study, we experimented also to put buttons on the props for the declutching in order to justify our choice for the foot pedals.

In our current prototype, when mapping the rotations of the props to the virtual fragments, the center of rotation is the midpoint of the virtual fragment's bounding box. However, in the future, we plan to let the user adjust the center of rotation for more accurate positioning.

3.3 Characteristics

One of the most important characteristics of ArcheoTUI is that there are two 6DOF inputs for a task that has twice 6DOFs. Furthermore, ArcheoTUI is a TUI according to the two axis taxonomy of [Fishkin 2004]. Concerning the first axis, i.e. the relation between the input (the props) and the output (the display), the *embodiment* is distant. Concerning the second axis, ArcheoTUI has only the *metaphor of verb*: the motion of the physical objects corresponds to motion of the virtual fragments. In order to acquire also the *metaphor of noun* so that the shape of the physical object corresponds to the motion of the virtual fragments, we would have to print the fragments (and all the obtained partial assemblies) with a 3D printer, and then find a way to track the printed fragments.

Moreover, ArcheoTUI is a two handed interface using passive real-world interface props. The visualization on the display provides a feedback, and the props provide real-world tactile and kinaesthetic feedback ([Hinckley et al. 1994]). Thanks to the two handed interaction, ArcheoTUI exploits proprioception, because a kinaesthetic feedback is given by the relative position of the hands. For example, when both hands are simultaneously moving to the left, the two virtual fragments are moving to the left as well.

In the following section, we present how the ArcheoTUI software exploits the ArcheoTUI user interface for more complex assemblies, when the fractured objects consist of more than two broken fragments.

4. THE ARCHEOTUI SOFTWARE

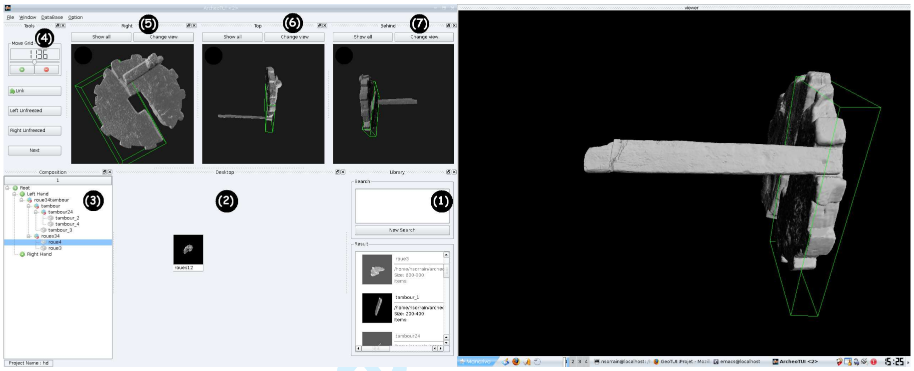


Fig. 3. A screenshot of the ArcheoTUI software.

We implemented the software for ArcheoTUI in C++ on a Linux Workstation. We used Qt for the graphical user interface and OpenSG for the rendering back-end. The assembly of the pieces is represented in a scene graph, and the interior nodes contain the transformations that are specified during the user interaction. The broken fragments are organized in an SQL database that we integrated using SQLite.

A screenshot during the usage of the ArcheoTUI software on a dual screen can be seen in Figure 3. On the right screen, in the assembly window, one fragment (or a partial assembly) corresponds to the props of the left hand, and another fragment (or partial assembly) corresponds to the right hand. At any time, the user can assemble the two objects by hitting the space bar, and undo the assembly by pressing the DEL key. When two objects are assembled, the resulting partial assembly is associated to the left prop, and the right prop is liberated, so that another fragment (or partial assembly) can be associated. Note that assembling and disassembling by the space/DEL keys is an intermediate solution, and we are currently planning to use a third foot pedal.

On the left screen, there are drop-down menus for the import of new 3D fragments, and for loading and saving assembly hypothesis. Furthermore, there are 7 windows that can be resized according to the user's preferences:

The fragment library (1). allows the user to browse through the database, and a list of the results shows thumbnails of the corresponding 3D fragments. These fragments can be associated to the left or right prop by a context menu, or they can be dragged to the desktop.

The desktop (2). provides a space to render certain fragments or partial assemblies easily accessible.

The scene graph of the current assembly (3). illustrates the assembly hierarchy. By clicking on the nodes on the scene graph, the corresponding fragment (or partial assembly) is highlighted by its bounding box, and it can be taken out of the entire assembly by dragging it to the desktop or to the fragment library.

The status bar (4). provides visual feedback which foot pedals are currently hold down. Furthermore, the speed of the translation of the fragments can be adjusted using a slider.

The side view (5),. top or bottom view (6), and rear view (7) help the user to better perceive the 3D space.

We take advantage of the rendering power of OpenSG, but of course, for very detailed 3D objects, the framerate drops. We plan to integrate some in-core or out of core progressive level of detail techniques in the near future.

We also integrated a collision detection using the Open Dynamics Engine (ODE). Our first approach was to stop the movement of the virtual fragments when a collision was detected. We found this solution rather disturbing due to the lack of an active haptic feedback. Consequently, by default, the collision detection is disabled. Nevertheless, we are currently implementing a second approach where we do not stop the movement of the virtual fragments, but highlight the intersecting geometry in a different color. Note that during all the experiments described in this paper, we used the ArcheoTUI software without the collision detection.

5. FIRST USER STUDY

5.1 Aim of the user study

We conducted a cognitive walkthrough based user study ([Polson et al. 1992]) to evaluate the ArcheoTUI user interface's ability to support the assembly task. The users were in an exploratory learning mode. We conducted the study on-site at the workplace of the archeologists, and in our research institute. The aims of the user study were the following:

- —to see whether even non 3D accustomed archeologists accept the ArcheoTUI interface,
- —to see whether the non 3D accustomed archeologists manage to solve simple 3D assembly tasks by using the ArcheoTUI interface,
- —to know whether the archeologists can imagine using the ArcheoTUI interface for their daily assembly tasks,
- —to evaluate whether the two foot pedal solution is efficient,
- —to see whether the two foot pedals were used rather separately or simultaneously,

—to see whether the declutching mechanism (that breaks the correspondence between the relative position of the hands and the relative position of the props) does not perturb the user,

—to see whether there is a preference for the dominant hand,

—and to get user feedback for the development of following ArcheoTUI prototypes, from both non 3D accustomed and 3D accustomed users.

The ArcheoTUI interface is designed for setting up initial positions as an input to automatic alignment methods. Consequently, we rather strived to estimate whether the users were capable to roughly position the objects, and did not evaluate the precise alignment.

In this first explorative user study, we did not include a comparison to classical 2D interfaces. Past experiments have shown that non 3D experienced archeologists had major difficulties to learn the manipulation of 6 degrees of freedom with the 2D mouse. Furthermore, we wanted the users to fully concentrate on our new ArcheoTUI interface, and did not want to scare them with the more complex 2D metaphors to manipulate 6DOF.

5.2 The set-up of the user study

15 subjects participated in our first user study, 8 archeologists that are regularly confronted by assembly tasks, and 7 computer scientists. They were not paid. 3 of the volunteers were female (all archeologists), and 12 volunteers were male, aged from 25 to 56 years, 34 years in average. 13 volunteers were right handers, one was left-handed, and one ambidextrous. 9 subjects were 3D experts, and 7 subjects had already manually assembled 3D objects.

In order to efficiently collect and exploit the results of the user study, three researchers organized the study. A first person explained the task and conducted the experiments, a second person observed how the users were handling the props, and a third person was accompanying the questionnaire in order to catch all relevant feedback. The questionnaire was designed to get a qualitative and subjective feedback of the ArcheoTUI user interface. In addition to our observations, we recorded the important user actions of the ArcheoTUI software into a logfile.

5.3 The assembly tasks of the user study

The participants were asked to accomplish 6 simple assembly tasks that we divided into two families. The first family consists of 4 pair wise assembly tasks. For each task, the subjects were asked to assemble two fragments from an initial starting position (Figure 4(left)) to a given target assembly that we printed on a paper sheet (Figure 4(right)). We limited the time to achieve each task to two minutes.

The second family consisted of 2 assembly tasks with more than two broken fragments (Figure 5) in order to see if there were missing features in the software used in the ArcheoTUI system. The time was limited to 3 minutes for the task 5, and 4 minutes for the task 6.

5.4 The overall success of the assembly tasks

Of course, our major interest concerns the question whether the subjects managed to solve the 6 given simple 3D assembly tasks by using the ArcheoTUI system. For

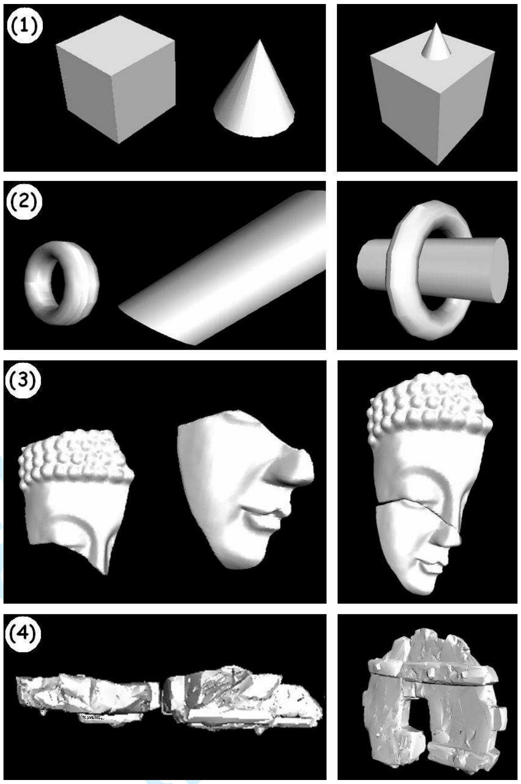


Fig. 4. The first family of four pair wise assembly tasks.

	Left pedal		Right pedal		Left and right pedal simultaneously	
	Number	Accum. time	Number	Accum. time	Number	Accum. time
Mean	52.2	221sec.	57.9	277sec.	4.7	22sec.
Standard deviation	9.8	61sec.	24.2	100sec.	8.0	49sec.

Table I. Means and standard deviations for the foot pedal usage of the 15 subjects.

the tasks 1 to 5, we considered the assembly successful when the fragments were roughly well aligned. However, the success of task 6 was more difficult to evaluate due to the lack of time for the experiment. We decided to validate the success of this task when 3 pieces were roughly well assembled.

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
yes	15	15	15	12	11	12
no	0	0	0	3	4	3

Table II. Success of the 6 assembly tasks.

The success of the 6 tasks is depicted in Table II. All the participants accom-

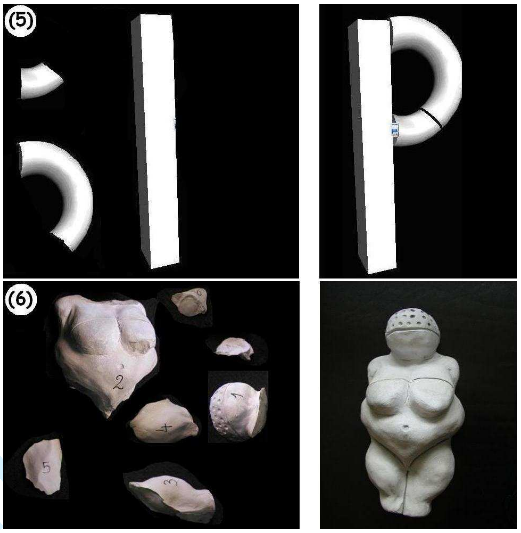


Fig. 5. The second family of assembly tasks with more than two fragments.

plished the first three assembly tasks without having used the ArcheoTUI user interface before. The last three assembly tasks were more difficult. However, we explain that some few participants had no success due to the very tight time restrictions.

In the questionnaire, some questions had to be answered on a scale from 1 to 6 (6 was best). The subjects rated 5.2 on average the easiness to learn the interaction, and they averaged 4.3 for the easiness of use. The subjects rather think that the ArcheoTUI user interface could help them to solve 3D objects assemblies (4.6 on average) and to solve archeological assemblies (4.5 on average).

The questionnaire also showed that estimating the depth dimension of the virtual fragments on monoscopic displays is difficult. We observed that the non 3D experts are often surprised to discover incorrect assemblies after rotation. On the other hand, the 3D experts tended to repeatedly validate incorrect assemblies on purpose, in order to refine the assembly under a different viewing angle. We regret that we did not integrate shadows on a floor and some walls in the 3D scene for a better perception of the depth dimension. This would have given the opportunity, even for non 3D experts, to elaborate better navigation strategies.

5.5 The props

The users were taught that the props are designed to control two digital objects at a time with the left and right hand. We observed that one participant was manipulating one single prop with two hands. Moreover, we noticed that the attention of the users was sometimes focused to only one prop, and sometimes to the two props at a time.

The answers in the questionnaire revealed that the users like the easiness and rapidity to position and orient the virtual fragments in 3D space. They also enjoyed the bilateralism to manipulate two digital objects with two hands in space. Some users complained about twisting their wrists. This is due to an insufficient use of the declutching mechanism, and these users need more training. Moreover, the users found it easy to roughly position and orient the fragments, but they had difficulties to finalize a very precise assembly. This confirms our idea of a semi-automatic method: we allow the users to elaborate assembly hypothesis using ArcheoTUI that can then be used as an initial position for automatic alignment methods such as the ICP.

5.6 The foot pedal declutching mechanism

We were particularly interested in the usage of the foot pedals, and especially the number of times each pedal was pressed down and how long it was hold down during all the assembly tasks, and whether both pedals were used at the same time. The results that we collected from the logfile are shown in Table I, and they gave us various important insights.

First of all, the declutching mechanism of the pedals was used. Moreover, there is no big difference between the usage of the left and right foot pedal, despite the fact that 87% of our subjects were right handers. We were a little bit suprised because we expected a more frequent usage of the foot pedal of the dominant hand for local precision tasks.

The logfile shows also that the foot pedals were used one after another rather than simultaneously. This implies a limitation in parallel bimanual performance, what is not surprising concerning the insights of symmetric bimanual interaction ([Balakrishnan and Hinckley 2000]).

We observed the users in order to see whether the users looked at their feet and the foot pedals during the manipulation. Starting from the 4th task, all the subjects did not look at their feet anymore, and nine subjects never looked at their feet at all.

The questionnaire revealed that the users were very enthusiastic about the idea to use foot pedals for a declutching mechanism. They especially liked to rapidly fix object positions by simply releasing the pedals. Moreover, they appreciated the possibility to reposition their hands for a better focus on the assembly task. However, some users requisitioned simple buttons on the props instead of the foot pedals, and one user complained about fatigue.

Thanks to the clutching mechanism, the user can start the movement of the props at any desired location. Note that in contrast to the ActiveCubes ([Kitamura et al. 2001]), the physical assembly of the props is not performed, but only the assembly of the virtual fragments. The relative position of the props is not mapped to the virtual fragments. The resulting discontinuity between the relative position of the props, and the relative position of the virtual fragments, could perturb users. However, as the users focused on the view of the virtual fragments, we did not notice real perturbations. Indeed, the feedback for the user is only a visual one. Nevertheless, this fact did not hinder the user in its assembly task.

We conclude that the declutching mechanism with the two foot pedals is an interesting approach when assembling two broken fragments. Since the users are already familiar with foot pedals (for example in their cars), and since the *left* (resp. *right*) foot is associated to the *left* (resp. *right*) hand, the users did not encounter strong difficulties.

6. SECOND USER STUDY

6.1 Motivation

Despite the success of the foot pedal declutching mechanism, we received a lot of comments wondering why we did not simply put buttons on the props for the declutching mechanism. There were also some users in the first user study that requisitioned simple buttons on the props instead of the foot pedals.

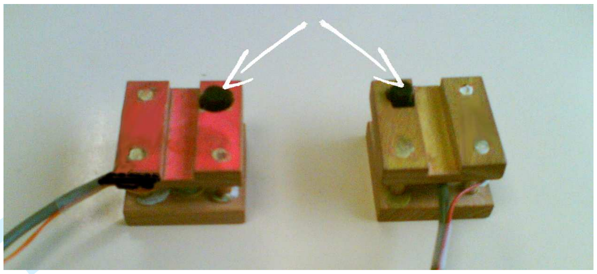


Fig. 6. The props with buttons for declutching.

This initiated us to enhance the ArcheoTUI system by putting buttons on the props. Pressing a button on a prop has exactly the same effect like pressing down the corresponding foot pedal. Since the Polhemus Liberty system used in ArcheoTUI does not provide buttons on the props, we rigged up a regular mouse device by soldering on two cables in order to use the left and right mouse buttons on the props (see Figure 6).

6.2 Aim of the user study

We conducted a second, comparative user study in order to evaluate the user performance of the foot pedal declutching mechanism compared to the button declutching mechanism. The aims of this second user study were the following:

—to see whether there is a preference in favor of the foot pedals or the buttons on the props,

—and to see whether the two different declutching mechanisms imply different interaction metaphors.

6.3 The set-up of the user study

26 subjects participated in our user study, among them 12 archeologists that are regularly confronted by assembly tasks. They were not paid. 10 of the volunteers were female, and 16 volunteers were male, aged from 13 to 56 years, 33 years in average. 21 volunteers were right handers, three were left handers, and two ambidextrous. Among all subjects, there were 11 frequent users of CAD software, and 14 frequent 3D video game players. Note that only one of the subjects had used the ArcheoTUI system before.

Similar to the first user study, we were three persons to organize it, and we recorded the important user actions of the ArcheoTUI software into a logfile.

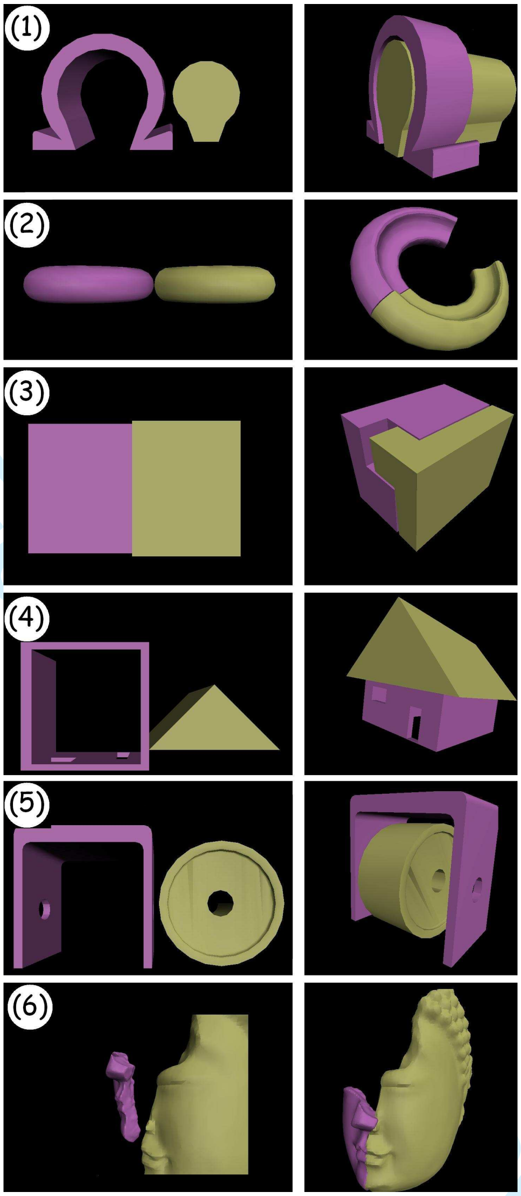


Fig. 7. The six pair wise assembly tasks.

6.4 The assembly tasks of the user study

The participants were asked to accomplish 6 simple assembly tasks, 3 by using the foot pedals for the declutching, and 3 by using the buttons on the props for the declutching mechanism. Similar to the first user study, for each assembly task, the subjects were asked to assemble two fragments from an initial starting position (Figure 7(left)) to a given target assembly that we printed on a paper sheet (Figure

7(right)). We limited the time to achieve each task to either two minutes (task 1, 2, 4, and 5), or 4 minutes (task 3 and 6).

In order to mask out learning effects, half of the subjects started with the foot pedals, and half of the subjects started with the buttons on the props.

6.5 The overall success of the assembly tasks

First of all, we can state that 24 out of the 26 subjects (92%) managed to solve at least one assembly task after a short learning period. One of the major difficulties remains the perception of the depth dimension of the virtual fragments. The results of the success of aligning the assemblies of the 6 assembly tasks are depicted in Table III.

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
yes	5	15	18	18	22	24
≈	16	9	5	5	4	2
no	5	2	2	2	0	0

Table III. Success of the 6 assembly tasks (**yes**: completely well aligned on all views; ≈: aligned on at least one view; **no**: not aligned at all)

This table nicely reflects the learning curve: the number of subjects that completely well aligned the assemblies steadily increases, except between task 3 and task 4, where the declutching mechanism changes.

6.6 Foot pedals vs. buttons on the props

The major aim of this user study was to see whether there is a preference in favor of the foot pedals or the buttons on the props. The success of the assembly tasks did not show any significant preference of the users in favor of one of the declutching mechanisms (see Table IV and V).

	Pedals			Buttons		
	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
yes	4	7	9	9	10	12
≈	8	5	2	4	3	1
no	1	1	1	0	0	0

Table IV. The 13 subjects that started with the pedals: success of the 6 assembly tasks.

	Buttons			Pedals		
	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
yes	1	8	9	9	12	12
≈	8	4	3	1	1	1
no	4	1	1	2	0	0

Table V. The 13 subjects that started with the buttons: success of the 6 assembly tasks.

However, in the questionnaire, we asked the users about their preference. 57% of the subjects prefered the foot pedals, and 43% prefered the buttons on the props. There is no correlation between the preference and the profession of the subjects. The strongest argument in favor of the foot pedals was the higher precision. In fact, the users complained about a slight movement of the props when releasing the buttons that can hardly be avoided. As in the first user study, only few users manipulated the two props at the same time, and when they did, it was mainly for global positioning rather than for precise efficiency.

Although we could not identify a significant preference between the two declutching mechanisms, we observed a fundamental difference on the interaction behaviour: when using the foot pedal declutching mechanism, the users made longer movements and declutch less often compared to the declutching mechanism with buttons on the props. The logfile confirms our observations: the mean time of the movements is 6.59 sec. for the foot pedals compared to 3.96 sec. for the buttons, and the user declutched only 9.76 times with the foot pedals compared to 12.15 times with the buttons. Note also that the subjects who started the assembly tasks with the pedals made even longer movements than those who started with the buttons on the props.

This observation shows that there is a change of the interaction metaphor with the buttons on the props: instead of a long continuous movement as done with the foot pedals, the movement is divided into several small movements in the physical world. We observed that this is due to the fact that with buttons, the props cannot be differently grasped by the users for greater rotations because the buttons have to remain accessible. We are convinced that the gesture of few long continuous movements by using the foot pedals is closer to the real-world behaviour than several small movements. Indeed, the subjects can keep on concentrating on the actual assembly task and reason every movement globally instead of decomposing it into several small movements. According to the *metaphor axis* of [Fishkin 2004], the user action is more similar to the real-world effect when using the foot pedal declutching mechanism.

7. CONCLUSIONS AND FUTURE WORK

We used the ArcheoTUI interface to solve a real-world assembly task. We scanned 8 fragments of a fountain that was found on the site of the Barzan thermae, Charente Maritime, France. The origin of the fragments is estimated to the 1st century AD. Figure 8 shows a photograph of the fragments.

We reassembled the scanned fragments with our ArcheoTUI user interface. The fragments and the final assembly can be seen in (Figure 9). We plan to continue the assembly of over 150 remaining fragments of the fountain by using the ArcheoTUI user interface.

With the ArcheoTUI system, archeologists are now capable to interactively assemble 3D fractured archeological objects. Thanks to the virtual assembly, they are no longer limited by the physical restrictions of broken fragments such as the heaviness that they encounter in traditional archeology. The results of this first user study underlined the acceptance and usability of the ArcheoTUI interface in our particular archeological context. We noticed a very short learning period. The

Fig. 8. Photos of the fractured fountain parts.

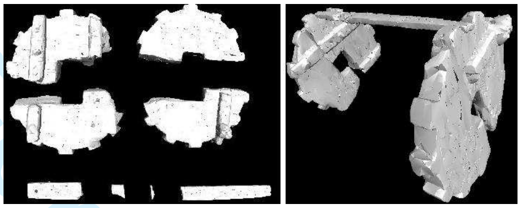


Fig. 9. The virtual fragments and the assembly.

results of the second user study demonstrated that the movement of the hands is more similar to real-world assembly scenarios, and that the users can keep on concentrating on the actual assembly task and reason every movement until the end.

During both user studies, we observed that the users were annoyed by the use ofthe space bar on the keyboard for fixing current assemblies, both for the foot pedals and the buttons on the props. Consequently, the users constrain their movement in order to have their hands in the reach of the keyboard. We strongly believe that a third foot pedal instead of the space bar would improve the user's performance, since the implied foot movement is commonly accepted for similar tasks like switching between the brake and gas pedal in a car. Notice that one user requisitioned a slight inclination of the pedals to feel more comfortable. Concerning the props, a circular shape would prevent users from having a predetermined way to hold it.

All these results encourage us to further improve ArcheoTUI and to drive additional user studies in order to evaluate the efficiency of the interface in comparison to other more classical user interfaces.

Thanks to the second user study, we met an enthusiastic archeologist that was convinced that ArcheoTUI with the foot pedal declutching mechanism would assist him to reassemble ancient and fragile ovens.

One part of ongoing work addresses the perception of the depth dimension of the virtual fragments, for example by indicating transparent lines of the 3D grid. Obviously, increasing the realism with shadows on a floor and a wall also improves the perception. However, we are convinced that virtual assembly is even more efficient with stereo displays, either by using reality centers or auto-stereoscopic displays. We are currently porting the ArcheoTUI system for our virtual reality center on a 10mx3m stereoscopic wall and we are integrating an ARtracking head tracking system. Thanks to the implementation in OpenSG, this is rather straightforward. It would also be interesting to see the contribution of active haptic feedback, for example by replacing the two electromagnetically tracked props by two Phantoms. We are also currently integrating the ICP algorithm for an automatic snapping as a precise alignment of the initial position indicated by the user interaction. In the later future, we strive to integrate any automatic reconstruction technique, as for example [Huang et al. 2006; Sagiroglu and Eril 2005]. Indeed, these techniques could reduce the amount of required user interaction.

In addition, we think that an interesting though expensive direction is to print the 3D fragments with a 3D printer and analyze the benefits when the shape of the physical objects corresponds to the shape of the virtual fragments.

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