ArcheoTUI - Driving virtual reassemblies with tangible 3D interaction

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ArcheoTUI—Driving Virtual Reassemblies with Tangible 3D Interaction

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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.

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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 using classical 3D modeling software such as Blender, Maya, or 3D Studio. On the other hand, automatic reassembly techniques become feasible; see, for example, the stunning results of Huang et al. [2006].

Since all the automatic methods rely on pairwise 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 pairwise 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 3D modeling 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 article, 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.

We developed two prototypes of ArcheoTUI: the first one uses foot pedals for declutching, and the second one uses buttons on the props for declutching. In order to test both prototypes, we conducted two user studies. The first user study evaluated the first prototype with foot pedals. It was designed as a cognitive walkthrough-based user study [Polson et al. 1992] to evaluate the ArcheoTUI user interface's ability to support the assembly task. The results of this study (see Reuter et al. [2007]) have shown that the declutching mechanism with the two foot pedals was accepted for the reassembly of broken fragments. The second user study was designed to compare the foot pedals for declutching to buttons on the props for declutching. This second user study showed that the user action by using foot pedals for declutching is more similar to the real-world behavior compared to using buttons on the props for declutching.

This article 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 setup of our ArcheoTUI system. In Section 4 we describe the involved software. In Sections 5 and 6 we present the two user studies, before we conclude and show directions for future work in Section 7.

2. STATE-OF-THE-ART

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.

2.1 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] and Fröhlich and Plate [2000]). We consider our user interface to be a Tangible User Interface (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 axes: the *metaphor axis* classifies the TUI in the way 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], and Pierce et al. [1999], and 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 held 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 the 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.

2.2 Automatic Assembly Methods

The automatic assembly of fractured 3D objects is a challenging 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 article. Nevertheless, we state that the automatic techniques are generally based on pairwise matching of either geometric or photometric features. Geometric pairwise 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 nonpenetrating iterative closest point algorithm (ICP; [Besl and McKay 1992]). Other pairwise 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 pairwise matching has been proposed by Sagiroglu and Erçil [2005] by estimating the photographic affinity between neighboring fragments: the texture outside the border of the fragments is predicted using texture synthesis.

To our knowledge, all the automatic methods rely on pairwise 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 proposed 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

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 setup 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 are the translations 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.

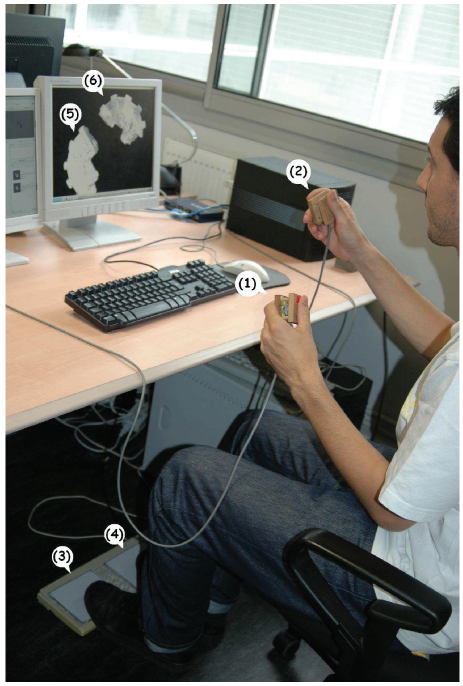
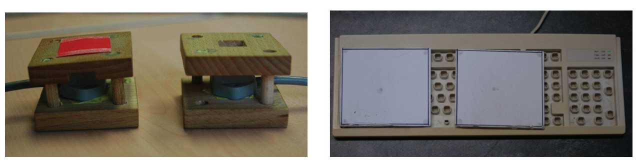


Fig. 1. The ArcheoTUI user interface.



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

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

Thanks to this declutching mechanism, the user can also be switched while the virtual fragments stay in position, and thus another user can propose a new assembly hypothesis. Moreover, the declutching mechanism prevents fatigue, since the users can work on a table, and so they can simply take a break by putting the props down.

3.1 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.

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 by putting 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.

3.2 Discussion on Technical Choices

One can think that it would be interesting to use the additional information channel of haptic feedback, for example, by replacing the two electromagnetically tracked props by two Phantoms or similar devices with haptic feedback. Indeed, such devices allow the users to literally feel whether the pieces fit together, or how the parts would entangle. Furthermore, they are clearly useful in order to capture information about the collision of the fragments. We plan to test these solutions for comparisons. However, we rather prefer solutions based on vibrating sensors embedded in the props instead of Phamtoms, because they fit better in the desired interaction paradigm that respects the affordances in computer-human interaction [Norman 1988]. The affordance refers to the potential of actions which are perceived by the user of an object. Like a mouse, a Phantom has no affordance. In contrast, props embody archaeological fragments, and therefore the users perceive the affordances of manipulation. For the same reasons to preserve affordance, we avoid to use objects that are similar to the cubic mouse equipped with dials for the rotation and space positioning, even though the cubic mouse is very powerful in 3D project review. Our goal is to provide the user an interaction technique with the computer as if it were an interaction with the real fragments. Imagine the archaeologist in the process of reconstructing a pot, and instead of fragments in his/her hands, he/she handles the props. Note that at the beginning of the project, we tried wireless optical tracking with one camera and ARToolkit. However, we quickly abandonned this idea due to occlusion problems, and once again to preserve affordance. ARToolkit tags are today still a little bit too big and too invasive (tags on all sides of props) for our specific use. Concerning occlusion problems, one solution could be to put a camera under the table by using a transparent table. This is a solution which is technically sound and very interesting for an experimental laboratory. However, our objective is to create a employable interface at the workplace of the archaeologists, and it is not reasonable to demand that all the users' desks are made of transparent material. That's why we have ruled out the ARToolkit solution.

3.3 Characteristics

One of the most important characteristics of ArcheoTUI is that there are two 6DOF inputs for a 6DOF task. Furthermore, ArcheoTUI is a TUI according to the two axis taxonomy, embodiment and metaphor, defined by Fishkin [2004]. Concerning the first axis, that is, how closely tied is the input focus to the ouput focus, the *embodiment* is distant in ArcheoTUI, because the input is with the hands on the two props and the result is perceived by looking at a nearby screen. Concerning the second axis, ArcheoTUI does not have the *metaphor of noun*, that is, the physical shape of an object in the system is analog to the shape of such an object in the real world. In order to acquire also the *metaphor of noun*, 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. ArcheoTUI has only the *metaphor of verb*, that is, acting with the system is like acting in the real world: in ArcheoTUI the motion of the physical objects corresponds exactly to the motion of the virtual 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

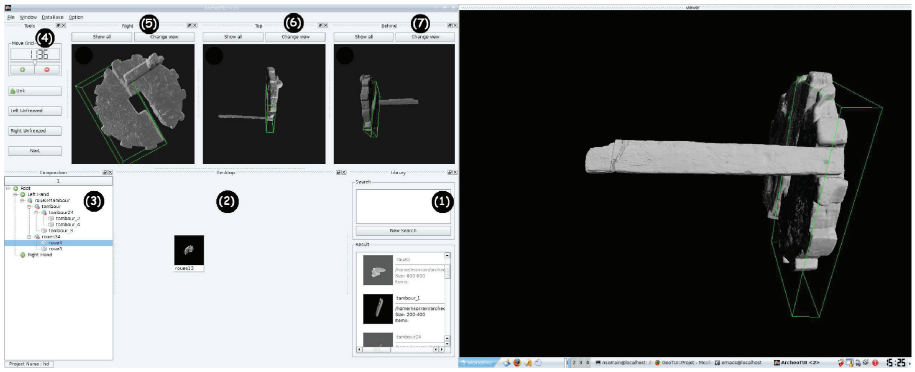


Fig. 3. A screenshot of the ArcheoTUI software.

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

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 backend. 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 the assembly hypothesis. Furthermore, there are 7 windows that can be resized according to the user's preferences.

The Fragment Library (1). This 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). This provides a space to render certain fragments or partial assemblies easily accessible.

The Scene Graph of the Current Assembly (3). This 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). This provides visual feedback which foot pedals are currently held 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)*. These 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 article, we used the ArcheoTUI software without the collision detection.

5. FIRST USER STUDY

We conducted a first user study [Reuter et al. 2007] in order to evaluate the ArcheoTUI user interface's ability to support the assembly task. It was a cognitive walkthrough-based user study [Polson et al. 1992], and 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, with 15 subjects, of whom 8 were archeologists that are regularly confronted by assembly tasks, and 7 computer scientists. Using the two props and the two foot pedals, the participants were asked to accomplish 6 simple assembly tasks, each composed of 2, 3, or 7 geometric or archeologic broken fragments. A maximum time of up to 4 minutes was allocated to accomplish each assembly task. At the end of the test, the subjects answered a questionnaire, and, in addition to our observations, the important user actions of the ArcheoTUI software were recorded in a logfile.

For the details of the results, we refer the interested reader to Reuter et al. [2007]. Summing up, the subjects successfully completed 89% of the overall 90 assembly tasks in the given time. We explain that some few participants had no success due to the very tight time restrictions. Secondly, the declutching mechanism of the pedals was used. During the 6 assemblies, the number of times the left pedal was pressed down is 52.2 in average, and 57.9 for the right pedal. Thirdly, the users performed bimanual interaction. How long the pedals were held down during all the assembly tasks was also measured in the logfile; the users accumulated 221s in average with the left pedal and 277s with the right pedal. 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. Finally, the users found it easy to roughly position and orient the fragments, but they had difficulties in finalizing a very precise assembly. This confirms our idea of a semiautomatic method: we allow the users to elaborate the assembly hypothesis using ArcheoTUI that can then be used as an initial position for automatic alignment methods such as the ICP.

From this first user study, we conclude that the manipulation in space of two props is efficient to roughly position the objects in a short time, and it is very quick to learn. 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*

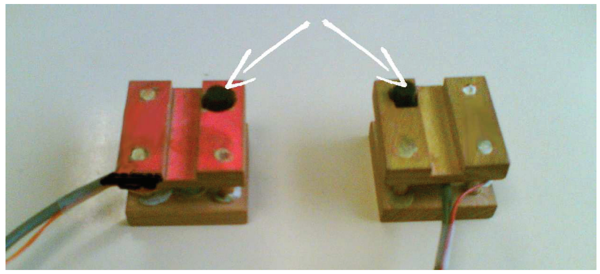


Fig. 4. The props with buttons for declutching.

(respectively, *right*) foot is associated to the *left* (respectively, *right*) hand, the users did not encounter strong difficulties. However, some users requisitioned simple buttons on the props instead of the foot pedals.

6. SECOND USER STUDY

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.

This motivated 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 4).

6.1 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.

6.2 The Setup of the User Study

Twenty-six subjects participated in our user study, among them 12 archeologists that are regularly confronted by assembly tasks. They were not paid. Ten of the volunteers were female, and 16 volunteers were male, aged from 13 to 56 years, 33 years in average. Twenty-one 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.

6.3 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 5(top row)) to a given target assembly that we printed on a paper sheet

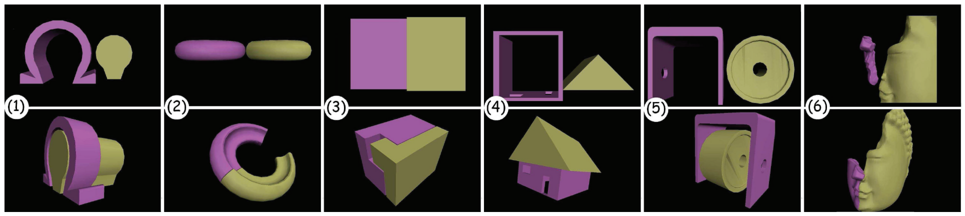


Fig. 5. The six pairwise assembly tasks.

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

	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 II. The 13 Subjects that Started with the Pedals: Success of the 6 Assembly Tasks

	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

(Figure 5(bottom row)). We limited the time to achieve each task to either two minutes (tasks 1, 2, 4, and 5), or 4 minutes (tasks 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.

6.4 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 I.

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.

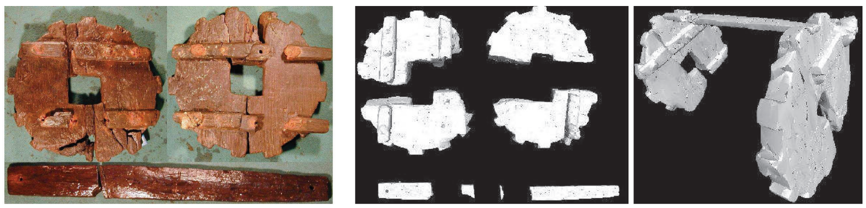
6.5 Foot Pedals vs. Buttons on the Props

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 Tables II and III).

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

Table III. The 13 Subjects that Started with the Buttons: 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



(a) photos of the fractured fountain parts

(b) the virtual fragments and the assembly

Fig. 6. The assembly of the Barzan fountain.

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 behavior: 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 6.59s for the foot pedals compared to 3.96s 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 behavior 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 A.D. Figure 6(a) 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 6(b). 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 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 of the 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 autostereoscopic 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]. Indeed, these techniques could reduce the amount of required user interaction. Another direction to reduce the user intervention is the pruning of the decision graph by rejecting pairs with no photographic affinity [Sagiroglu and Erçil 2005].

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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