The activation of modality in virtual objects assembly

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Abstract Manual assembly of virtual 3D objects is required in several application fields. We focus on tangible user interfaces which offer the opportunity to the user to perform virtual assemblies efficiently and easily. In each hand, the user manipulates a tracked prop, and the translations and rotations are directly mapped to the corresponding virtual object. However, with such interfaces, both hands are requisitioned, and the user cannot drop the props without changing the action or the expected results. We list and discuss the choice of four possible modalities to activate/deactivate the assembly modality: vocal modality, gestural modality, buttons, and foot pedals. We conclude that when using the foot pedals, the user's gesture is closer to the real-world behaviour.

Keywords CHI · TUI · Modality · Virtual assembly · Clutching

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1 Introduction

Our aim is the design and the development of a new tangible user interface, based on multimodal interaction, for the efficient pairwise assembly of virtual 3D objects (for an example, see Fig. 1). The key idea is to use two props as physical representation and control for the virtual objects. In each hand, the user manipulates an electromagnetically or optically tracked prop, and the translations and rotations are directly mapped to the corresponding virtual objects on the display. During the process of assembly, the user needs to reposition his/her hands in order to overcome physiological constraints, and to be comfortable. Moreover, in certain situations, such as at the end of the assembly, or when being disturbed, the user needs to put down the props. In all these cases, the movements (translations and rotations) of the props should not be mapped anymore to the corresponding virtual objects on the display. In other words, the current assembly must be frozen for a while, and the user can do what ever she/he wants with the props. Hence, the system has to provide a modality to associate or dissociate the movement of the props to the movement of the virtual objects. We call this modality the clutching/declutching modality where the declutched state disengages the mapping of the position and orientation of the props to the virtual object. Accordingly, in the clutched state, the movements of the props are directly mapped to the virtual objects.

The salient point that we address is the following question: "How does the user activate the clutching/declutching modality?" Both hands are requisitioned, and so the user cannot drop the props and use the hands to activate a new modality without changing the action or the expected results. There are various other solutions than using the hands to activate a new modality. However, we are convinced that the choice of the modality deserves further investigation
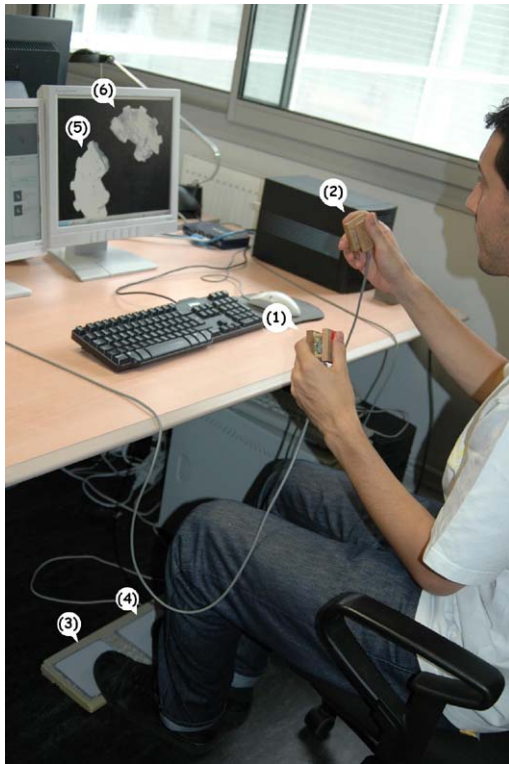
Fig. 1 Virtual scanned archeological fragments assembly with ArcheoTUI
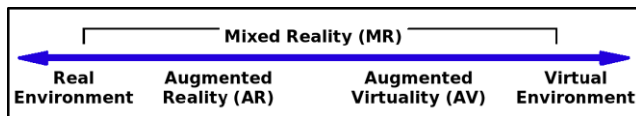

Fig. 2 The reality-virtuality continuum [7]

since straightforward solutions are not always the most efficient ones. Consequently, in this paper, we discuss the activation of a modality by another modality in the context of the design and development of tangible interaction techniques for virtual objects assembly.

Let us first define the context of our work: we use *tangible user interfaces* in an *Augmented Virtuality* system. We refer with tangible user interfaces to the definition of Ullmer and Ishii [13]: TUIs *give physical form to digital information, employing physical artefacts both as representations and controls for computational media*. In order to better understand the involved Augmented Virtuality system, consider the "virtuality" continuum, introduced in [7], and illustrated in Fig. 2. At one extreme of this continuum, the task is embedded in the physical real-world environment of the users and at the other extreme, the task is embedded in the purely digital virtual environment. Between these extremes, Augmented Reality consists of embedding some digital information in the real-world, and Augmented Virtuality consists of embedding some physical information in

a virtual world. According to this continuum, in essence, tangible user interfaces are part of Augmented Virtuality. TUIs allow the user to perceive and/or to modify the state of the digital information thanks to physical object properties. To illustrate the TUI concept, consider the example of PinWheels [6] where a flow (such as car traffic in a street or stock market exchanges) is represented by the rotation speed of the pinwheels. In this example, the pinwheels represent physically the digital information, *i.e.* a flow, without user control capacity.

The remainder of this paper is organised as follows. First, in Sect. 2, we present the involved virtual assembly task of our study. Moreover, we present the concept of bimanual tangible interaction in terms of interaction modality, with a special focus on the clutching/declutching metaphor. In Sect. 3, we discuss various modalities that can be used for this metaphor. In Sect. 4, we present the two prototypes that we have developed for the clutching/declutching. Moreover, we show and discuss the results of the user studies that we conducted in order to determine the best suited modality. Finally, in Sect. 5, we conclude and give directions to future work.

2 The virtual objects assembly

The pairwise virtual objects assembly consists in translating and rotating two 3D virtual objects in the 3D virtual space in order to put them in correspondence. It is easy to see that such a virtual object assembly is very difficult to accomplish with the standard mouse, a 2 degree of freedom (DOF) input device. Translating and rotating only one virtual object in 3D space is already difficult, since the user must repeatedly change rotation axes and thus perform a lot of different actions. Of course, translating and rotating two virtual objects at a time in order to put them in correspondence is even harder, and it becomes nearly impossible to concentrate purely on the actual assembly task without reasoning about the rotation axes constraints.

The concept of using a TUI to perform virtual objects assembly consists in representing the virtual objects by physical real objects (called props, passive props, or tangible objects). The 3D position and orientation of the physical objects in the real-world are directly mapped to the virtual objects displayed on a screen. Hence, the user performs two handed interaction by manipulating two physical objects in space. Consequently, she/he executes exactly the same movements as if the virtual objects were in her/his hands. This concept of TUI has been proposed for the virtual assembly in different application domains, as for example:

- virtual assembly of archeological fragments [10] (see Fig. 1),
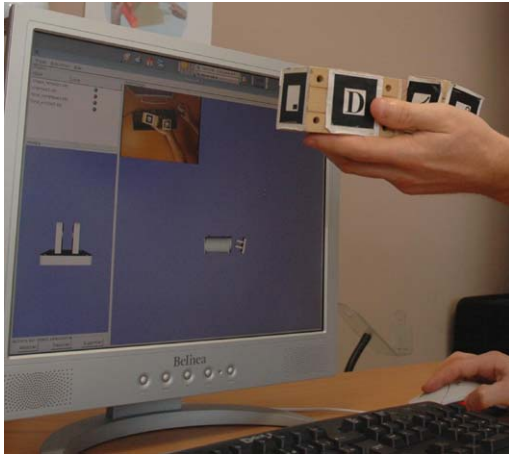- virtual assembly of CAD pieces [4] (see Fig. 3), and
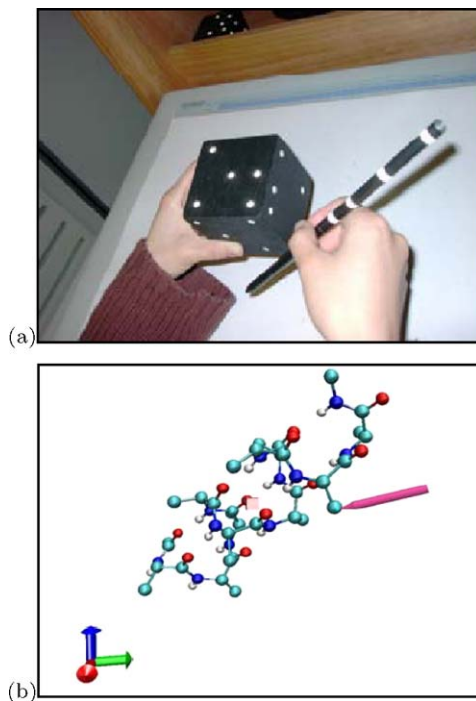
Fig. 3 CAD parts assembly with ESKUA [4]

Fig. 4 (**a**) The cube is coupled with the molecule, and the pen allows the user to select and move atoms. (**b**) The corresponding visualization of the molecule [9]

– visualization of atoms of molecules [9] (see Fig. 4).

Let us recall the definition of a modality given in [8] as the coupling $\langle d, l \rangle$ of a physical device d, that acquires (input device) or delivers (output device) information, with an interaction language l, that defines the set of all possible well-formed expressions that convey meaning.

Then, in terms of modality, the tangible interaction for 3D virtual assembly can be described as follows. Let m_{va} be the 3D virtual assembly modality such that:

$$m_{va} = \langle 2 \text{ props}, 2 \times 6 \text{ DOF} \rangle$$

where the devices are two props, and the interaction language is the position and orientation of the two props in space, *i.e.* the 6 DOF of each of the props. The props are physical objects, and moving the props leads to moving the corresponding virtual objects according to the 6 DOF.

Hence, the system has to provide a modality to associate or dissociate the movement of the props to the movement of the virtual objects. We call this modality the clutching/declutching modality where the declutched state disengages the mapping of the position and orientation of the props to the virtual object. Accordingly, in the clutched state, the movements of the props are directly mapped to the virtual objects.

There is a need to clutch and declutch the movements of the physical objects and the movements of the virtual objects. We identified at least four reasons why the clutching/declutching is essential.

– First, when the user begins to interact, he/she takes the physical objects on the desk, holds them up, and then, wants his/her movements to be reproduced.
– Second, when the user finishes to interact, he/she wants the system to stop the mapping of his movements before putting the props down on the desk, in order to keep the desired configuration.
– Third, when interacting, the user can also reach an uncomfortable position of the arms (extended, aparted or twisted) that would be cumbersome or could even prevent from continuing the assembly. Consequently, declutching the movement allows the user to reposition his/her arms in order to steadily be in a comfortable position.
– Fourth, due to the scale and shape of the virtual objects, the physical objects could collide, while the virtual objects do not. Again, declutching the movement allows the user to reposition the props in order to continue the assembly.

It is a great challenge to design such a TUI that provides a modality to associate or dissociate the movement of the props to the movement of the virtual objects. In this paper, we strive to identify the best way to allow the user to repeatedly clutch and declutch the movements of the props, in order to enable or disable the mapping of the motion from the physical objects and the virtual objects. It is a fact that both hands and fingers are busy to control the six degrees of freedom of each prop. Consequently, it is necessary to determine a new modality in order to activate/deactivate the modality m_{va}. When the modality m_{va} for one hand is deactivated, the movement of the physical prop is dissociated from the corresponding virtual object, and thus moving the physical prop has no effect on the position and orientation of the virtual object.

3 Exploration of some possibilities to activate the modality m_{va}

Let m_{cd} be the clutching/declutching modality such that:

$$m_{cd} = \langle d, l \rangle$$

where the device d and the language l have to be defined.

In the following, we present four possibilities to define the m_{cd} modality in order to activate/deactivate the modality m_{va}: first, a vocal modality, second, a gestural modality, third, a modality that is embedded physically in the props (the main device), and finally a modality that is embedded physically in a foot pedal device (an additional device).

3.1 The vocal modality

In this case, $m_{cd} = \langle \text{voice, keywords} \rangle$.

The vocal modality is the most commonly suggested solution by the users that participated in the user studies. Of course, at a first sight, the voice can be used to confirm, cancel or trigger an operation. Back in 1980, Bolt [1] first combined voice and gesture to interact with data projected on a large screen. Hinckley *et al.* [5] combine the manipulation of the passive props with the voice modality in a similar situation as our case study, applied to neurosurgery. They implemented the clutching and declutching of the passive props by using speech. A doll's head allows the users to control the orientation of a virtual brain, and a rectangular plate allows to specify the position and orientation of a slice (see Fig. 5). The declutching is used in order to freeze the image in a desired configuration, and this allows the user to put down the props. The user says "move ⟨prop⟩" to associate the motion, and "stop ⟨prop⟩" to dissociate the motion from the props. The experiments with the passive props for neurosurgery pointed out several constraints for the use of speech for interaction. The authors explain that the latency due to the voice recognition system is a source of embarrassment. However, even though state-of-the-art speech recognizers can provide an immediate response, there still remains the intolerable time to pronounce the command during the interaction. Imagine clicking the mouse button on your computer would last one second! Hinckley *et al.* [5] also highlight the interference that may exist between the speech and the short-term memory. Contrary to the ideas of the users, the voice modality is probably not the best suited solution in this case. This is mainly due to the fact that a discrete operation should also be triggered by a brief and discrete action. We consider these two constraints, *i.e.* the time to pronounce the command and short term memory interferences, too much annoying when the user is reasoning to solve his assembly trade task. Consequently, the vocal modality was not retained, and a discrete action would be better.
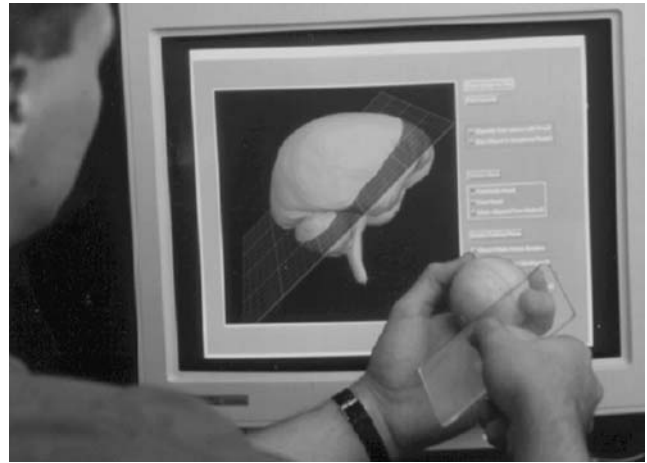

Fig. 5 The passive props for neurosurgery [5]

3.2 The gestural modality

In this case, $m_{cd} = \langle \text{props, velocity} \rangle$.

The second possible modality for declutching the virtual objects is to freeze the desired prop in its position without moving it. A threshold for the time period t has to be defined, and when one prop is immobilized longer than t, the declutch is triggered, and the user can put the corresponding prop down.

Besides the problem of preciseness to distinguish a fine movement from the desire to declutch, the solution of freezing the props during a specified time period can also be stressful and irritating for the user. On the one hand, the user must take care not to stop moving the props too long in order to avoid triggering a non-intentional action. Hence, the user cannot stop moving while thinking or discussing with a colleague. On the other hand, waiting for the end of the delay before the action is triggered is also annoying. Again, a discrete action would be better. Furthermore, if on the one hand freezing the props is adapted for deactivation, on the other hand this action is not suitable for deactivation.

We also considered leg and knee gestures. For example, a knee pointing device is experimented in [3]. But in general, the monopolizing of the user body gestures is quite intrusive and can become stressful because the user must take care of each body movement in order to prevent from unintentional triggering of actions. This is why we did not retain the gestural modality. However, one gesture (combined with a specialized device) attracted our attention: hitting the ground with the foot. We will study an equivalent action in Sect. 3.4 that uses a foot pedal.

3.3 The modality embedded in props

In this case, $m_{cd} = \langle \text{button, on/off} \rangle$.

The third solution is to embed the activation modality directly on the main device, in our case, the props. In the work
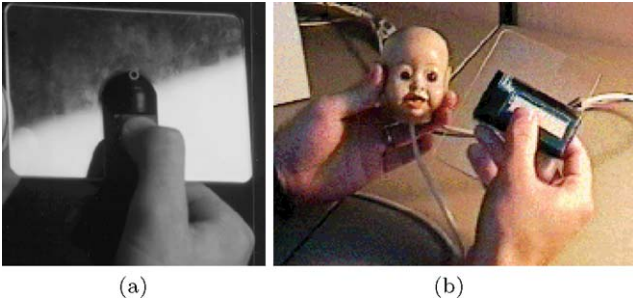
Fig. 6 The two versions of the buttons on the rectangular plate [5]

of the declutching mechanism for passive props applied to neurosurgery [5], a button was embedded on the rectangular plate (see Fig. 6(a)). This button, activated by the thumb of the hand, allows the user to start controlling the position of the cutting plane represented by the rectangular plate. It has later been changed to a membrane switch (see Fig. 6(b)), because a button required too much force to press it down. Note that no button was placed on the doll's head in order to keep it easy to manipulate with six degrees of freedom. Indeed, adding a button on a physical object that is manipulated with six degrees of freedom implies accessibility problems and the risk of non-intentional triggering.

The modality embedded physically in the props is illustrated in the I/O Brush [11]. The change of modalities exists in order to modify the use of the brush: acquire an image, acquire a colour, and acquire a sequence of images. The change of modalities is performed by turning a knob that is attached to the handle of the brush. In these two previous examples from the literature, the apparent equipments affect the conventional use of the props. Thus, even though putting physically embedded actuators on the props seems to be "self-evident", it appears to be a non-ubiquitous solution. From the handling point of view, these equipment buttons lead to problems of discomfort, loss of freedom, as well as loss of accessibility. Furthermore, they may also be activated unintentionally. It seems therefore to be difficult to integrate this kind of modality efficiently in the interaction.

3.4 The modality embedded in foot pedal

In this case, $m_{cd} = \langle$foot pedal, on/off$\rangle$.

The fourth solution is to delegate the clutching to a foot pedal. The user controls the movement of the virtual object by keeping the corresponding foot pedal pressed down. Consequently, the user keeps a total freedom of movement with his/her hands. The modality embedded physically in an additional device, the foot pedal, appears in both previous examples cited above ([9] and [5]), respectively in part 2, Fig. 4 and in part 3, Fig. 5.

In the first example, the molecular visualization [9], two foot pedals are used. A first pedal allows the user to asso-

ciate the movements of the cube to the molecule, and a second pedal allows the user to enable the motion of an atom, once the top of the virtual pen intersects and selects the target atom. In the second example [5], the passive props for neurosurgery, the foot pedal is used to clutch the doll's head.

4 Determination of the optimal solution

When designing ArcheoTUI (Fig. 1) for the assembly of archeological virtual fragments, we needed a modality to repeatedly clutch and declutch the movement of the prop from the movement of the corresponding virtual object. In Sect. 3 we have presented and discussed 4 possibilities for the activation of the modality m_{va}. Even if the foot pedal modality seams to be the best solution, the solution of putting buttons on the props is often requested and desired while doing a user-centered design. We had to show empirically that this solution is not appropriate. Consequently, we tested and compared the following two solutions for the activation of the m_{va} modality in ArcheoTUI: we put a button on each of the two props according to Sect. 3.3,

$$m_b = \langle\text{button, on/off}\rangle$$

and we associated the props with two foot pedals according to Sect. 3.4:

$$m_{fp} = \langle\text{foot pedal, on/off}\rangle.$$

In the following, we present the design of the two solutions, the results of the user study we conducted, and our conclusion.

4.1 Design

At least two languages are possible for the buttons and the foot pedals.

The first language l_1 is to keep the button (resp. the foot pedal) pressed down to clutch and thus to associate the movements of the corresponding prop to the virtual object, and to release it to declutch (see Fig. 7(a)).

The second language l_2 is to press down and release the button (resp. the foot pedal) each time the user wants to change between the clutching mode and the declutching mode (see Fig. 7(b)).

Applying either language on the button and the foot pedal results in the four possible modalities for clutching and declutching, and we denote the four modalities as follows:

- $m_{b1} = \langle\text{button}, l_1\rangle$,
- $m_{b2} = \langle\text{button}, l_2\rangle$,
- $m_{fp1} = \langle\text{foot pedal}, l_1\rangle$,
- and $m_{fp2} = \langle\text{foot pedal}, l_2\rangle$.

When using m_{b2}, the user is free to manipulate the props with the six degrees of freedom. However, the button may not be accessible when the user needs to clutch/declutch. Moreover, with the second language l_2, the state of the button or of the foot pedal does not reflect the state of the system (clutched or declutched). This fact is known with the bounce-back buttons that are used for computer on/off switches [2]: they typically have to rely on an indicator light to represent the state of the computer.

When using m_{b1}, holding the button down with one finger may imply a loss of manipulation freedom.

Note that in [5], the l_1 language was implemented in order to reduce mode errors, according to [12] who has shown that such a tension (when the button is hold down by the user) can reduce mode errors. One can imagine that holding down the foot pedals continuously during the manipulation of the props can become tiring. The foot pedals of Archeo-TUI are not designed to capture a proportional action such as the pedals of a car (see Fig. 8(a)). The foot pedals of Archeo-TUI only capture a discrete "on/off" action, the form is quite flat (see Fig. 8(b)), and consequently it allows the user to simply let his foot rest on the foot pedal without any particular effort. The l_2 language would force the user to disengage his feet from the pedals (and then the user has to locate it again), and would also require a feedback to inform about
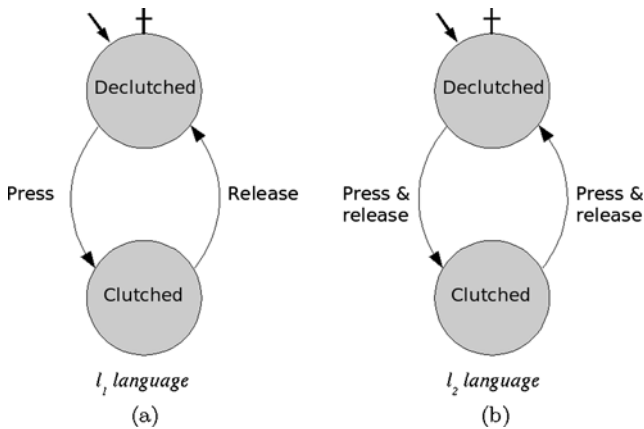
the clutching state. Using sound, light or color would be an extra information to perceive and analyze by the user, especially for the assembly task that requires complex reasoning. Moreover, playing a short sound would not inform the user continuously, and playing a continuous sound would be unpleasant. Again, with the l_1 language, the position of the foot on the pedal provides passive haptic feedback that informs about the state of the clutching.

For the sake of accessibility, mode error and ergonomy concerns, we implemented the modalities m_{b1} and m_{fp1}.

4.2 User study

The ease of use and the efficiency of using the props of ArcheoTUI in combination with foot pedals for clutching/declutching in order to perform virtual assemblies was demonstrated in a first pilot study [10]. A second user study was conducted in order to compare the two modalities, *i.e.* the use of the pedals (see Fig. 9(a)) and buttons (see Fig. 9(b)) when performing virtual assemblies. A log file recorded the user actions, and the subjects filled out a written questionnaire in order to gather feedback and preferences. The experiment lasted 2 days, and 26 persons took part. Each of the participants had to accomplish six assemblies (illustrated in Table 1). They were 10 females and 16 males, aged from 13 to 56 years old. 21 participants were right handed, 3 left handed and 2 ambidextrous. Note that twelve participants were cultural heritage professionals. All the participants went through the buttons and the pedal conditions (within-subject design), and the order of using the pedals and buttons was counterbalanced. Half of the subjects began the test using pedals to perform the first three
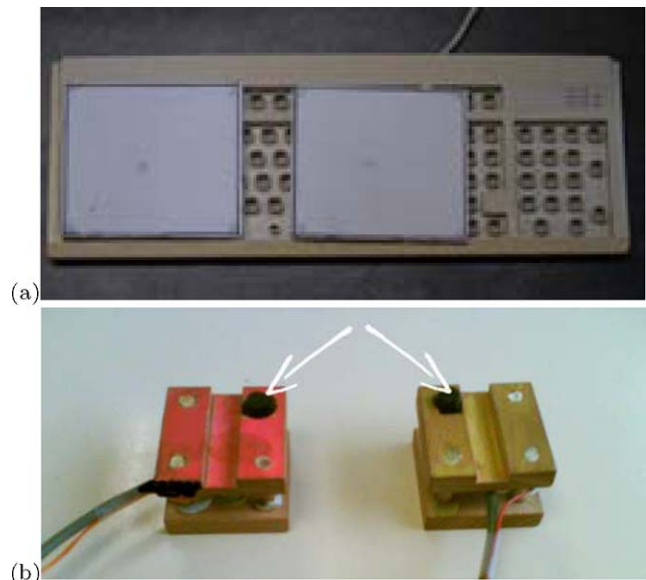

Fig. 7 (**a**) language l_1, (**b**) language l_2

Fig. 8 (**a**) Continuous action: the foot pedals of a car. (**b**) Discrete action: the "flat" foot pedals of ArcheoTUI
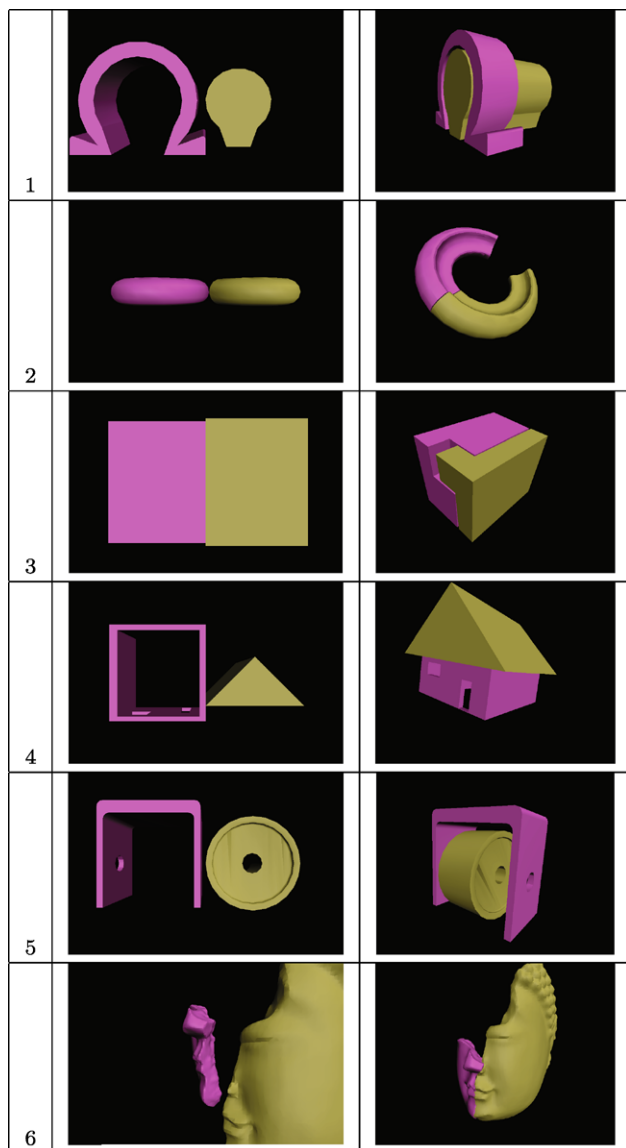

Fig. 9 The two modalities: (**a**) The foot pedals m_{fp}. (**b**) The buttons on the props m_b

Table 1 The six assemblies (left: the initial position, and right, the result to obtain)

assemblies and finished the last three assemblies with buttons, and the other half began using the buttons and finished with pedals.

The subjects did not express a significant preference: 57% of the subjects preferred the foot pedals, and 43% the buttons. We believe that for more complex assemblies that require more time, we would identify a more significative preference for the foot pedals. This is due to a qualitative observation of the users during the experiments that showed that the users perform long continuous movements when using the foot pedals, while doing short jerky movements when using the buttons. A log file analysis confirms these observations. We measured the mean time of a movement from the time that a virtual object is clutched. For the foot pedals, the mean time was 6.59 s (with a standard deviation

of 5.33 s), compared to only 3.96 s for the buttons (with a standard deviation 2.87 s). According to the feedback of the users in the questionnaire, some of the subjects expressed that using the pedals allows the user to perform their reasoning efficiently, and to accomplish the real assembly gesture to the end. The user study revealed that the movement of the hands is more similar to the real-world assembly scenarios when using the two foot pedals, and that the users can keep on concentrating on the actual assembly task.

We also measured the total times to accomplish each assembly. However the results are not significant. Our one site study had to be designed in a way that each participant spend 30 minutes for the whole experiment, and the times allocated to the exercises were short (2, 3 or 4 minutes). Longer experiments with more complex assemblies (a dozen or about twenty fragments per assembly) would allow to gather more significant results.

4.3 Discussion

The aim of ArcheoTUI, and more generally of TUIs for virtual assembly, is to allow the user to execute exactly the same movements as if the virtual objects were in his/her hands. But when using buttons on the props, holding down one finger on the buttons introduces a limitation of freedom of movement. The user decomposes one assembly gesture in a series of shorter movements by repeatedly clutching and declucthing the props. Recall that the clutching is needed to overcome some constraints, but it is not desired at first (in an ideal world). The consequence is that the metaphor is broken. The manipulation of the props with the buttons leads to movements that are different from the assembly gesture. Moreover, we noticed an extra inconvenience that can happen when using the buttons. When pressing down the button to continue an assembly in progress, or when releasing the button in order to declutch, the change of finger tension can make the hand or the other finger moving and thus implies a slight move of the virtual objects' position. This becomes irritating for the users since they cannot work precisely on their actual task.

When using the foot pedals, the user's hands and fingers are free to perform all translations and rotations. We noticed that the users performed complete and full movements of the arms, and rotated the props freely with their fingers. They used the clutching/declutching mechanism in order to reposition the hands when an assembly gesture is finished. Indeed, using the foot pedals allows the user to perform full movements in only one gesture that corresponds more to the real assembly gesture.

5 Conclusion

The results presented in this article focus on the assembly of virtual 3D objects by means of tangible bimanual inter-

action. The interaction metaphor consists in providing two props to the user to hold in her/his hands, and the movements of the two props are directly mapped to the two corresponding virtual 3D objects. We highlight that in various situations, it is necessary to disengage this mapping for a while. Accordingly, in terms of user interaction, we focus on the design and development of the activation and deactivation of the this modality, that we call m_{va}, by taking into account the particular context of tangible bimanual interaction. From a general point of view, we have displayed the fact that to achieve some tasks, a modality has to be activated to realize the principal modality. We first discussed two "self-evident" possibilities to activate/deactivate the modality m_{va}: the vocal modality and the gestural modality. Although voice input is a nice solution, and in spite of today's progress in voice recognition, it lacks from efficiency due to the duration of pronouncing the commands. Gestures often suffer from the problem to trigger actions non-intentionally.

It appears that is often necessary to add an equipment to the system. In the specific case of the assembly of virtual 3D objects using tangible bimanual interaction, we have studied two types of equipment: buttons on the props, and a foot pedal. We explored four possible modalities, depending on the chosen languages.

The button solution seems to be very simple, but there is a real impact on the interaction, preciseness, and handiness of the props. Even more, with buttons embedded on props, the tangibility metaphor of props representing the virtual objects is totally broken.

Using the foot pedals, the pure tangibility metaphor is slightly broken as well, but less than with the buttons, because the clutch is used less often, and the movements are longer. Indeed, when using foot pedals, the user's gesture is closer to the real-world behaviour.

We have shown that for the activation of the modality $m_{va} = \langle 2 \text{ props}, \ 2 \times 6 \text{ DOF} \rangle$, the best modality is $\langle \text{foot pedal, on/off} \rangle$ with the l_1 language, *i.e.* to keep the foot pedal pressed down to clutch and thus to associate the movements of the corresponding prop to the virtual object, and to release it to declutch.

In the near future, we plan to conduct a user study with more complex assemblies and more fragments, in order to give a significant statistical evidence that validates the superiority of the foot pedals compared to the buttons. Moreover, we seek to find other interaction techniques where the use of foot pedals could be beneficial.

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