A Survey of Immersive Systems for Shape Manipulation

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ABSTRACT

Immersive modelling systems have predominantly used non-natural interfaces and devices for shape modification. The new technologies for gesture and speech interaction can provide more familiar interface and reduce the cognitive complexity of current user interfaces of traditional visualization and modelling systems, making it possible manipulating and modifying the shape in a simple and effective manner even by non-expert users. In this paper, we present a survey of existing approaches for immersive shape modelling and manipulation. Current approaches are analyzed according to three characterizing key aspects: input method, supported operations and type of representation of the shape. Finally, the paper briefly introduces our current approach to verify the existence of consistency in hand motions/gestures among different users for 3D modelling tasks in virtual environment, as a first step for the creation of natural interfaces in immersive shape manipulation.

Keywords: 3D Modelling, Shape Modification, Natural Interfaces, Mid-air Gestures, Immersive Environments
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1 INTRODUCTION

The recent advances in Virtual Reality (VR) systems paved the way for their increased use in several industries. Indeed, the availability of low-cost VR tools and the new means to acquire and print 3D shapes enlarged the number of possible applications and the type of users that can benefit of these technologies. Currently, only experts can use CAD software to create and modify 3D shapes. This poses a big barrier to entry to end users, as the over-complicated applications are hard to understand for even simple modifications. With the development of appropriate shape interaction and manipulation techniques, the inclusion of end users in the design and customization of products can become possible.

For instance, it can become possible for consumers to easily modify an object present in a 3D model library by changing its shape or other key characteristics and to send the renewed design to a 3D printing company that will finalize the model and bring it to reality.

To allow a full integration of any potential customer in this scenario, it is important to provide very natural shape modelling functionalities, and immersive VR may offer suitable environment to achieve this goal. To understand the state of play of current immersive 3D manipulation systems, this paper provides a survey of research works addressing shape interaction and modelling in immersive VR environments. Moreover, our research objectives in this perspective and current achievements are introduced briefly.

This paper is organized as follows. Section 2 introduces the set of criteria adopted to illustrate the various approaches for manipulating 3D shapes in immersive environments, and provides an overview of the main trends of existing systems. Section 3 briefly illustrates our current achievements in the investigation of user behaviour to define more natural shape interaction methods in VR. Section 5 concludes the paper.

2 SURVEY ON SHAPE MANIPULATION APPROACHES IN IMMERSIVE ENVIRONMENT

To provide a meaningful classification of the relevant works available in literature, we selected three key characteristics that we think have considerable implications for the future of immersive shape modelling and its effective usage in working context.

The first characteristic considered is the input method used for interacting with 3D shapes. The second aspect considered regards the types of operations on 3D shapes that the proposed methods support. Lastly, we focused on the shape representation adopted in the reviewed approaches. The first two aspects provide indication on how much the user experience can be natural and effective in terms of obtainable shapes, while the objective of the last one is to highlight the ease of use and integration with modelling and production systems.

Table 1 provides an overview of the works that, in our opinion, have contributed to the advance of immersive modelling. The considered works are analysed and clustered according to the enabled input methods (columns) and the type of provided shape manipulation capabilities (rows); moreover, for every work the type of shape representation on which the modification is applied (sub-rows) is indicated.

Concerning the input methods, we consider the possibility of capturing free movements, which generally correspond to sketching of curves and surfaces (*Free gestures*); the use of a gesture grammar corresponding to specific actions (*Pre-defined gestures*); the use of physical tools for element selection e.g. controller, or additional equipment able to track the hand(s) movements, e.g. gloves, (*Input device*). *Semi-free hands* indicate the use of passive markers for tracking the hand gestures, while *Free hands* indicate that no markers are used. *Voice* specifies that the system is able to understand vocal instructions. Finally, Menu indicates the use of traditional menus or graphical widgets for the selection of the operations or for the indication of the element to insert or modify.

Regarding the type of shape manipulation, in the table, we clustered works according to the following functionalities: *Object interaction without shape modification*, *Shape creation*, *Direct shape deformation*, *Indirect shape deformation*. *Object interaction without shape modification* indicates actions, which do not change the shape except for its dimension (i.e. scaling). *Shape creation* refers to the capability of defining new shapes either by drawing curves/surfaces or by instantiating constructing primitives in VR. *Direct shape deformation* indicates the possibility for the user to modify the shape acting directly on some elements (points/curves/surfaces) of the object to drive the modification. *Indirect shape deformation* refers to modification of the shape through the change of its construction parameters (e.g. the diameter of a hole). For each operation category, the works are further distinguished according to the type of shape representation on which operations are performed. *CAD model* indicates that the operations are performed on a precise geometry representation (B-rep or NURBS) generally using a CAD kernel or modeller functionalities; *Mesh* specifies that mesh representation is used both for the visualisation and shape modification. Finally, *Other* collects all the works that adopt specific types of shape representation (e.g. generalised cylinders) or creation history tree and/or feature graph. It is worth to note that some works support shape modification through the history tree or feature graph modification but allow the user to directly select the shape elements belonging to the concerned feature instead of having to browse the feature/history graph. These works are clustered on the sub-category *Oher* in the *Direct shape deformation* category.

TYPE OF SHAPE MANIPULATION		INPUT METHOD						
		Free gestures	**Pre-defined gestures**	**Input devices**	**Semi-free hands**	**Free hands**	**Voice**	**Menu**
	Shape representation							
Object interaction without shape modification	*Cad model*	[10]	[10], [14], [28]	[13][23]		[10], [28], [34]	[14]	[13]
	Mesh							
	Other	[5]	[5]			[5]		
Shape creation	*Cad model*	[2], [8], [11],[16], [26] [29], [36]	[1], [6][16]	[1], [2], [6] ,[7], [8], [11], [16], [26], [29] ,[35] [36]		[6]	[1], [26], [29], [30]	[1], [12], [30]
	Mesh	[24], [31], [25]	[15], [27]	[24], [25]	[15], [27]	[31]		
	Other	[9] [12],	[9][22]	[9], [12]		[22]		
Direct shape deformation	*Cad model*	[2], [6], [8], [11] [26], [36], [37]	[1], [19],	[2], [6], [7], [8], [11], [19], [26], [35], [36], [37], [38]		[2], [6],	[26],	[12], [38]

		Mesh	[18][21], [24], [31], [25]	[18], [27]	[17], [21] [24], [25]	[18], [27]	[31]		[18]
		Other	[9], [32]	[9], [22]	[9], [20], [33], [38], [12]		[22], [32]		[1], [20], [33], [38], [12]
	Indirect shape deformatio n	*Cad model*							
		Mesh							
		Other		[3]	[3]			[3]	

Table 1: Overview of relevant works classified according to the considered criteria.

2.1 Input Method

The earliest approaches mainly used a tablet with a pen device [23], later a tracked stylus was introduced, [6] [24] [36] to interact with the virtual environment. As an alternative to this paradigm, several works have used data gloves as their input devices [9] [11] [13] [16] [17] [19] [29] [37]. The use of flex sensors for individual fingers of the users' hands has been largely considered since it allows hand movements and gestures, that can be tracked, analyzed and interpreted as specific application commands [1] [7] [8] [13] [19] [25]. This hardware allows tracing all the users' fingers independently, consenting a high level of accuracy when capturing gestures. However, these gloves are plugged frequently into desktop computers, making the interaction space much small. Another approach consists in using a tracked controller with dedicated buttons. These two approaches have been combined in [3], pairing a wand device capable of six degrees of freedom for direct manipulation with a data glove. Controllers from the gaming industry have also been used in research, for instance, the WiiMote or the FlyStick [20] [21] [38]. However, some are not adequate due to their ergonomy, and their adoption was a bit prejudiced because they do not resemble classical drawing devices (e.g. pencil).

More recently, colour and depth sensing cameras have been used to try to achieve the same level of precision as tracked devices, but with inexpensive technologies. Different setups, including Kinect sensor for hand tracking, have been tested [5] [6] [14] [22] [28] [31]. A similar solution has also been achieved, by substituting the Kinect sensors with PlayStation Eye cameras [34]. This last approach was limited to scenarios where the users' hands can be distinguished from the background, in order to segment them. The Kinect is the superior alternative, as the depth sensor can segment background from foreground data, but while it can detect body movements, it has limits in distinguishing hand and finger movements. The use of small markers in the users' hand for motion capture has also been tested [15] [18] [27]. A more recent alternative to such sensors is the leap motion [10] [2] [31]. This device only tracks hands and arm motions, but its accuracy is superior to those mentioned above.

Hand motion is proven to be a powerful and potentially natural input mechanism in computer aided design systems, in particular, in the initial shape design process when the overall shape of the object is specified before detailing it. Several works address the use of hand gestures; some of them recognize a set of predefined gestures commands for the interaction with 3D models (translation, rotation and scaling) [5] [10] [28] [34] as well as for the creation of a concept model [16] [6] [15] [27] [9] [26] and for shape modification [18] [27][22] [26]. Despite the considerable advances in gesture recognition technologies, general gesture grammars with a wide set of gestures not depending on a specific context has not been achieved yet.

Free hand gestures are used to draw shapes and draw over surfaces both for the creation of new shapes [2][8][9] [11] [36] [24][31] [25] and for their modification [2] [6] [8] [9][11] [18] [21] [36] [37] [24] [31] [25]. In this case, the system does not recognize pre-defined gestures but simply tracks the hand motion to interpret the drawing for the shape creation and/or its modification.

Voice commands are also addressed with a limited vocabulary in [1] [3] [14] [26] [29] [30] for shape creation and possibly modification.

Summarizing, in the most recent systems hand gestures and movement are considered a key mean to provide user inputs. The data glove was the most common interaction device used. It is easy to use, ergonomic, but since it requires data cables to transfer data to the system, it is impractical for applications that require large areas of movement or fully immersive approaches. Controllers are an extension of a desktop mouse, by providing the buttons and its pointing capabilities. The precision is very device dependent, with the state-of-the-art devices providing millimetre precision. The increased accuracy when tracking controllers makes them the best non-natural interface solution. The Kinect sensor offers full-body tracking, making it a robust solution when more than a hand tracking is required. Multiple Kinects can be used simultaneously in order to resolve occlusion conflicts and increase the tracking area. Even though the sensor can only recognize open and closed hand gestures, it is not robust enough to correctly track finger movements. The leap motion on the other hand, developed specifically for hand tracking, provides a much higher level of precision. There are still occlusion issues while using this hardware, as the fingers of one hand can prevent the sensor from seeing behind them. It works especially well when paired with a head-mounted display, as the user usually performs the actions in front of the sensor. Moreover, to achieve natural interfaces, it is important to limit predefined gesture vocabularies, thus reducing the learning effort for the users.

2.2 Types of operations on the Shape

Immersive assembly and modelling systems are capable of providing different and more engaging information onto the parts that compose an object. Indeed, the visualization method chosen has a considerable influence on how users perceive and interact with the objects. Looking at the existing tools for shape manipulation in immersive environments, we can distinguish works that focus solely on the interaction with the objects [5] [10] [13] [14] [23] [28] [34] and others specifically addressing shape modelling operations, i.e. that also allow the creation and/or modification of 3D shapes. These are fundamentally different operations to take into consideration to develop a complete modelling environment.

The aim of the first category of works is to support object inspection/evaluation and assembly tasks. In this perspective, scaling, translation and rotation are the key operations to support. Systems like the one described in [13] support users in the relative positioning of parts by providing, for instance, constrained motions of objects along specific meaningful axis, and can provide both one-hand and two-hand assembly of parts. Despite all the aiding features, the use of virtual reality causes a lot of physical strain on the user, making this approach not suited for large assemblies or long task sessions. For these reasons, most of the previous research work utilized CAVE like environments, some with the addition of 3D glasses, since they require less body movements from the user.

In [23] authors propose an integrated environment in which the user may interact with the desktop CAD system by using a tablet in the virtual environment: to aid in the visualization of the assembly, users are able to select and see inside all the parts selected by positioning the tablet on the virtual object. For the visualization and transformation of a complete assembly, users can utilize rotate, pan and zoom gestures with a Leap Motion sensor [10] or by using different types of depth colour cameras [5] [28] [33] or by the aid of hand markers [15].

Some immersive modelling systems can only support the creation of new shapes [15] [16] [30] [29], others allow only the modification of primitive shapes or objects already created in traditional CAD systems [17] [18] [19] [20] [21] [32] [33] [38]. Finally there are systems supporting both the creation and the modification of shapes [1] [2] [6] [7] [8] [11] [24] [25] [27] [36].

The first are targeting creative users, supporting them in sketching the conceptual model of the object as in [16], or mechanical engineers in creating solids as in [15] and [30]. In [15] parts are modelled by combining volumes obtained by sweeping geometric primitives specified by the user through gestures, while in [30] parts are created by features instances specified by the user through voice commands and position indications for the parameters definition.

The creation of surfaces and volume primitives by sweeping curves along specified trajectories generally drawn by hand movements is a very common modelling functionality supported by many systems [15] [6] [25] [35] [19]. In [19], for instance, the resulting curves can be twisted and swirled in order to arrive at a "sweep surface". While [25] directly creates a sweep surface following the hand movement, which is quite convenient for industrial design objects made by organic shapes.

The majority of the works present in literature provide capabilities for modifying existing shapes. These works can be further distinguished into those allowing the modification of the objects by interacting and changing directly the shape elements from those allowing the modification of the constructive elements included either in the history tree or the feature graph [1] [3] [33] [38] [20]. Among these latter, [3] reports a system that thoroughly integrates VR and CAD software and uses gloves to resolve the poor accuracy of free-hand gesture interaction. While [1] [12] [18] [20] [33] use the combination of gestures and menus to overcome the accuracy problem in the specification of the parameter values. Also, newly available commercial system Mindesk [39], even not exploiting the history graph, follows the combined approach to guarantee a large number of modelling operations and precise input, providing a virtual reality interface to Rhino®. In most of these systems, gestures are used to resize, orientate and transform geometry, while the menu provides access to the modelling capabilities.

In case of free-form objects, surface modelling by sketching curves and by transforming surface control points are also proposed [19] [11] [7] [24] [36]. One of the first systems following this approach is FreeDrawer [36], which allows the direct creation of surfaces by drawing and filling in between curves, which can be further adjusted by selecting their control vertices. In [24] rotational shapes are created through the sketching of the silhouette, which is then used for the shape modification by pulling its points as handles. Other modelling systems for the modification of objects with symmetries are also proposed. In [22] modifications of symmetrical parts are obtained through skeletal bending, sectional deformation and sectional scaling schemes by using a predefined set of gestures. Only rotational objects are also considered in [31]; here, vase-like shapes are treated and the type of modification is automatically understood by the system based on the position and movement of the hand fingers with respect to the object. This work is particularly interesting since it aims at avoiding the use of predefined gestures and at detecting the user intent from fine finger-level movements by using a depth camera.

Free-form deformations (FFD) are also supported by some systems. For instance, [21] makes available local deformations guided by a virtual brush and directional curve as well as global deformations like Twist, Bend, Swell, Taper and Stretch, driven by the users' gestures. One of the main advantages of this tool is the storing of the modifications in a deformation curve that permits to see the shape at previous steps or to perform further adjustments. FFD or similar operations are also available in the systems adopting the virtual clay metaphor to mimic physical shaping [17] [27] [37]. Among them, in [27] a variety of clay-like sculpting operations including deforming, smoothing, pasting, and extruding are proposed using direct finger input combined with a deformable physical prop. The physical prop is a sponge acting as a physical proxy to the virtual model, since it provides good tactile feedback and enables the user to have an instant idea of the extent of their manipulations.

Shape sculpturing together with primitives' combination and push and pull operations are the main capabilities provided by commercial applications, such as Sculpting or Oculus Medium [39] and MakeVR, which use specific hardware paired with their own controllers to provide complete shape modelling capabilities in immersive environments.

Even though these approaches are moving in the right direction, they still require the use of controllers and menus, limiting their usefulness for non-experts. Moreover, a specific shape can be obtained through different types of operations; the choice depends on the user preferences, habits and knowledge background. Therefore, the creation of a 3D modeling environment that can be used in a simple and effective way by non-expert users requires an in-depth investigation of these aspects, which, as far as we know, has not yet been made exhaustively.

2.3 Shape Representation

When working within a virtual environment, 3D shapes have to be represented differently than when using traditional CAD software. In VR environments, objects are represented as meshes to allow visualisation and fast collision detection, whereas CAD systems are using Boundary representations with precise geometry, e.g. NURBS. Therefore, models created in CAD systems need to be adapted to be usable in VR tools. This preparation is not a trivial conversion, but it normally requires some mesh simplification. This has the drawback to cause the loss of all the semantic information available in CAD data thus making almost impossible the backward conversion when modifications occur in the VR environment. Additionally, it is important to note that the choice of geometric representation critically affects the fluidity and interactivity of shape manipulation operations [9].

Works addressing the CAD/VR integration have followed two different approaches by connecting the virtual environment to a CAD application [13] [14] [23] [28] [35] [26], or by integrating the CAD kernel through its Application Programming Interface (API) [1] [20] [29] [35] [38] [15] and developing ad hoc interfaces. In the first case, main creation and modification operations are activated by accessing the CAD menu functionalities with voice, controller or other interaction medium. Regardless the approach followed, a representation of the object linking the VR mesh representation with the CAD B-rep is used. It allows transforming the change commands expressed in the VR environment into actual shape modification actions in the CAD environment. Thus, requests and changes occurring in one of the applications immediately appear in the other. In some cases, this combined representation maintains also the parameters and information of the history construction tree or of the feature graph [3] [1] [12] [13] [20] [38] [33] [30] [33]. In this way, the initial design intent and procedure can be applied in VR. Among the CAD systems used, we can list SketchPad [26], SolidsWorks [1] [10] [29] [28], Pro/Engineer [23], Rhino [14], Catia [20] Protean Clay [5], Autodesk Inventor [33]. The most used CAD kernels are OpenCascade, [12] [35] [3] [38] and ACIS [7]. Systems that can provide this type of integration are inherently superior to those that require manual integration. Even with the advances these works have shown, there are still problems when integrating CAD applications in a virtual environment, mostly notably the difficulty is in creating an appropriate interface.

Mesh representation is a de facto standard in VR applications as it allows fast visualization and rendering. However, modelling capabilities are somehow limited in purely mesh environment, allowing less high-level controlled modifications, e.g. through parameters or leading curves, and this is a big limitation in particular when the specification of the model requires several parameters with mutual constrained relationships. Thus, all the work addressing only assembly tasks [5] [10] [13] [28] [33] represent objects through meshes in the VR environment possibly directly linked to CAD representation, as shown in table 1. Even if more limited in the range of operations allowed, many systems are using meshes as a unique shape representation [17] [31] [18] [27] [24] [25] [39].

Some works aimed at shape modifications adopt different ad-hoc representations best fitting the supported type of objects and operations, such as generalized cylinders for rotational shapes [22] and voxel-based [32]. Authors in [6] use a simplified B-rep representation where objects are described by planar faces. Fuge et al. in [9] propose a dual representation combining point-based and surface-based representations for exploring conceptual designs without the need for detailed surface operations such as trimming or continuity constraints in early design stages. However, even if these techniques facilitate iterative exploration and evaluation of low-fidelity conceptual surface design, before the formal parametric CAD modelling, their creation and modification is still not natural.

In conclusion, depending on the type of objects treated, coupling with traditional CAD systems can be advantageous. This is the case of mechanical objects, which are generally modelled in professional environments and for which the use of analytical primitives and feature-based modelling is particularly convenient allowing a fast shape modification through few parameters changes. However, in industrial design and in general for users without an engineering background, it is important to interact with shapes without taking care of the underlying shape representation.

3 AN APPROACH FOR UNDERSTANDING NATURAL SHAPE INTERACTION IN VR

Despite recent technological advances in virtual reality, there is not a natural interface for immersive effective shape modification. Although natural interfaces cannot be suitable for all the applications, in future, we expect an even bigger interest in more natural approaches for shape manipulation driven by both hand/body motions and speech interfaces. The ability to control a system without resorting to any device is very compelling, indeed, one of the most important prerequisites for a natural use of immersive systems is cordless head- and hand-tracking.

The ambition of our research is to understand how to achieve a natural interface for shape modelling allowing non-expert users to easily modify shapes by using as less as possible technical media or pre-defined languages for the interaction with the 3D model. Moreover, low cost equipment should be used.

With this objective in mind, we conducted a user study to understand how users act to perform specific modelling tasks, and whether there is a consistency of hand motions/gestures and speech among different users.

3.1 Experiment Implementation

In order to analyse how users would interact with 3D digital models for their modification, we set up a low-cost VR environment and selected some modelling tasks, which can be achieved with different interaction strategies, i.e. symmetrical/asymmetrical, two/one hand movements. Taking into consideration cost and precision capabilities, to retrieve the pertinent information from the user hand motions we used a Leap Motion sensor. For the visualization component, an HTC VIVE head-mounted display is used, in combination with two VIVE cameras. A hand avatar provided the echo of the user movements in the VR environment. To provide the feeling of an operating system, a Wizard of Oz approach was used, where a human operator performs the user actions from behind the scenes, without the user being aware of this. For the 3D environment, the Unity 3D engine has been adopted.

The experiment involved 21 users of different age not skilled in VR technology. Before starting the experiment, users were informed that they should perform the required tasks in the most natural way by using hand gestures or speech. Tasks consisted of five different manipulations/modifications of a 3D shape in the virtual environment (see Fig.1). The first task was to assembly a cylinder and a box with a cylinder-shaped hole. In the second one users were asked to perform a twisting deformation on the object. The third task required a bending deformation; while in the fourth task users had to change the size of the object. Fig.2 illustrates a user during the resizing operation. Finally, users were asked to perform a triangle-shaped local depression deformation on the presented object.

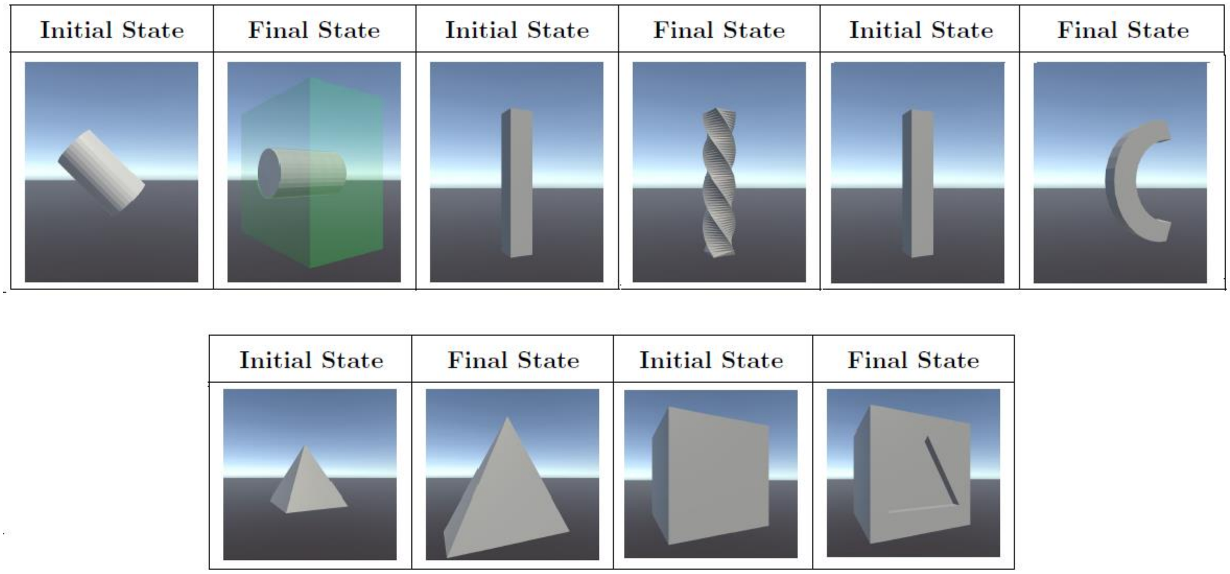

Figure 1: The shape modification tasks in the experiment.

3.2 Main experiment outcomes

The outcomes of the experiment confirm that if the user could act in the virtual environment and with virtual shapes freely the task is performed in a simple and direct way; in general, the user tends to behave as he/she would in the real world if he/she manipulated a physical object. From the data gathered and analysed it results that the use of physically plausible movements to interact with the virtual objects is prevalent, even if users adopted different strategies. A well-defined set of gestures has been identified across the majority of participants. For instance, for the resizing operation the majority ideally selected and dragged horizontally/vertically the vertices; some of them using simultaneously and symmetrically two hands, some instead preferred to move only a vertex at a time. Speech interaction was very rarely used and never to express a command to the system but only to better specify the action performed on the virtual shape by the hands. Details on the experiment carried out and the related results may be found in [4]. In the future, we will extend the tests to additional selected shape modification operations.

4 CONCLUSIONS

In this paper, we reviewed the current works for shape modelling and assembling in immersive environments. The new hand and body tracking hardware allow the exploration of new interaction techniques. The trend started with data gloves, which allow capturing free movements with high precision but at the price of burdensome technology addition; then programmable controllers were used acting as mouse in the 3D space; currently the goal is a media-free communication with the use of depth and colour sensors. These improvements are paving the way for the creation of more natural interfaces, which will enable the use of shape modification tools by non-experts in the 3D shape modelling area. The development of such natural interfaces requires a comprehension of how users would interact and modify shapes if no constraints are imposed. With this objective, we carried out a preliminary study aimed at advancing the understanding of hand and voice interaction for 3D shape modifications in immersive environments. Experiment results indicate some communalities in the user behaviours and represent an important information for continuing and orienting the exploration of this research area to build fully natural interfaces for 3D modelling without additional input devices or controllers.

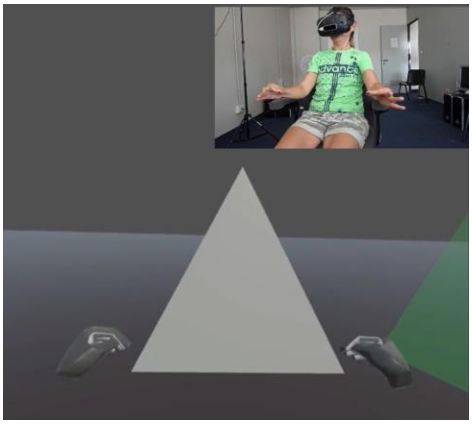

Figure 2: A resizing task during the real experiment.

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