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THE DRAWING PARADIGM REPRESENTATION AND INTERACTION WITH VIRTUAL IMAGE

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Traditional drawing involves drawing on some surface, often a plane, e.g. a sheet of paper, a school board or a wall. This type of drawing therefore takes place in two dimensions of this surface. Transferring this activity to a computer, or rather to the surface of its screen, did not change the two-dimensional nature of this action. Practically all applications today, from Paint to sophisticated computer-aided design tools, still operate in two dimensions, with even three-dimensional objects being developed using only appropriately selected flat cross-sections. This is partly due to pre-computer drafting canons, partly to the construction of the most popular computer interfaces which are essentially two-dimensional (screen, mouse), and partly to the ease of presentation using popular two-dimensional devices (screen, printer). However, modern Virtual Reality devices enable drawing in three-dimensional space, and this is not only about 3D modeling, which involves building a scene from blocks (geometric solids) and surfaces (grids, meshes), but also, and perhaps above all, about sketching lines and surfaces with a virtual pen in the air and thus creating a 3D drawing. But does this new drawing paradigm have a chance of catching on? Will artists, architects and designers reach for it in the future? Can they gain anything by using such a solution? This paper does not provide an answer to this question, it just shows possible ways of drawing in 3D along with their advantages and disadvantages. It is left to the Readers to decide how useful this approach can be in their artistic, architectural, design, etc. activities. The author, being a computer scientist, also invites the Readers who give a positive answer to these questions to cooperate in searching for the optimal three-dimensional drawing interface and its useful applications.

Keywords: *3D drawing, 3D objects, 3D interface, Virtual Drawing, Virtual Reality.*

Introduction

Drawing is one of the basic creative activities of humans. It has been used by humans since the dawn of time, as evidenced by the cave paintings at Lascaux. However, it always had a flat, two-dimensional character, determined by the surface on which the drawing was created. Even if this surface was characterized by large curves (e.g. the surface of a sculpture), the drawing on it was created using methods used for a plane (such as a wall or a sheet of paper). The limitation here was the technology, which required a physical drawing surface. Only Virtual Reality made it possible to draw in space without the need to place the drawing on a strictly defined physical surface. This means that it is necessary to use new techniques for creating a drawing, without the need to touch (physically or virtually) the drawing medium, i.e. its surface, with a pen (pencil, brush, mouse cursor, stylus, etc.) or an eraser. In the case of drawing in space, there is actually no such medium, or - if you prefer - the entire space is the medium. The paper explore, we will look at the different 3D drawing techniques that already exist and consider what other techniques can be used.

Experiments with various types of interaction with the three-dimensional virtual world have been conducted for many years in the Immersive 3D Visualization Lab[1] located at the Faculty of Electronics, Telecommunications and Informatics of the Gdańsk University of Technology. In addition to various headsets, several Virtual Reality caves are used there, which enable convenient interaction with the virtual environment by several people at the same time and easy viewing from outside. The largest of them, BigCAVE, is

[1] Lebiedź, *Virtual immersive environments; Id., Virtual reality as a tool for development and simulation*; Lebiedź, Redlarski, *Applications of Immersive 3D Visualization Lab*.

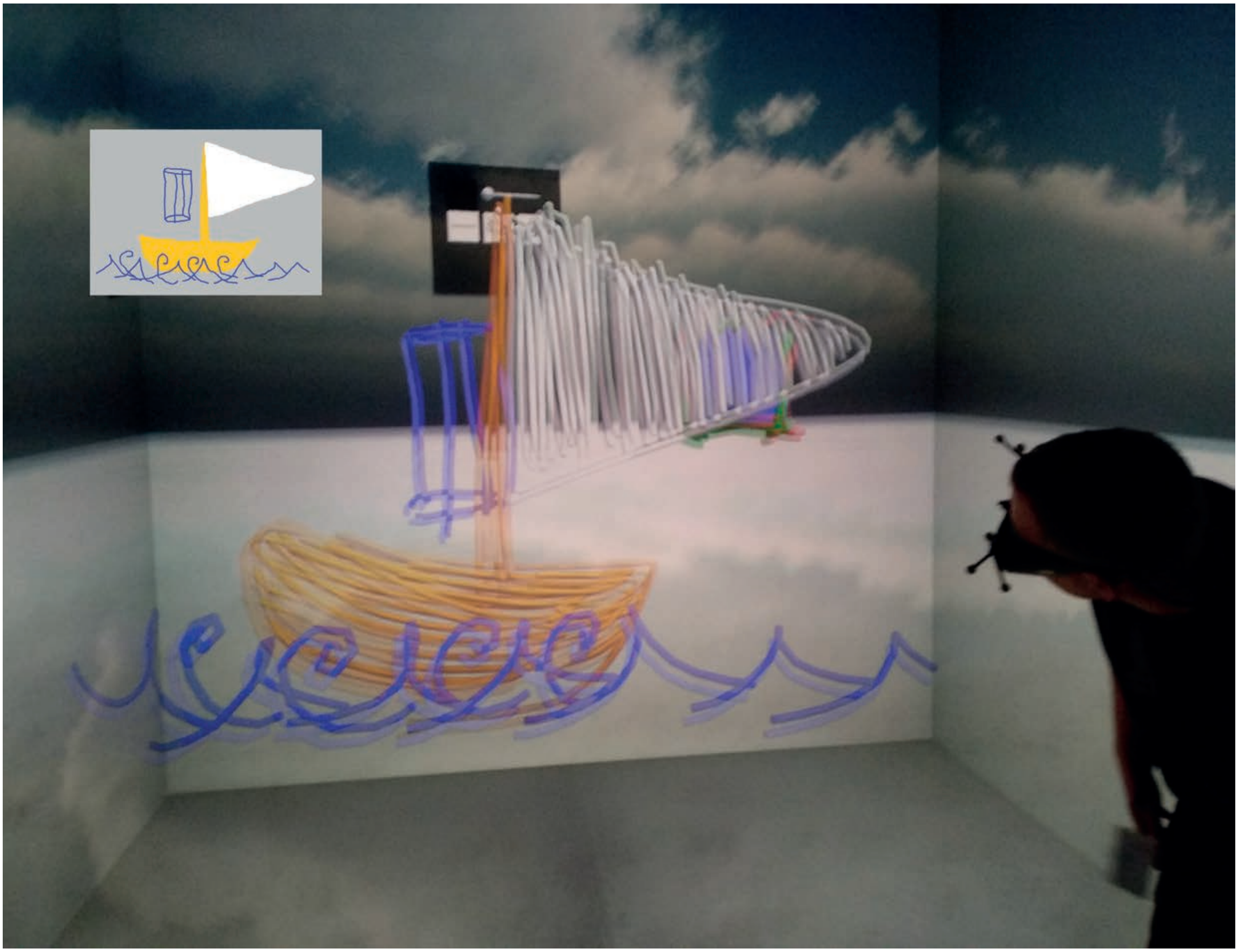
1 | *BigCAVE and digital twin of Długa (Long) Street in Gdańsk.*

a 3.4 m cube (fig. 1) and is perfect for experiments with interaction in three dimensions. One of the research areas is the search for convenient methods of creating objects in three-dimensional space, not only through classical modeling techniques[2], but also through virtual sculpting[3] and drawing[4]. This article is largely a summary of the research conducted in this area.

Drawing 3D curves

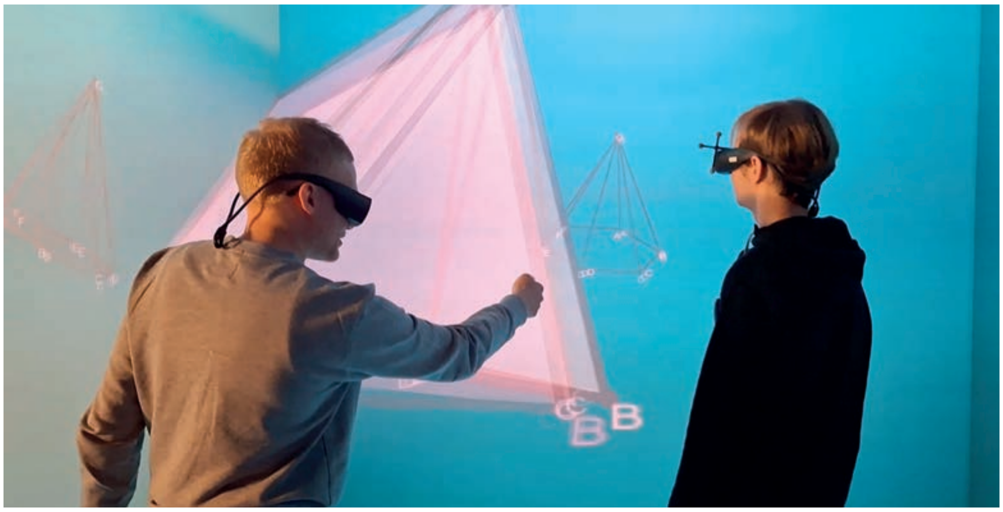
The most obvious way to draw in space is to transfer the methods used in classical drawing to a physical surface[5]. For this purpose, metaphors of well-known painting tools are used, such as a brush, palette, paint, etc. The controller held in the hand imitates the selected drawing instrument and with the movements of the hand an appropriate line is drawn in the air, or more precisely a ribbon or tube. In physical reality, drawing occurs as a result of contact between the drawing instrument and the drawing medium (surface). In the case of drawing in space, there is no *medium* or, as some prefer, the *medium* is everywhere. The draftsman must therefore start and stop drawing in separate actions so that the controller does not draw continuously and can be moved to any location without drawing.
Today's technology also allows us to use an empty hand[6] for drawing instead of a controller, but then various actions such as turning drawing on and off should be replaced with hand gestures (in the simplest case: flexing and straightening the index finger). While hand tracking may be more inaccurate for now, conceptually the hand could act as a controller, and hand gestures could replace the controller's buttons and joysticks.

2 Murgrabia, *An Attempt to Implement BlenderVR Visualization System Based on Blender3d in a Virtual Reality Cave Environment*.
3 Małasiewicz, Strauss, *Virtual sculptor*.
4 Muńko et al., *Magic 3D pencil*.
5 Cfr. Keefe et al., *CavePainting: a fully immersive 3D artistic medium and interactive experience*; Muńko et al., *Magic 3D pencil*, cit.; Rosales et al., *AdaptiBrush: Adaptive General and Predictable VR Ribbon Brush*; *OpenBrush community*, *OpenBrush documentation*;
6 Zeleznik et al., *SKETCH: An interface for sketching 3D scenes*.

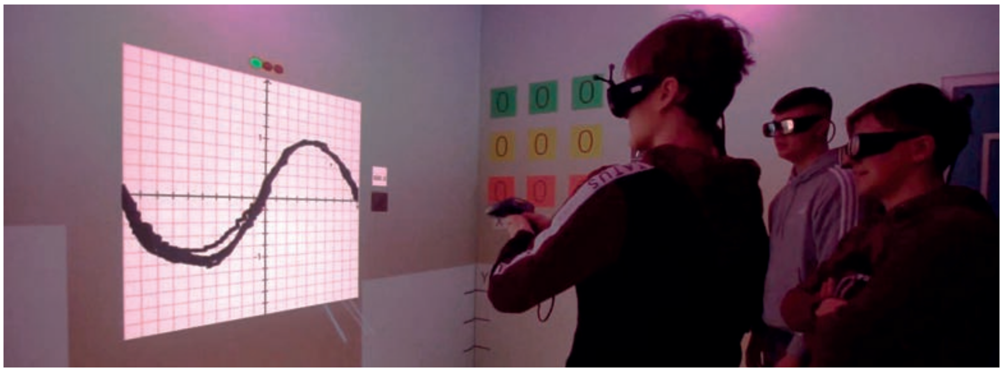


2 | *Example 3D drawing and its 2D equivalent (top left).*

Therefore, we will conduct further considerations assuming the use of controllers and their buttons or joysticks, remembering, however, that they can be replaced by hands and their gestures.
Alternative ways of creating a drawing include voice commands and eye pointing using eye tracking. In both cases, the challenge is to develop a convenient interface that allows for high drawing precision. Additionally, both approaches do not use hands, so there is some concern about the naturalness of such an interface. For this reason, we will limit the description of both methods to this paragraph only.
Drawing directly in the air has its drawbacks. However, reaching into different places with the controller in draftsman's hand is quite tiring, especially when drawing over a large area. One can of course allow scaling (enlargement) the drawing, but then we lose precision, which is limited due to the lack of hand support. Scaling can be done after the drawing is completed or while drawing using a virtual pantograph that creates an appropriately larger object next to it.
The low accuracy of 3D drawing compared to 2D drawing (fig. 2) results from the fact that when drawing carefully on a piece of paper, we only operate with hand (fingers, metacarpus and wrist) movements, usually resting the wrist on the table top, whereas when drawing in space, we move the whole upper limb without any support. Drawing with just one's hand, even without support, but with a comfortable hand position allows for greater accuracy and in such a case scaling can lead to higher precision.
In the context of drawing accuracy, the



3 | *An application to support the learning of descriptive geometry.*



4 | *Problems in drawing a curve on a virtual whiteboard identified in a virtual math escape room.*

“The most obvious way to draw in space is to transfer the methods used in classical drawing to a physical surface.

precision of tracking the controller held in the draftsman’s hand is also important here. A drawing application should provide a controller-controlled, clearly visible pointer that indicates the position of subsequent points of a drawn line. This pointer can be a physical tip of the controller or a virtual object (ball, brush, pencil, eraser) virtually connected to the controller[7], which – following the terminology used in robotics – we will call an end effector. In the latter case, it is worth having the ability to change the distance of the end effector from the controller to easily reach distant places in space. This can be achieved by a separate graphical control element (widget like a slider) hanging somewhere in the workspace or by a button/joystick on the controller. The end effector then moves away and towards the controller as if it were placed on a telescopic mechanism.

The above method only allows for freehand drawing without precision. To draw a perfectly straight line segment or a perfect circular arc, a different approach is necessary. For this purpose, the straight line segment drawing mode can be used by pressing the appropriate controller button (e.g. the trigger) to mark the starting point and releasing it to mark the ending point[8]. However, drawing modes for other lines (such as circular arcs) require a more sophisticated interface. The technique of “towing” the drawn point with one or even two hands can be also used[9]. Moreover, it is possible to indicate characteristic points of a graphic object. In the case of a straight line, it is enough to indicate two end points. In a similar way, by indicating the position of key points, it would be possible to create lines with a more complex mathematical description (circular arcs by specifying the center of the circle, the starting point of the arc, and the point designating the end of the arc, *Bézier* and *B-spline curves* by specifying their control points, etc.). Controlling single points rather than individual curve points seems more convenient when we require high precision of the shaped line. Note that the situation is similar for flat drawings created in 2D editors.

To enable the draftsman to modify the appearance of a line (changing its color, thickness, cross-section, etc.), a graphical interface is placed in the virtual drawing

7 Fröjdman, *User Experience Guidelines for Design of Virtual Reality Graphical User Interfaces Controlled by Head Orientation Input*.
8 OpenBrush community, OpenBrush documentation, cit.
9 Keefe et al., *Drawing on air: Input techniques for controlled 3D line illustration*.

5 | *Example 3D drawing in the "Magic 3D Pencil" application.*

space, allowing the definition of various line parameters. This interface often takes a metaphorical form, referring to traditional solutions, such as buckets of paint in which a controller imitating a classic paintbrush is dipped[10]. In extreme cases, one can even splash paint from such a bucket on an object in space[11]. The interface may also take the form found in classic graphics editors: windows (floating in space), buttons, dialog boxes, etc.[12], or an intermediate form[13]. Also valuable are the mechanisms that allow you to change the character of the line even after drawing subsequent objects, by selecting them and modifying their parameters using the same interface that is used to set the appearance of lines drawn in the future[14].

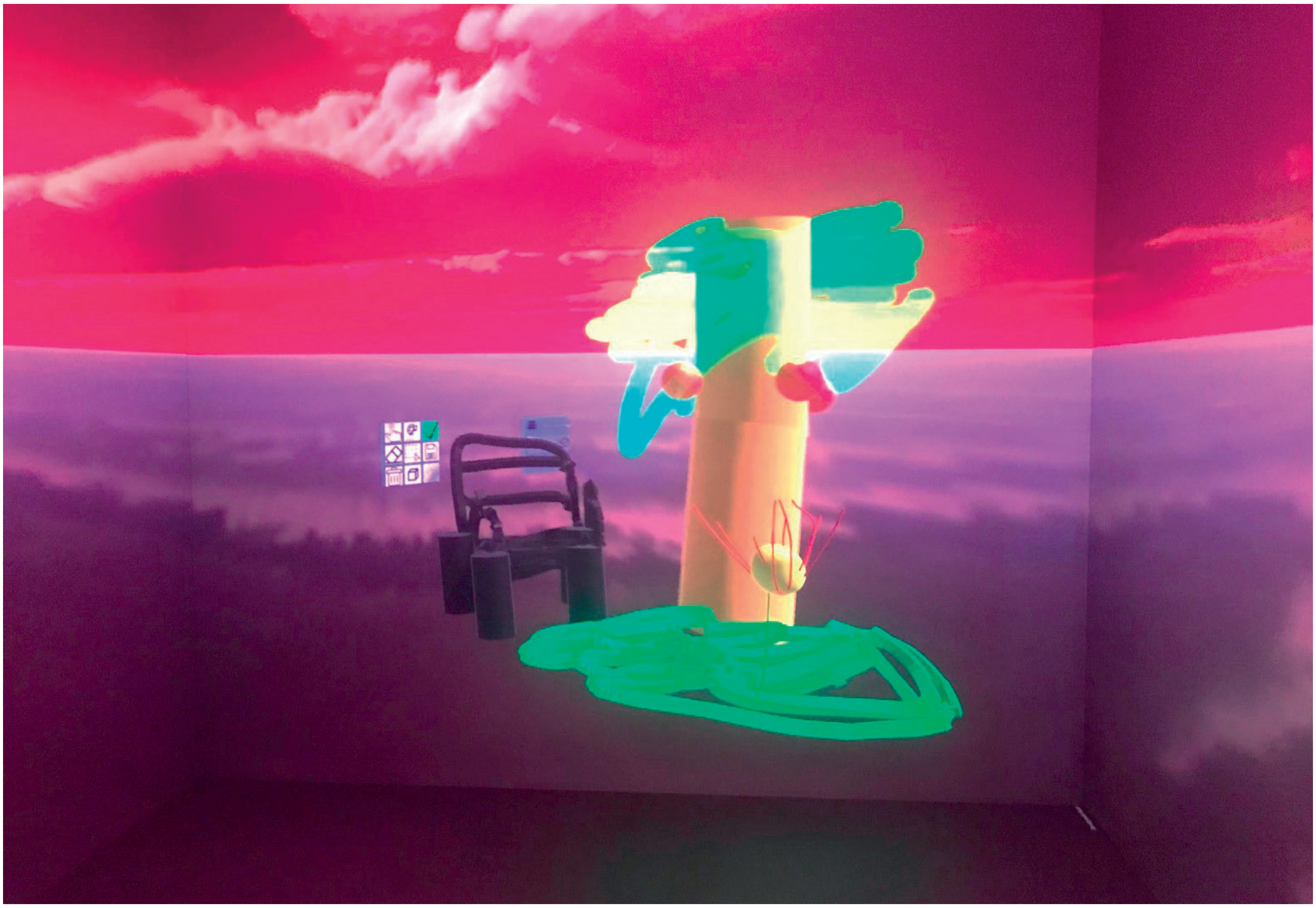
Drawing surfaces and solids

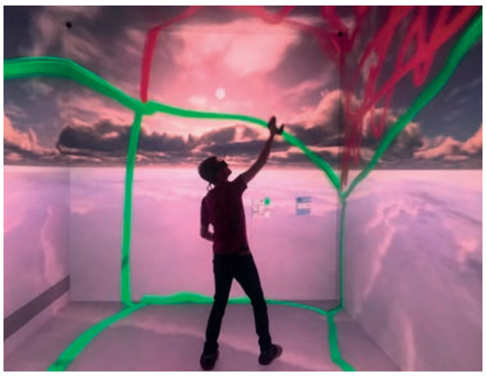
Drawing lines in 3D space does not exhaust the needs of a draftsman. After all, these are only one-dimensional creations, even when they are strongly curved. However, they would like to be able to also create surfaces and volumes, i.e. truly two- and three-dimensional objects. This can be achieved by filling the given surface or volume with appropriately "thick" lines – ribbons or tubes (similarly to how a surface is painted over with a crayon), but this method should be considered as not very efficient (fig. 2). However, it is more convenient to create figures and solids by indicating the location of their key points (e.g. for a circle or a sphere – the center and any point on the edge). Polygons and polyhedra can be defined by specifying all of their vertices. Regular objects, such as a squares or a cubes, can be defined with fewer points[15], but this requires additional interface elements (e.g. buttons) to select them.

Surfaces can also be thought of as parametric surfaces defined by a set (or rather an array) of control points, such as *Bézier* or *B-spline surfaces*. The user then specifies the location of individual control points and receives a surface patch, which can then be modified by moving the control points that designate it, acting as specific magnets that repel or attract the nearest fragments of the surface. These surface patches can then be used to form solids.

Solids can also be shaped by imitating the actions of carving in a hard material or molding from a plastic substance such as plasticine or clay[16]. Cutting off unnecessary elements of a block, kneading it, or even turning it on a simulated potter's wheel can be a useful way of constructing a solid, especially since these are familiar and natural activities. An interesting alternative is to use self-orga-

10 Keefe et al., *CavePainting*, cit.
11 Ibid; Lim, Aylett, *MY virtual graffiti system*.
12 Muńko et al., *Magic 3D pencil*, cit.
13 Hughes et al., *CaveCAD: Architectural design in the CAVE*.
14 OpenBrush community, OpenBrush documentation, cit.
15 Pan, Haberkorn, *Interactive 3D Modeling with Virtual Reality*.
16 Cfr. Bill, *Computer Sculpting of Polygonal Models using Virtual Tools*; Bill, Lodha, *Sculpting Polygonal Models using Virtual Tools*; Calabrese et al., *cSculpt: a system for collaborative sculpting*; Galyean, Hughes, *Sculpting: an interactive volumetric modeling technique*; Mizuno et al., *An interactive designing system with virtual sculpting and virtual woodcut printing*.





6, 7 | *Examples 3D drawing in the "Magic 3D Pencil" application.*

nizing feature maps (SOFM)[17] or vector fields[18] for sculpting. Maybe it is worth considering completely new ways of shaping solids, because in Virtual Reality we are not limited by the laws of physics.

The solid creation interface can also use 2D drawing in Virtual Reality. Various planes can be arranged in three-dimensional space, which can allow easy definition of cross-sections or projections of modeled solids. We are currently preparing a special VR application to support the teaching of descriptive geometry, which is based on projection planes on which the user places projections of points and then observes the projected object in space (fig. 3)[19]. In the near future. we plan to use this application in an experiment on students taking this subject, but initial tests are already showing great promise.

However, drawing on such virtual surfaces is not easy.

It seems to be a simplification to eliminate the drawing switch (on and off) and treat this plane as the drawing medium. Nevertheless, our experiments with a virtual mathematical escape room show that students have great difficulty in drawing a smooth and accurate graph of an absolute value function (two diagonal straight half-lines) or a sinusoid on a virtual board (fig. 4)[20]. Coupling physical displays, e.g. personal digital assistants (PDA)[21], with such planes allows for precise design of object cross-sections on their screens using methods known from working with ordinary computers, but at the same time directly observing the result of these works in the three-dimensional space generated by Virtual Reality. This approach can be preceded by a rough sketch of the shape[22], which makes it easier to orient yourself in space. Virtual displays are out of the question here, even if they provided the touch functionality of their virtual screens, because it would then be better to provide these capabilities directly to the cross-section plane. Unfortunately, VR

17 Knopf, Igwe, *Deformable Mesh for Virtual Shape Sculpting*.
18 Steele, Egbert, *Vector Field-Based Tools for Virtual Sculpting*.
19 Ruczyński et al., *Projection space and projection methods in virtual space. How are 3D objects projected onto planes?*; Id., *Reconstruction of solids in the VR CAVE environment based on their projections on given planes*.
20 Baziak et al., *Virtual escape room with extent mathematics*; Id., *Virtual escape room in mathematics*.
21 Igarashi et al., *Teddy: A sketching interface for 3D freeform design*.
22 Kim et al., *Agile 3D sketching with air scaffolding*.

8 | *Example 3D drawing in the "Magic 3D Pencil" application.*

headsets prevent simultaneous use of physical displays such as a PDA, unless Augmented Reality is used. It is more convenient to use an alternative solution to Virtual Reality, such as VR caves. These are rooms whose walls consist of 3D screens generating an image from the observer's point of view. The VR cave user is surrounded by a virtual scene, but at the same time sees his or her body and hand-held devices. This is not the only advantage that VR caves have over headsets. In the VR cave, several people can work together and see each other. The VR cave does not require wearing half a kilogram of optoelectronic equipment on your head, but only lightweight stereoscopic glasses known from 3D cinema. Moreover, the discomfort known as simulator sickness is much rarer in VR caves, which is why using a VR cave is characterized by a much higher quality and easiness of work. This is probably because in a VR cave the image is waiting on all sides of the user, whereas in a headset it has to be generated anew after each head rotation, and therefore with a certain delay.

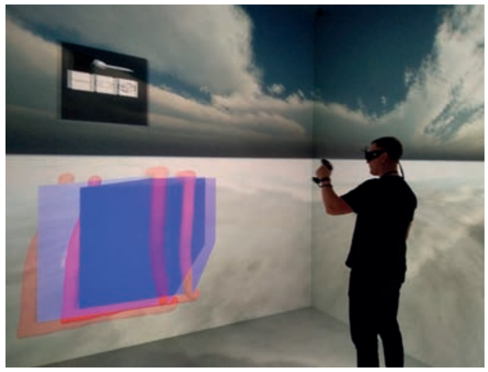
Experiments

The Immersive 3D Visualization Lab has developed a prototype application called "Magic 3D Pencil" that enables the creation of three-dimensional drawings (figs., 5-8)[23], and its virtual widgets (mainly buttons and sliders) allow the selection of a drawing tool and the type, color and thickness of the line drawn, as well as the placement of popular geometric shapes in space (cube, sphere, cylinder, etc.) and the saving of the created scene for later use. The conducted experiments in the BigCAVE prove the high potential of the implemented solution.

The BigCAVE uses the ARTTRACK2 tracking system, whose average translation and rotation error (error in recognizing the position and orientation of the tracked object, respectively) is 0.67 mm / 0.12° in the static case and 0.92 mm / 0.16° in the dynamic case[24]. Taking these data into account, an experiment was carried out which consisted in drawing a vertical and horizontal straight line segment by hand (fig. 9). The naked eye can see deviations that far exceed the above-mentioned values, less than 1 mm and amounting to dozen centimeters, i.e. exceeding the tracking error many times over. These deviations are due to the low precision of the movements of the human hand. When a person moves their hand from top to bottom or from left to right, they tend to trace an arc that is bulging in the middle, because the rotational movement of the upper limb mounted on the arm joint is not fully

[23] Muńko et al., *Magic 3D pencil*, cit.

[24] Jung et al., *Multi-Modal Dataset Acquisition for Photometrically Challenging Object*; Id., *House-Cat6d – A large-scale multi-modal category level 6d object pose dataset with household objects in realistic scenarios.*



9 | *Drawing vertical and horizontal lines in the "Magic 3D Pencil" application.*

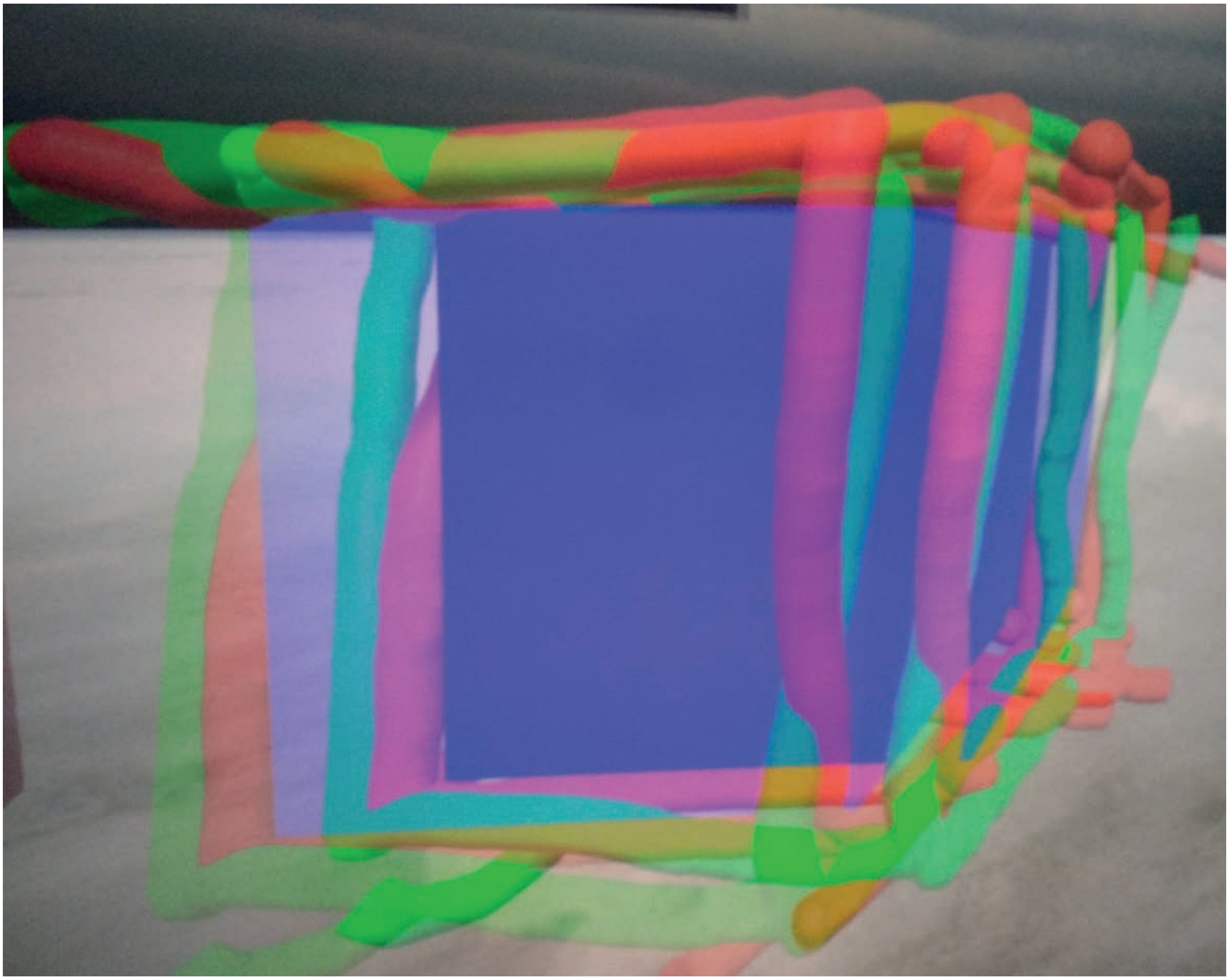
10, 11 | *front lower right vertex (fig. 10) and front upper right vertex (fig. 11).*

compensated by the flexions in its other joints. We perform a similar movement when driving a nail with a hammer or serving a volleyball ball. The optimal movement of the hand would be a straight line, whereas in reality it is an arc movement. The main cause of inaccuracy in the drawn 3D line is the human anatomy, not the precision of tracing.

Another experiment consisted in drawing a pink-orange color around the edges of a blue cube levitating in a virtual scene (figs. 10, 11). The results of this experiment revealed significant inaccuracy in the hand-drawn skeleton of the cube. The position of the tip of the controller held in the left hand of the simulation participant, shows the position of two adjacent vertices of the cube seen by him, defining the edge that has just been drawn (the red vertical element on the right side of the cube, which distinguishes the two figures). In figure 10, the controller tip points to the front, lower, right corner of the cube, and in figure 11, it points to the front, upper, right corner of the cube. The edge of this cube was therefore about 20 cm (the difference between both photos of the height of the controller held in the hand). Because the two images of this cube for the simulation participant's left and right eyes are displayed on a screen that is about five times farther from the user's eyes than the controller tip, the size of its edge on the screen is five times larger, at about 1 meter. It is worth repeating that the cube for the simulation participant was approximately 20 cm × 20 cm × 20 cm. It is visible to the naked eye that the precision of the cube's outline with its edges is difficult to accept. The error is over 2 cm, or over 10% of the outlined cube, even though the cube was relatively small.

To avoid the accusation that the reason for such a large error could be a lack of drawing practice, the experiment was repeated on a cube that had just been outlined with edges, this time using the color green to draw the new edges. The results are not much different from the previous result. The accuracy of both outlines is similar (fig. 12).

The experiments carried out have shown that freehand drawing in three-dimensional space is burdened with low precision, which results directly from the limited human ability to precisely define shapes in space. One could of course assume that this accuracy can be taught to the user, but this means that freehand 3D drawing can be treated as a natural and intuitive interface, but only for rough drawing, where accuracy is not crucial by definition. Accurate drawing, if it is to be natural and intuitive, requires other solutions, examples of which was presented earlier in this paper. The development of



12 | *The result of outlining the cube in the "Magic 3D Pencil" application. The photo appears double because it contains images for both eyes (stereoscopy).*

methods for natural and intuitive drawing with high precision will not be possible without further research, which should involve their future potential users, because they will ultimately verify the methods for increasing the precision of 3D drawing. These studies should therefore be conducted with the participation of people who use drawing as a work tool on a daily basis, hence this paper should be treated as an invitation to cooperation addressed to such people. An alternative method to 3D drawing to creating a three-dimensional object using a 3D interface is virtual sculpting. Currently, the Immersive 3D Visualization Lab is working on a new application called "Virtual Sculptor", which will allow to assess the advantages and disadvantages of an interface based on carving in various materials, from stone to clay[25].

Conclusion

The paper presents a wide range of possibilities for creating a three-dimensional scene using direct interaction in space, which involves drawing one-dimensional objects (3D lines) and creating two- and three-dimensional graphic objects (surfaces and solids). It is difficult to judge the usefulness of these approaches without trying to implement them in real life. Their potential seems enormous, but only the end user can confirm or deny their usefulness. Therefore, the author encourages the Reader to jointly undertake the effort of implementing and testing this type of solutions. Collaboration between architects and computer scientists on the use of Virtual Reality can yield interesting results[26].

25 Małasiewicz, Strauss. Virtual sculptor.
26 Cfr. Galasso et al, *Virtual fruition of architectural drawings. 3D models and dynamic platforms for heritage knowledge*; Kowalski et al., *New skills for architects: 3D scanning for an immersive experience in architectural education*; Lebiedź, Szwoch, *Virtual Sightseeing in Immersive 3D Visualization Lab*.

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