Automation in Construction 103 (2019) 104–116

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Usability studies on building early stage architectural models in virtual reality

Rui de Klerk[a,b], André Mendes Duarte[b,c], Daniel Pires Medeiros[b,c], José Pinto Duarte[a,d], Joaquim Jorge[b,c], Daniel Simões Lopes[b,c,*]

[a] Faculdade de Arquitetura, Universidade de Lisboa, Rua Sá Nogueira, Pólo Universitário, Alto da Ajuda, 1349-055 Lisboa, Portugal
[b] INESC-ID Lisboa, Rua Alves Redol, 9, 1000-029 Lisboa, Portugal
[c] Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[d] College of Arts and Architecture, The Pennsylvania State University, 121 Stuckeman Family Building, University Park, PA 16802, United States of America

ARTICLE INFO

Keywords:
Architectural design
Voxel-based modeling
Box shaped objects
Case studies
Early stage maquette
User participation
Professional evaluation
Virtual reality

ABSTRACT

Despite its marked success in recent years, it is still not clear how Virtual Reality (VR) can assist architects at the early stages of ideation and design. In this paper, we approach VR to build and explore maquettes at different scales in early design stages. To this end we developed a VR environment where user interactions are supported by untethered, easy to operate, peripherals, using a mobile virtual reality headset to provide virtual immersion and simplified geometric information to create voxel-based maquettes. Usability studies with laypeople suggest that the proposed system is both easier to use and more effective [better suited] than current CAD software to rapidly create simplified models. Additionally, tests with architects have shown the system's potential to improve their toolset. This is partly due to VR combining real-time performance with immersive exploration of the content, where body-scale relationships become visible to support the creative process, allowing architects to become both builders and explores of spatial constructs.

1. Introduction

It is commonly accepted that sketching, such as hand drawing or model making using analog or digital media, is an appropriate conceptual activity in architectural design since it promotes the discovery of relevant concepts [1,2]. At early stages of the design process, sketched models and maquettes, which consist of scaled models of building proposals, are used to describe essential shapes, mass volumes and topological configurations. Maquettes are considered as a valuable architectural commodity, as they are quick and easy to create due to their low level of detail, and are effective in communicating spatial relationships and ideations. They afford preliminary exploration of the spatial layout besides their aesthetic qualities, while being also useful for communicating concepts and design intentions to clients, providing a glimpse of the building's composition and appearance on site. Furthermore, initial simplified models can be detailed iteratively, thereby supporting the architectural design process.

Analog maquette building requires modelers to cut and bind independent physical material components (e.g., styrofoam, balsa wood, corrugated cardboard, etc.) to construct three-dimensional representations of design proposals. Despite its tangible qualities, this approach limits the formal possibilities and cannot be used to produce full-scale models without significant effort and cost.

Fortunately, such analog practices provide useful metaphors that are applicable to digital media [3]. Although less time consuming than their analog counterparts, current CAD software tools such as Revit [51], AutoCAD [50], Vectorworks [60] or Rhinoceros [57], require considerable initial effort and interaction to produce early stage maquettes. This makes them neither very useful for early stage design nor very suitable to iterate over different models and quickly explore design alternatives. Since they were designed for precision and not to rapidly capture initial concepts or ideas, such CAD tools lack the immediacy and expressiveness of sketches [1]. Such is mostly because of the inherent complexity of their WIMP[1] interface.

Recent technological advances in augmented and virtual reality have made portable head-mounted displays more accessible. These technologies rely heavily on novel gesture-based spatial interaction techniques, and carry the promise to improve architectural practice by

---

* Corresponding author at: Edifício IST, INESC-ID Taguspark, Room 2N9.19, Avenida Professor Cavaco Silva, 2744-016 Porto Salvo, Portugal.
E-mail addresses: ruideklerk@fa.ulisboa.pt (R. de Klerk), andre.mendes.duarte@tecnico.ulisboa.pt (A.M. Duarte), daniel.medeiros@tecnico.ulisboa.pt (D.P. Medeiros), jxp400@psu.edu (J.P. Duarte), jorgej@tecnico.ulisboa.pt (J. Jorge), daniel.lopes@inesc-id.pt (D.S. Lopes).

[1] WIMP denotes Windows, Icons, Menus and Pointing, an approach characteristic of Desktop systems.

https://doi.org/10.1016/j.autcon.2019.03.009
Received 15 July 2016; Received in revised form 24 February 2019; Accepted 8 March 2019

allowing direct manipulation, situated and body-scale interactions, and more expeditious means to rapidly build a maquette ([3–14,49,52]).

However, for all their promises, VR systems have been used mostly to explore finished designs rather than to create new ideas [15–19]. Alternatively, this paper focuses on how VR can assist architects by exploring its use to build maquettes at different scales in early design stages. The goal is to facilitate the externalization of ideas for a new building and the assessment of early-stage designs (not to produce highly detailed mockups), with the option to include representations of the surrounding physical context (site) in the design process. These sketchy externalizations are favored by architects since they facilitate the testing of spatial hypotheses and provide insights into a design problem, without requiring costly physical maquettes or detailed and time-consuming 3D renderings. Ultimately, our goal is to develop immersive environments that support rough modeling with an expeditiousness and expressiveness that should be similar to hand sketching or physical scale modeling, enabling architects to engage with their digital models in space and quickly explore design alternatives.

Architects can quickly sketch a building in, remarkably, just a few strokes [1–3]. Based on this observation, we have developed a spatial interaction system that can be used by professionals to quickly build maquettes and externalize ideas in early design stages. In our system, modeling gestures are constrained to produce box-shaped objects of standard dimension (voxels) and also parallelepipeds of various sizes. Each box-shaped object requires a single mid-air stroke. These box-shaped objects are constrained to a grid, exploring an improved Minecraft [58] paradigm. The platform also uses a cordless (untethered) system and a walking metaphor for navigation to allow people to move freely within the available room space (4.8 m × 4.2 m × 2.5 m = 50.4 m3), so that Architectural users can directly engage with the virtual content and explore their designs. We have chosen not to include ray casting menus in the interface and all tools were made easily accessible via the controller, using just two fingers.

Usability tests with laypeople were conducted to assess both the ease of use of the interface and the effectiveness of the underlying modeling paradigm. Finally, additional tests were carried out with internationally renowned professionals to determine the suitability of our system to design practice. Results confirm the architectural expressiveness of gestures in 3D space and their ability to quickly create voxel-based maquettes.

2. Related work

CAD systems have been lauded as effort savers in the workflow of many disciplines. However, this is mostly true for *design changes* and *design detailing*, where rigor and precision are fundamental. Entering a new design from scratch is a morose endeavor, second only to manual design. Perhaps because of this difficulty, most architectural CAD systems focus on building complex models full of intricate details. Well established tools such as AutoCAD, Vectorworks or Rhinoceros are good examples of this architectural modeling paradigm. These programs offer many design functionalities, present a steep learning curve, requiring a long time to master, and demand considerable effort to produce a complete design and maquette. Therefore, such conventional CAD systems are not suitable to support initial architectural design concepts and even less so to propose alternative designs.

Following a different paradigm, SketchUp ([20, 53]) with its push-and-pull modeling method is probably the most notorious counter-example to mainstream CAD software. It presents a much less constrained approach to digitally modeling of ideas or concepts, supported by a simpler interface. A more recent and mediated tool for creating sketch models is presented by Minecraft [21–23], a popular sandbox video game that allows players to creatively build virtual objects with textured cubes in procedurally generated worlds made entirely from voxels.

In line with Minecraft's voxel-based modeling paradigm [24,25], several approaches feature modeling with building blocks or construction toys as a crucial activity to develop spatial skills and spatial awareness [26–28]. These toys may even have influenced modern architectural styles [29]. Indeed, educational toys such as Lego [30,31] and MinecraftEdu [59], despite their ludic nature, can be useful design tools for building early stage maquettes or even city-scale models [32]. This is even more relevant if we consider that most buildings found in architecture present orthogonal layouts [33–35], some with rather complex arrangements (e.g. Moshe Safdie's Habitat 67 in Montreal, Canada), which are compatible with Lego's and Minecraft's characteristic assembly constraints.

Despite being upstream tools, SketchUp and Minecraft still feature WIMP interfaces. These present limitations to 3D visualization and interpretation during the architectural design process. In particular, digital objects are displayed on flat surfaces, 3D objects are modeled on 2D media, computer input is performed with 2D devices such as mice and keyboards, and often requiring a combination of commands to navigate in 3D space (orbit, pan and zoom). Within architectural design, WIMP limitations such as lack of expressiveness and steep learning curves have been approached by adopting sketch-based modeling techniques [36]. However, few papers have reported on spatial interfaces and/or Virtual Reality systems specialized in producing early stage maquettes [37–40].

Regarding spatial interfaces, de Araújo, Casiez, Jorge, and Hachet [41] proposed a semi-immersive environment for conceptual CAD modeling where designers use gestures on and above a multi-touch surface to create and edit 3D models in a stereoscopic environment. By considering two interaction spaces, i.e., on and above a multi-touch surface, users can seamlessly pick and choose the most appropriate technique for a given modeling task. Their approach combined user posture tracking with a depth camera and three-dimensional finger tracking using Gametrak devices. Their usability studies seemingly validated the technique in architectural contexts where people sketched early stage maquettes of houses using push and pull operations performed on faces. A natural limitation of this system lies in its inability to work at full size, as the touch-sensitive table constrains the scale factor of the 3D content to fit the table's dimensions. Another issue that limits proper 3D spatial exploration is the lack of full (visual) immersion that only VR systems can offer.

Using immersive VR technologies to produce early stage maquettes is not a new topic, as many aspects of human-computer interaction have been examined and design guidelines proposed for VR in the early design phases [42,43]. In particular, exploring how VR tools can facilitate architectural design in early stages of the design process has motivated research in the past two decades. Specifically, Donath and Regenbrecht [5,38] and Regenbrecht et al. [40] developed a VR system for early stage architectural designs where people could build 3D models using voxels, while being immersed in a virtual modeling environment that had the same size of the real interaction space (voxDesign, 1995). However, their interaction paradigm was more that of a bricking system rather than a sketching system as it was necessary to manually lay voxel after voxel as if laying bricks. Despite offering a real walking metaphor for navigation, their system only supported a single scale (1:1) user experience. Due to hardware limitations at the time, tracking systems sometimes failed and at ~2000 voxels the system slowed down significantly, the same happening when textures were added. Their system presented other technical restrictions such as requiring a tethered drawing device and HMD and having the cables hanging from a rod-like structure. Furthermore, their system was not evaluated by professional architects but only tested with students.

Following a similar voxel-based approach, Vries and Achten [44] presented an interesting work on VR applied to initial architectural design that allowed designers to rapidly build voxel-based models using hand gestures. The metaphor that inspired the development of their

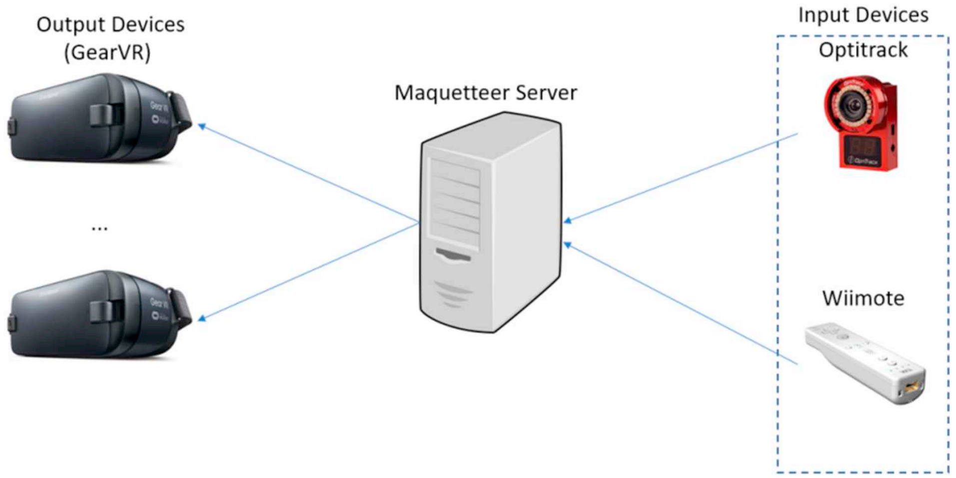

Fig. 1. Architecture of the Maquetteer system.

system, called DDDoolz, came from experiences observed in scale-modeling workshops, where model building relied on a grid structure, while edition was accomplished by dragging sets of voxels to create or delete new spaces. Although architectural students participated in usability tests, their work still lacks proper validation as no feedback from professionals was collected. In addition, the authors did not compare DDDoolz to other CAD tools. This prevented a situated assessment of VR applied to early stages of the architectural design process.

Recently, the development of early stage maquettes in VR environments has received a renewed attention. Sasaki et al. [45] introduced *facetons*, a geometric modeling primitive for easy and fast prototyping of architectural buildings in virtual reality. Essentially, a faceton was an oriented point in mid-air that defined an infinite plane passing through that point. Given a set of facetons and using a six degrees of freedom (6DoF) input device in a virtual environment, designers could generate a polygonal mesh model by taking the intersection of the associated infinite planes. A single pilot user study with eight laypeople revealed that the resulting models had fairly complex structures. However, when building concave models, their polygonal mesh algorithm was unable to distinguish between the insides and outsides of solids. This is a serious modeling limitation, as the generated model did not always correspond to the expected configuration of facetons, leaving people with the tiresome task of finding alternative groupings of facetons in order to obtain the intended shape. In addition, the generated model could become unstable with certain faceton configurations.

Another interesting work related to VR-based early stage maquette modeling was presented by Jackson and Keefe [46]. Their work followed a modeling approach similar to TiltBrush [55]. Although tailored to 3D modeling in general, the Lift-Off interface allows people to create models in a controlled, handcrafted style, yet always relative to reference imagery. After sketching on paper, the images are imported and positioned in VR space. Image processing algorithms then extract 2D curves from the sketches. The user can interactively select and lift these curves into space to create a 3D curve network from which surfaces are swept to create a 3D model. The interface was evaluated both by novice and experienced users, including an architect that produced a model of a cabin using a perspective sketch and orthographic drawings as input. The resulting models had a visual style considered to be similar to traditional fine art imagery. Despite the interesting visual results, the interface was only evaluated by a single professional architect who took over six hours to produce a fairly simple 3D model. In addition, a bimanual 3D user interface was necessary to assure controllability of the freeform curves, thus requiring two drawing devices. A 4-wall CAVE™ environment was used. This limited proper 3D exploration due to the lack of full visual immersion and constrained the usable interaction space, when compared to wearing HMD combined with tracking in open spaces.

3. Virtual reality system

We call our VR system Maquetteer [56] after the term maquette [54] used in arts, namely in architecture, to refer to rough scale models of larger designs. Maquetteer was designed to create 3D models using a voxel-based approach, where each voxel is constrained both in size and position to a regular, three-dimensional grid to minimize errors of precision during freehand modeling. Hence, the resulting objects are box shaped or parallelepipeds. The system enables designers to build, edit and visualize (at different scales) parallelepipeds created with swift gestures in 3D space, in close relation to their bodies and, optionally, to preloaded 3D content.

Designs produced in the immersive VR environment of Maquetteer may also be simultaneously reviewed, by other designers running the application either on conventional PCs or wearing Head Mounted Displays. This may be done either locally or remotely, providing that all systems share the same data input from the controller and tracking system. This approach was adopted during usability tests, using a PC, to follow participants' actions in VR and to provide support when requested. In the following subsection, we present Maquetteer's architecture and main features.

3.1. Maquetteer architecture

Our system features a client-server architecture, where data from the input devices are sent to a server. This server processes the data and changes the visualization on each of the output devices accordingly (Fig. 1). The server also maintains a common 3D virtual space for each client. We capture position and orientation of each user's head and their controller by using an optical tracking system and optical markers attached to both the HMD and the controllers (Fig. 2(A)).

Each Maquetteer client runs on an independent device. These are responsible for processing and displaying the virtual environment according to the user's point of view. People interact with the system through a graphical user interface (GUI). The immersive virtual environment consists of an infinite space depicted in dark blue with a working area marked on the floor System state and prompts are displayed via floating diagrams. Users interact with a 3D digital representation of the controller accurately registered with the physical device held in their hands (Fig. 3(A)). This provides a high contrast background to better visualize the grey-white 3D models being created, in a soothing color. The graphical depiction of the virtual environment also affords a sense of spaciousness that contrasts with the confined

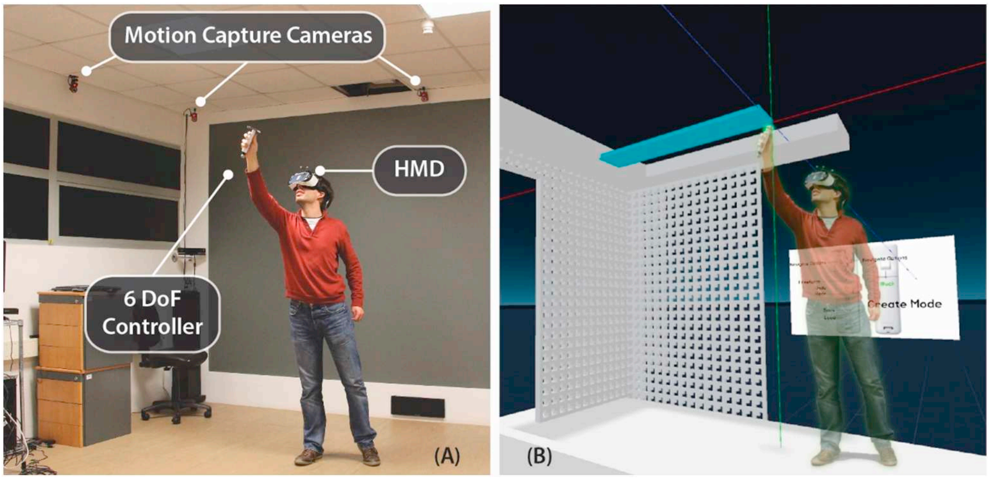

Fig. 2. (A) Hardware setup and (B) immersive virtual environment of the spatial interaction system.

space of the design room. A white rectangle on the floor marks the working area in the VR environment, which corresponds simultaneously to the free space of the room and to the working area of the optical tracking system. To prevent collisions, and alert distracted people to the limits of the physical space, the system shows warning panels when they get critically close to the limits of the working area.

The users do not see their hands, only the virtual representation of the controller. The commands available at the interface are displayed in contextual menus as text labels attached to the virtual controller, hovering above the corresponding button (Fig. 3(B)). Inside the virtual modeling environment, people can create content and explore either modeled objects (Fig. 2(B)) or import 3D models of a site with surrounding buildings (Fig. 3(A)). Outside the working area, contextual figures provide helpful information regarding button functionalities according to the mode being used. These are fashioned as "cheat sheets" for quick reference. The figures also offer additional reference to the physical limits of the room by marking the position of its walls.

The controller GUI allows invoking different modeling, editing and visualization functionalities. By interacting with the content, people can select, translate, rotate, scale and edit voxels through freehand gestures. After building the model, the resulting meshes can be saved for later use or exported to a CAD-compatible format. These may then be imported into other CAD, BIM and Architectural Visualization software or sent to a 3D printer. The application was developed in Unity3D (version 5.1), to support dynamic 3D content in real-time and support powerful interactions, while offering the possibility to use different platforms, and HMDs.

In our evaluation studies, we used a Wiimote controller coupled to optical markers, to track its position and rotation in 6DoF (Fig. 2(A)). As for the HMD, we adopted the Samsung GearVR. The Samsung GearVR is a lightweight HMD that uses a Samsung Galaxy smartphone that typically affords a resolution of 1280 × 1440 pixels per eye and enables a 101-degree field-of-view. Another advantage of the GearVR is its wireless nature, providing a richer and free interaction in comparison to tethered HMDs such as the HTC Vive or Oculus Rift, which would hinder the VR user experience.

To capture the orientation and position of both the user's head and controller, the room is surrounded by 16 Optitrack Flex3 motion capture cameras operating at 100 Hz. These track optical markers placed on the head-mounted display and the controller (Fig. 2(A)) with a measured latency of 0.3 ms. This low latency is very important to provide a good sense of presence and immersion. To this end, position and orientation data are transmitted via UDP (User Datagram Protocol) to the applications. Additionally, we used the gyroscopes of the headset device to reduce update latency, and improve precision.

Combining the GearVR and Optitrack presents several advantages over using off-the-shelf HMD with a dedicated tracking system, such as the HTC Vive. These include an untethered connection, allowing people to move freely inside the tracked area, a larger tracking space and the possibility to include more than one user in the same modeling session, by sharing the same VR setup. Furthermore, by using multiple Optitrack cameras distributed along the perimeter of the room's ceiling, our approach improves tracking accuracy and mitigates tracking problems caused by undesired marker occlusion. Last, but not the least, our

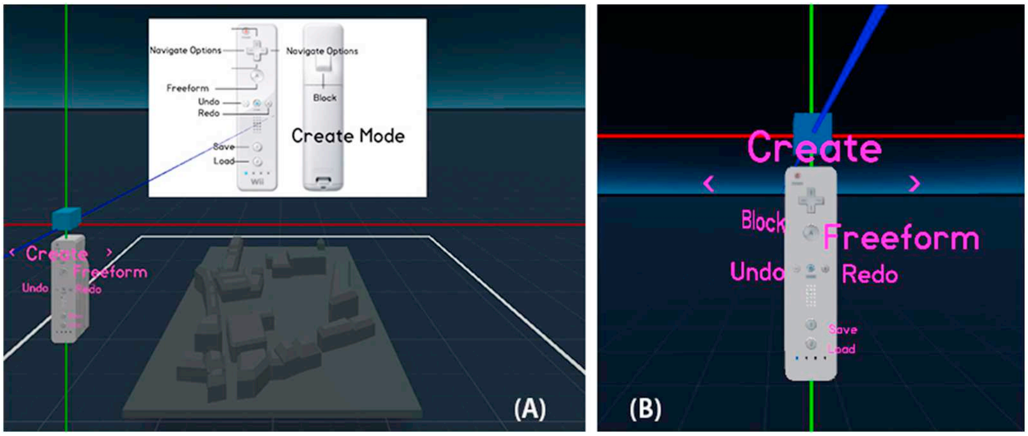

Fig. 3. (A) GUI showing the menu settings for the "Create" mode and (B) Virtual representation of the controller featuring the infinite orthogonal axes of the voxel grid, the cursor (voxel) and the commands available under the "Create" mode.

system allows multiple people to share the same physical space when interacting with Maquetteer, in contrast to the single user limitations typical of Commercial Off-The-Shelf systems, designed for single user experiences. In what follows we detail system functionalities and provide further technical information.

3.2. Voxel-based rendering

When creating models, it is possible to generate parallelepipeds, much larger than a voxel, for flexibility and efficiency reasons. In these cases, voxels are not rendered individually, as this would lead to poor performance. Indeed, contiguous voxels are coalesced into a single mesh to depict the outer faces. A similar process is used in Minecraft.

Regarding lighting, we adopt two different setups: one for the modeling environment and another for full-scale view. For modeling, we use a single directional light at a higher position relative to the user and tilted towards the modeling scene. Within the full-scale view, we adopt a real-time global illumination day/night cycle to simulate sunlight with no ambient lighting. Both lighting setups consider shadows. We apply the Phong model for surface shading and use a brick texture to cover the model in full scale view, to afford a better grasp of the models' dimensions.

3.3. Interaction

Maquetteer allows designers to create virtual 3D models within the confines of a room physical space. This is analogous to scaled physical architectural models, a.k.a. mockups or *maquettes*. Architects using our system move inside the physical space of the room and place virtual building blocks (voxels, cubes, parallelepipeds) at the precise positions with to their bodies, the existing virtual model or the surrounding environment.

Maquetteer supports interaction using a wand-like controller for drawing and mid-air gestures. The dominant hand manipulates and operates the controller to activate or deactivate commands, as well as to create, delete, select, edit, move, rotate and scale voxel-based parallelepipeds through freehand gestures. The interaction space is discretized into a regular three-dimensional grid, and although the controller movement is fluid, the cursor position is constrained to grid coordinates. Furthermore, object orientations are constrained to multiples of 90-degree angles. Functionalities are accessed by pressing buttons on the controller and navigating between contextual menus (Fig. 3(B)). The permissible modes of operation are depicted in the state machine diagram in (Fig. 4).

As Fig. 5 illustrates, people are free to use the available space within the working area to create their models. The wireless setup enables people to easily explore the space of the 3D modeling environment. People create box-like shapes in mid-air, within their reach, simply by pushing a button while moving the controller using a click-and-drag approach. Users are free to walk around and assume any position they like while modeling or exploring the 3D content, such as standing (Fig. 5(A) and (B)), squatting or kneeling (Fig. 5(C)), or to traverse 3D virtual models and engage with them from different points of view, including from within a model.

Maquetteer follows a modeling metaphor originating from architectural education and practice. We designed the 3D modeling environment to manipulate scale models that fit in the working area. Given the total dimensions of the available modeling space (4.8 m × 4.2 m × 2.5 m), architects in Maquetteer can create 3D models at scale 1:100 corresponding to a 480 m long, 420 m wide and 250 m high built volume. Again, given the untethered system, the modeling space can be easily expanded to a larger design room, by upgrading the optical tracking system to use more cameras.

3.4. Voxel-based modeling

Placing and orienting 3D objects in space with mid-air gestures can be a difficult task. We can ensure precise interactions with the 3D content by using a regular grid. Unlike other systems, no ray casting is needed to select objects as people directly instantiate blocks at grid positions either to add or remove material. The freedom of movements in conjunction with variable scale operations, removes the need for remote operations. Furthermore, by relying on a regular grid, designers can overcome imprecise three-dimensional gestures at the expense of freeform modeling. All modeling tasks (i.e., content creation and deletion, editing, selection, copy, rotation, translation) are constrained to the grid. Under this modeling framework, the resulting 3D objects are rapidly and easily built and always present orthogonal shapes.

As mentioned in Section 3.1, a voxel at the tip of the controller, represents the cursor. It also depicts one building block or modeling unit. Irradiating from the cursor, three orthogonal and color-coded line segments provide visual feedback regarding relative distances and alignments between cursor, floor, walls or existing content. The cursor is constantly snapped to the grid. Larger, contiguous arrays of voxels can be defined by stroking the largest diagonal of the desired parallelepiped.

Maquetteer supports three different content creation tasks: introducing discrete voxels; inserting a parallelepiped defined by its diagonal, created through click and drag motion following the cursor position (Fig. 6(b)); and copying selected blocks of pre-existing voxels.

Editing requires moving and rotating 3D content. After selecting a block of voxels, it can be deleted (Fig. 6(c)), moved along the grid axis, or rotated by 90-degree angles around the x, y, and z axes. Rotations are performed using the Wiimote, to control the yaw-pitch-roll of the 3D object, in 90-degree multiples.

3.5. Virtual maquette navigation

Within the virtual environment, designers are able to walk through their creations or through existing models. Content can be visualized at several scales (1:5, 1:10, 1:20, 1:50), as shown in Fig. 6(d) and (e) and, more interestingly, at full scale (1:1), as illustrated in Fig. 6(f). This allows architects to effortlessly switch between a scale model of their designs and their virtual mock-ups. Changes to the 3D models can be immediately examined at any of the available scales, enabling architects to test different spatial solutions and inhabit the virtual mock-up of each one of them.

Stereoscopic visualization and precise motion capture provide natural and immersive experience since it is possible to switch between scales, move around, above or underneath the content and catch different viewpoints in real time. With a virtual reality system such as Maquetteer, it is possible to capture and transmit the experience of being inside or outside a fully scaled building. It is also possible to alternate between scales of visualization and select the most favorable for a particular task. To enhance the virtual maquette exploration experience, we added another level of immersion by considering light conditions. This provides an overall experience of sun exposure depending on the time of the day and season of the year, when the model is presented at 1:1 scale.

The physical size of the room limits the roaming area within the virtual modeling environment. Thus, mock-up exploration (1:1) by walking is constrained to the area of the room. When modeling buildings at scale, architects will naturally overshoot the modeling space during mock-up exploration (1:1). To overcome this limitation and access parts of the mock-up represented outside the modeling area, people either reduce the scale, or they can drag the virtual mock-up using the controller, to pull the model towards them. To avoid a sense of vertigo whenever a user steps out of a virtual block, the virtual camera never falls off the model in the absence of a floor. Modeling

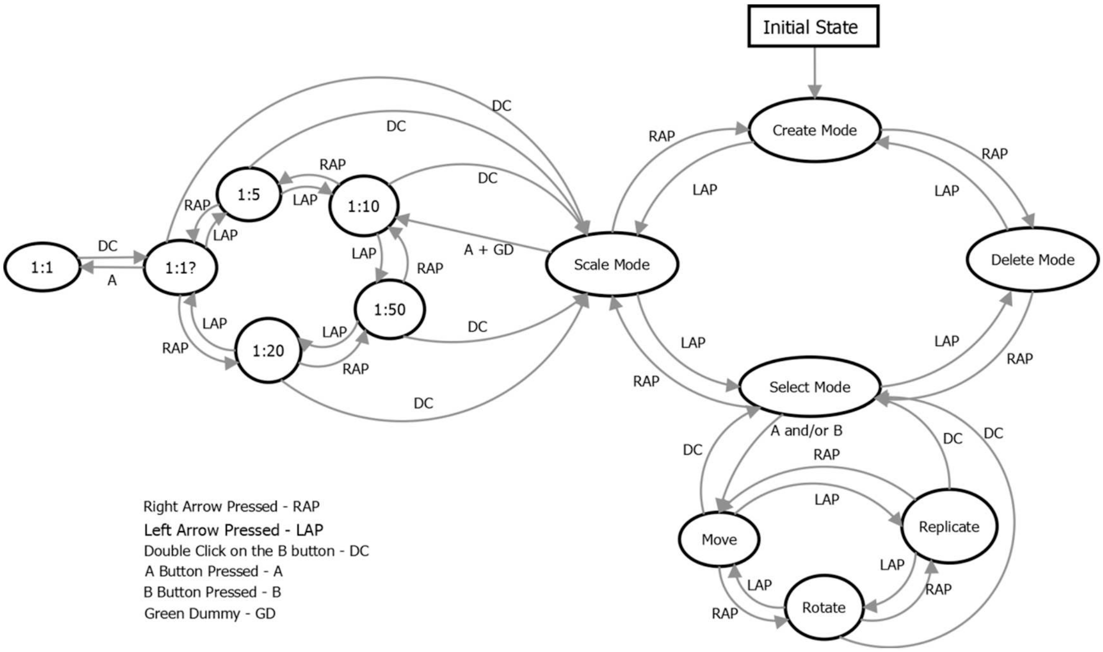

Fig. 4. Diagram of Maquetteer's state machine.

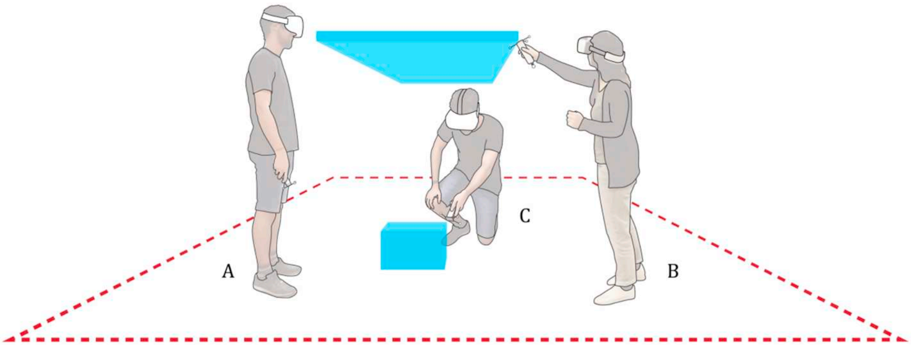

Fig. 5. Representation of Maquetteer's 3D modeling environment, illustrating user's postures and gestures while building a model in VR: user standing, idle (A); user standing, modeling in VR (B); and user kneeling, modeling in VR (C).

operations in full scale mode are not allowed, since it was conceived for design exploration and assessment.

4. Usability studies

To validate our system, we performed two distinct user evaluations in a controlled setting.[2] First, we conducted formal usability tests with laypeople to compare our system (VR) to a CAD tool (WIMP) with a similar modeling paradigm. This preliminary test aimed to assess our system's performance, its ease of use and to identify necessary improvements prior to the tests with professional architects. Second, after making the identified improvements to the system, we invited internationally renowned professional architects to assess the benefits and limitations of our approach and its adequacy to support the architectural design process. In what follows, we introduce and discuss the tests and present the salient findings of both user evaluation phases.

4.1. User tests with laypeople

We adopted SketchUp as the control example in the comparison study because its simple interface and ease of use make it an ideal candidate to introduce inexperienced people to 3D modeling. When using SketchUp, a user seated in front of a computer display inputs data via mouse and keyboard controls to perform both modeling and navigation[3] tasks. When using Maquetteer, users stand in the center of the work area (coincident with the center of the room). Wearing the head-mounted display and the controller, they are free to move in space. Contrary to Maquetteer, where participants create content by dragging the major diagonal of parallelepipeds, the modeling paradigm of SketchUp is based on pushing-and-pulling facets. To steer the experimental proceedings, we formulated the following hypotheses:

---

[2] Usability tests took place between the last week of January and the first week of March 2016.

[3] We refer to navigation in the sense of controlling the users' point of view towards the models and the modeling environment (camera control). When mentioning WIMP systems, navigation refers to mouse-keyboard interactions such as pan, 3D orbit, etc. In VR it refers to the movement (locomotion) and postures of people within the modeling environment, the change in scale of the models' representation and the “dragging” of the mock-up when at full scale (1:1).

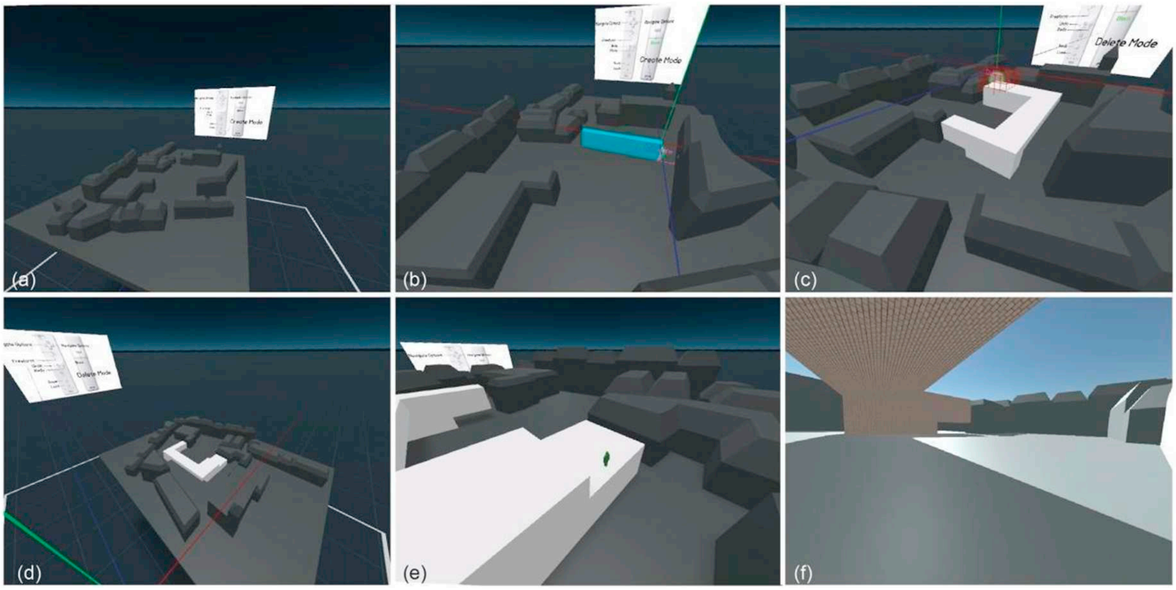

Fig. 6. Example of a modeling session using Maquetteer: (a) initial setup with the model of the intervention site; (b) creation of the first spatial container; (c) edition of the model using the delete command; (d, e) scaling the model; and (f) full scale view of the model with sunlight simulation.

Hyphothesis A (HA). : Maquetteer is easier to use than Sketchup when modeling box shaped objects.

Hyphothesis B (HB). : Users can perform box modeling tasks faster using Maquetteer than Sketchup.

A total of 18 participants with ages between 20 and 29 years (24 ± 5 years old) were asked to sketch virtual maquettes using both systems mentioned above, one after the other. Prior to starting the test, each participant was asked to fill a questionnaire on their experience with interaction and head-mounted display devices, as well as with 3D digital modeling systems (CAD). All subjects had at least a bachelor's degree. Furthermore, all of them played video games several times per day. All had experienced 3D displays (e.g., 3D movies or IMAX), but none had ever experienced a head-mounted display.

The test sessions were individual, and each modeling task was timed. The expected duration of a single test session for each system was about 30 minutes and was divided in three phases: (1) habituation to the system, (2) maquette modeling, and (3) answering a questionnaire about the system. The system to be used first, Maquetteer or SketchUp, was randomly selected to prevent biased results. This resulted in an even distribution of participants: nine started the test with SketchUp while the other nine started it with Maquetteer. Each participant was given a brief overview of the system regarding its interface, navigation in the modeling space, and commands available for creating and editing geometry.

The goal of the first test phase (habituation) was for participants to familiarize themselves with the system, learning how to create and edit 3D models. To accomplish this, subjects were asked to model five simplified structural elements commonly found in buildings and provided as references: flight of stairs, pillar, beam, slab and wall with window (tasks 1 to 5 respectively) (Fig. 7). Each task was randomly presented to the participant to avoid biased results, and s/he was given a maximum of three minutes to complete a replica of the given element as accurately as possible.

After completing the habituation phase, participants were introduced to the second phase of the test (maquette modeling), which required them to sketch in 3D different buildings of varying complexity, given as references: Farnsworth House, Empire State Building, and Falling Water (tasks 6 to 8, respectively) (Fig. 8). All models were created without surrounding information and presented to the in random order. Subjects were free to model at any size under a limit of five minutes. However, they were required to respect the model's appearance and proportions.

Finally, participants were asked to complete a questionnaire about the system and the tasks undertaken to classify the level of difficulty they felt while performing the tasks and using the features available. The questionnaire included a list of statements to qualify on a six-point Likert Scale, in a “forced-choice” approach to avoid neutral responses [47]. Value 1 meant that the person disagreed completely with the statement while 6 meant they fully agreed with it. After finishing the questionnaire on the first modeling system, participants repeated the same three-phase process for the other system. We used the findings of this study with laypeople to refine the system and fix bugs detected during these tests in order to prepare the evaluations with professional architects.

4.2. User evaluation with professional architects

The user evaluation studies with laypeople served to assess the overall performance of the system as a 3D modeling tool and its ease of use by inexperienced people. However, it was still necessary to appraise the system's adequacy as a tool to be used by architects in their practices. Therefore, five internationally renowned architects were invited as specialists to test our VR system at an early stage of a concrete project. Each professional was asked to analyze the benefits and limitations of Maquetteer as an architectural design tool.

The ages of the architects invited ranged between 34 and 54 years old. Two had more than ten years of professional experience, other two had more than fifteen years and one had over twenty-five years in the craft. Besides their professional practice, three of the architects taught architectural design studios to different curricular years, in both national and international architecture schools.

The evaluation conducted with architects had a different configuration from the tests conducted with laypeople, as the former were asked to test the Maquetteer system only after a thorough demonstration of all available functions and their application. The experience was divided into four phases with no time limitations and performed in the following order: (a) user habituation to the system, (b) conceptual modeling of a concrete project, (c) questionnaire for system evaluation, and (d) semi-structured interview.

The first phase (a) was intended to familiarize the architects with the Maquetteer system. They were asked to model freely in the system's

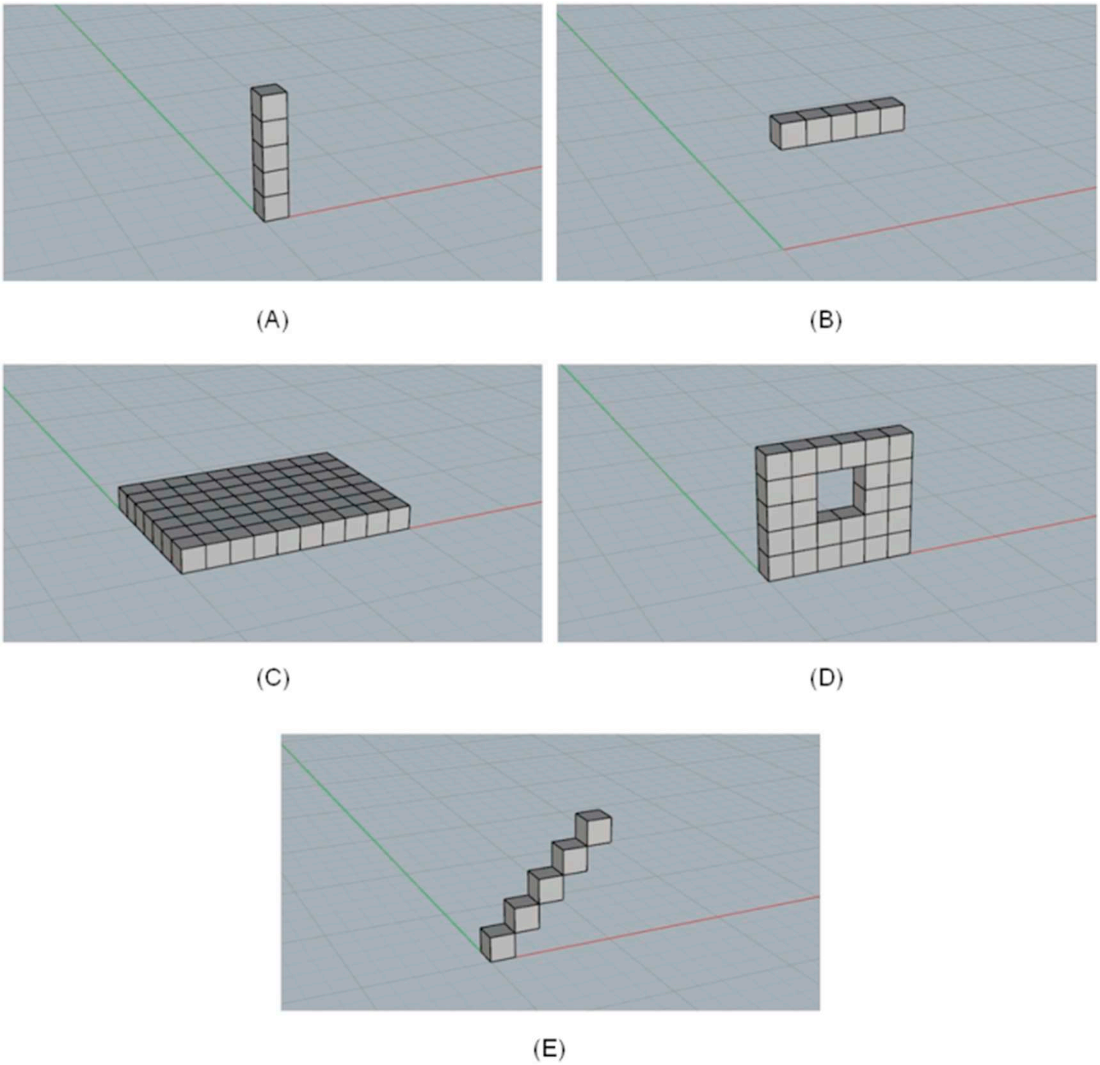
(A) (B) (C) (D) (E)

Fig. 7. Architectural structural elements used in the habituation phase: (A) pillar; (B) beam; (C) slab; (D) wall with window; (E) and stairs.

modeling environment, the only restriction being they had to exercise all available functions at least once. There was no time constraint and they were free to model at any scale they liked; when they felt confident with the system, they could proceed to the next phase.

In the second phase (b), the architects were presented with a 3D model of the site of a concrete project at an early stage of development in their offices, which they had previously provided. They were then asked to develop the project for that specific site using the Maquetteer system, either by creating new designs on the fly or by testing solutions they previously thought of, again with no time constraints. The fifth architect, who didn't have an ongoing project at the time, used the site and architectural program of one of the other professionals. During the first and second phases of each test, we asked each architect to verbalize his/her experience as much as possible, commenting on both the limitations encountered, as well as the positive aspects of the system and the experience. We also registered all of their comments, movements and expressions.

As with laypeople, prior to starting the tests we asked each architect

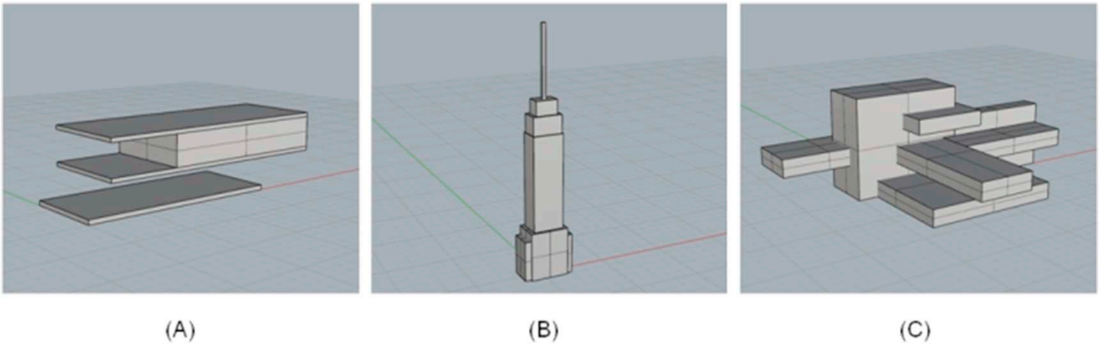
(A) (B) (C)

Fig. 8. Architectural models used in the user study: (A) Farnsworth House; (B) Empire State Building; and (C) Falling Water House.

to complete a questionnaire to identify their profile regarding experience with interaction and head-mounted display devices, as well as architecture modeling systems. At the end of the tests, they were asked to complete a more extensive questionnaire regarding the system, the tasks performed and the project they developed during the third phase of the test. The objective was to classify the level of difficulty encountered while performing tasks using the system features.

The fourth phase of the test took place after a period of reflection, which lasted approximately one week, semi-structured interviews with the professional architects were conducted to capture their lasting impressions about the system and its possible application to architectural practice – both professionally and in educational contexts. The interviews also went back to their observations during the tests and answers to the previous questionnaire, inviting them to elaborate as much as possible on the subjects they found to be the most relevant from their experience. We also asked them to share their thoughts and opinions regarding desirable improvements to the system.

5. Results and discussion

In this section, the main observations made during the tests with laypeople and architects are presented, as well as the difficulties they identified and the suggestions they offered regarding both systems – SketchUp and Maquetteer. Questionnaires' results and log files obtained during the tests are also analyzed.

5.1. *Results from the tests with laypeople*

Regarding the usability tests with laypeople, both systems support the construction of box-shaped virtual maquettes. These models can be used to represent initial concepts for buildings without intricate architectural details, focusing instead on the spatial arrangement. Given their simplicity, such models are ideal for expedite modeling with a spatial interface.

From the statistical analysis of the laypeople's questionnaires [61], it was found that the general use of Maquetteer was easier when compared to SketchUp ($Z = -2.0$, $p = 0.046$), but with similar learning curves. Another relevant topic of statistical significance was the navigation in the virtual environment ($Z = -2.176$, $p = 0.029$), although their perception of the cursor location does not show statistical difference. This data partially validates HA, which states that Maquetteer is easier to use in comparison to Sketchup when modeling box shaped objects, as illustrated in Fig. 9.

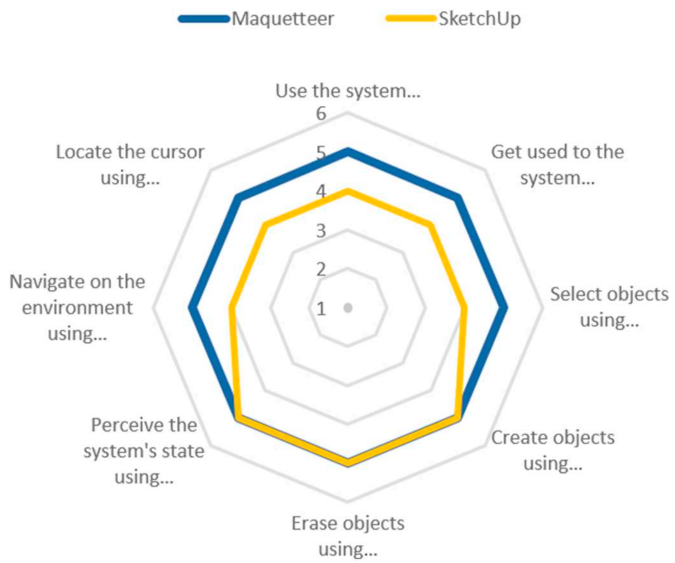

Fig. 9. Comparison between participant responses regarding different assessment criteria of the two systems studied for modeling box shaped objects (median), using a six-point forced-choice Likert scale: 1 – totally disagree, 2 - disagree, 3 - somewhat disagree, 4 - somewhat agree, 5 - agree and 6 – totally agree.

Table 1
Participant responses regarding different assessment criteria of two systems studied for modeling box shaped objects: Median (Interquartile Range). Likert scale: 1 – totally disagree, 2 - disagree, 3 - somewhat disagree, 4 - somewhat agree, 5 - agree and 6 – totally agree. A * after a criterion indicates statistical significance. An additional column shows the p-values associated with the performed statistical analysis for each of the questions.

It was easy to …	Maquetter	SketchUp	p-value
Use the system …*	5(1)	4(2)	0.046
Get used to the system …	5(1)	4(2)	0.054
Select objects using …	5(2)	4(3)	0.451
Create objects using …	5(1)	5(1)	0.776
Erase objects using …	5(2)	5(3)	0.873
Perceive the system's state using …	5(1)	5(1)	0.162
Navigate on the environment using …*	5(1)	4(1)	0.029
Locate the cursor using …	5(2)	4(3)	0.385

Table 1 shows the results of the qualitative part of the questionnaire of the user study mentioned previously. To look for statistical significance in the questionnaires' data we used the Wilcoxon Signed Ranks test, since the data is discrete. When confronted with the 3D models they created, participants strongly agreed that Maquetteer had the best results for task 8 ("Falling Water House", Fig. 8(C)), and was not significantly worse than SketchUp in task 6 ("Farnsworth House", Fig. 8(A)), thus reinforcing the quantitative results.

Fig. 9 illustrates the subjects' satisfaction regarding the proposed VR interface and its interaction techniques. The tasks completed by the participants allow us compare both approaches within a specific context: creating three-dimensional models using box-like shapes (i.e., parallelepipeds). All models were built using box shapes, and both Maquetteer and SketchUp were used to build such early stage maquettes. The qualitative results suggest that Maquetteer is better suited for early design stages than the WIMP alternative, when considering box shaped models (Table 1). Participants considered SketchUp to be less satisfactory, a result in line with other studies that mention the limitations of WIMP-based interfaces for early stage design [1,2,36].

Maquetteer is purposely simple and targets a very specific stage of the design process. It was not intended to become a generic CAD system, which targets precision and design detailing. Therefore, on one hand, we argue that conventional CAD systems are not designed for ideation. On the other hand, results reported in Table 1 and Fig. 9 indicate that VR tools with minimalistic interfaces and a reduced 3D shape library are more suitable for box shaped modeling during early design stages, hence verifying HA.

Regarding user performance, we used a Shapiro-Wilk test on time to assess if the sample follows a normal distribution. Since it does not follow a normal distribution, we performed a Wilcoxon Signed Ranks test to compare Maquetteer to SketchUp regarding the completion time of the task. In general, task execution times were lower when using Maquetteer, with statistical significance occurring in task 1 "Stairs" ($Z = -3.174$, $p < 0.01$) (Fig. 7(E)), task 3 "Beam" ($Z = -2.681$, $p = 0.07$) (Fig. 7(B)) and task 8 "Falling Water House" ($Z = -2.526$, $p = 0.012$) (Fig. 8(C)). Although most tasks present similar timings, Maquetteer presents significantly better results in the most complex tasks of each phase, namely, tasks 1 ("Stairs") and 8 ("Falling Water House", Fig. 8(C)).

The only exception occurred in task 7 ("Empire State Building"), where the execution time was slightly longer when using Maquetteer. This can be explained by the fact that participants had no constraints nor directives regarding the size of the models, apart from being told to keep the overall aspect of the original model and respecting the

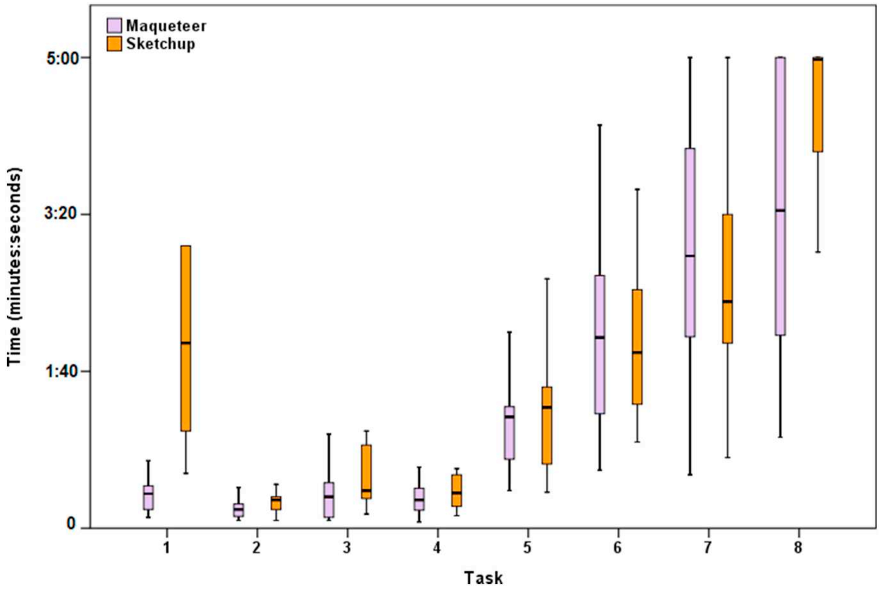

Fig. 10. Execution times (in minutes:seconds) of the modeling tasks using Maquetteer and SketchUp. Task: 1 – flight of stairs; 2 – pillar; 3 – beam; 4 – slab; 5 – wall with window; 6 – Farnsworth House; 7 – Empire State Building; 8 – Falling Water House.

proportions between its parts as much as possible. With this, we can verify HB for most of the tasks (Fig. 10), which stated that subjects could perform box modeling tasks faster using Maquetteer than Sketchup. For instance, in tasks 6 and 8 participants usually started by creating the bulkiest mass of the model (i.e., the largest parallelepiped) and then proceeded to the addition of smaller appendages. This modeling attitude gives a sense of control regarding the relative scale between different volumes. On the other hand, in task 7 subjects found themselves either creating parts of the model that were either too small (not allowing to relate different parts of the model appropriately) or too large, in some cases larger than the user him/herself. In other words, several participants were modeling at a full body scale!

While most of the subjects moved around the virtual space, approaching the models from different positions and points of view, only a few showed no inhibition in moving around the room, either ducking or stepping on their toes to model beneath or above existing geometry or to confirm if the results were correct. It was also noticed that some participants almost never moved, always modeling from the same position as if they were drawing on a two-dimensional surface, in a close resemblance to the WIMP approach. Execution times for each task of the habituation and maquette modeling phases are presented in Fig. 10.

As we can see in Fig. 10, execution times are widespread and were due, in most cases, to consecutive adjustments made to the geometry (delete/create/move) in order to achieve a desirable result. Measurements from task 1 revealed a clear discrepancy between the two systems: a consequence of the different ways each system handles geometry. In Sketchup, if we move a shape that shares a point, edge or face with another shape, the latter becomes deformed because the point/edge/face is moved along with the first shape. This happened many times as the participants were modeling the stairs (Fig. 7(E)), which were represented as a set of boxes displaced diagonally in a vertical plane (sharing edges). When participants attempted to make adjustments to one of the steps in the stairs in Sketchup, the adjacent steps became deformed and required further readjustments. Due to its voxel-based approach, Maquetteer made it very easy for participants to create each step in the stairs, requiring little or no adjustments. When using Maquetteer, all participants completed the model in task 1, with the slowest of them taking 1:28 (minute:seconds) to finish. When using Sketchup, five out of 18 participants were unable to finish the model within the three-minute time limit.

Regarding task 8 (Fig. 10), measurements from the tests with Maquetteer are more widespread than the ones from tests with Sketchup. When using Maquetteer, some participants took their time to analyze the existing model (e.g., by moving around it) before starting to model its replica, frequently comparing both models and making adjustments to the new design. One of these participants only started creating the new model after one minute into the test (20% of the time available). In Sketchup, as before, participants often deformed or erased parts of their models while attempting to make simple adjustments (e.g., moving intersecting boxes), unwillingly. The fastest participant to complete task 8 (the same for both systems) took 0:58 (minutes:seconds) in Maquetteer, far below the 2:56 (minutes:seconds) spent in Sketchup. Taking a closer look at participant performance in task 8, eight out of 18 participants - almost half (44,4%) - finished the task using Maquetteer in less than half the time allowed (2 min 30 s out of 5 min), while none achieved comparable speed using Sketchup.

Regarding comfort, the majority of the laypeople (14 participants, or 77.7% of the subjects) did not suffer any discomfort during the Virtual Reality experience. Detected side-effects in the minority of these people included ocular pain, eye strain, vertigo and slight headache, with one occurrence of each.

5.2. Results from the tests with professional architects

In the second experience, professional architects showed a tendency to create models around their bodies, during the free modeling phase, designing at full scale. In the interviews, all architects noticed the importance of designing while fully immersed in the spaces they were creating and referred to the fundamental need to properly assess scale, using their bodies as reference for spatial definition.

According to them, the system "runs really smoothly" and the "response times are very good." The interface was deemed to be clear and easy to use, noting the importance of having the remote control represented in VR and the clarity of the text associated with each button. Two main limitations were pointed out when modeling with a representation of a site: the impossibility of changing the dimension of the voxel once the system was running and the rigidity imposed by the three-dimensional grid, not allowing the user to create voxels with different orientations. Additionally, one of the participants pointed out it would be useful to have different layers where people could store alternative designs for comparison within the same VR session.

Overall, the voxel-based modeling approach was considered a good strategy – ensuring that one could choose the size and direction of the cubic grid, responding to the constraints and clues present in the model of the site. The use of a voxel system to design was referred to as having a huge pedagogic and propaedeutic potential in architectural design studios. The sense of scale was also pointed out as a key advantage of the system and fundamental to architectural education, referred to it as something that is commonly lacking in architecture students and difficult to convey.

When questioned about the use of Maquetteer in architectural practice, they referred to the system as a desirable complementary tool to those in use (both digital and analog), provided that the limitations mentioned above were overcome. One of the participants mentioned that "*having the possibility of testing the model being created virtually at 1:1 scale is fundamental for architects*", which is one of the key features of Maquetteer.

All subjects reported that the VR environment allows professionals to create virtual maquettes in a fast and simple way, and that hand gestures were suitable to define overall spaces and topology. Users rapidly understood how to interact with the system as they easily completed each task, without having experienced a spatial interaction system before. Indeed, our results suggest that Maquetteer can be a viable alternative to WIMP-based CAD tools for early stage maquette building.

Regarding the comfort of using the system, three out of five did not report any discomfort, one felt a slight perturbation after a session of one hour and only one mentioned feeling motion sickness at the end of the session.

6. Conclusions and future work

In this paper, we explored VR to build box-like maquettes at the early stages of architectural design. Inspired by Minecraft's approach to metaphorically create digital worlds, we proposed a VR-based design system to provide an environment to create rough three-dimensional solid models using only a simple set of operations. Usability studies, conducted with both laypeople and professional architects, suggest many distinct advantages of VR for early stage maquette building.

Above all, VR applications such as Maquetteer support alternative ways of working and offer a useful complement to existing CAD applications – not a direct competitor. Indeed, VR fills a gap in the architectural design process: creating spaces in direct relation to the body, making it possible to assess the design of spaces at full scale as they are created. The authors' experience with current CAD applications suggested that conventional CAD tools distance architects from architectural ideation, turning it into an artificial, cumbersome and abstract process, since the emphasis on structured input affect the flow of creative thought, by diverting attention away from creativity to interaction. This insight was supported by preliminary studies aimed at assessing current tools, providing foundational work to develop Maquetteer. This was also backed by comments by professional architects that helped us with the initial tests. Our application brings architects back into direct spatial ideation, enabling them to create conceptual space virtually in close relation to their bodies, affording them to experience their designs both as creators and as users.

Through a usability study with laypeople, we compared our approach to a conventional WIMP system. Our results show that people required less time to perform modeling tasks through spatial interaction with the 3D model. This suggests that gestures and sketch-based input can be effective for modeling voxel-based objects, in general, and box-like maquettes, in particular. Additionally, the study shows that simple maquette models can be successfully modeled with the proposed sketch system in a natural and simple fashion.

Both the performance results and user feedback indicate that VR systems may be a valid alternative to desktop CAD systems for early stage maquette building, reducing technical intermediaries in the design process. Even though VR setups may still cause discomfort when used for long periods of time, our approach revealed clear potential both for developing conceptual architectural models and assessing scale in spatial designs. Maquetteer provides capabilities that augment both modeling and visualization via simple 3D input using a wireless controller and freehand gestures. These capabilities support both direct and expeditious interaction to rapidly externalize initial concepts as compared to the conventional mouse and keyboard of CAD systems.

Maquetteer is a VR tool that builds on long-standing design methods and goes back to the roots of architectural design itself. It allows architects to design from either a god-like point of view or at human scale from within the built space. Subjects also reckoned our system to be a simple yet useful and effective design tool. Furthermore, grid and voxel constraints constitute a limited yet rapid and effective modeling tool, hence providing a systemic approach to design.

One limitation of the usability studies was that the proposed system was only tested with 18 laypeople and 5 professionals. A larger participant set could yield results with more statistical significance. However, those results were validated from feedback collected from professionals and point towards new research paths providing valuable insights on how VR can assist architects at the early stages of architectural design.

To become a more interesting tool for architects, additional functionalities would improve expeditiousness and help in creating more meaningful models: (i) the ability to create geometry at different scales, thus allowing architects to take a closer or distant approach to the design, at will; (ii) the possibility of changing the orientation of the voxel grid, thereby enabling architects to create geometry with different orientations – particularly when modeling within a given site context; (iii) allowing for sunlight studies while modeling; (iv) changing the size of the voxels at will, during a session; and (v) supporting changes to the geometry of imported site models, allowing virtual *demolitions* and *excavations*.

Some of the functionalities mentioned above have indeed been introduced after the usability tests. A distinctive feature of our system allows several designers to collaboratively create and edit maquettes inside a shared distributed 3D space. The system now allows people to introduce coordinate axes with varying spatial orientations, each representing an alternative spatial grid with its own layer. This allows users to create parallelepipeds with any orientation desired, enabling skewed designs. The system now allows storing alternative designs in different 'layers' (axes), switching their visibility on and off to compare different solutions. Preliminary tests with collaborative sessions show the potential of the system to bring design teams together into highly participatory work sessions. Tracking capability may be further improved with the addition of multiple depth sensing cameras, which reduces the chances of object occlusion and captures a greater diversity of body postures that appear in collaborative sessions [48].

In the future, we aim to use Maquetteer as a tool for architectural education, namely for freshman students. Additionally, we plan to explore collaborative scenarios (both local and remote) in architecture studios where Maquetteer will complement or even replace the physical maquette process. This might reduce scale models and mock-up costs by replacing physical with virtual maquettes, as well as eliminating waste resulting from model fabrication. Another clear research direction consists in connecting conceptual designs to Building Information Modeling, i.e., to create BIM-intelligent sketches that may directly influence the final design by allowing early cost and resource estimates.

Acknowledgments

Authors thank the generous financial support from the Portuguese Foundation for Science and Technology (FCT) through grants UID/CEC/50021/2019, TECTON-3D PTDC/EEI-SII/3154/2012, and IT-MEDEX PTDC/EEI-SII/6038/2014. Daniel Simões Lopes' work was also supported by FCT grant SFRH/BPD/97449/2013, Rui de Klerk's by FCT Doctoral Grant SFRH/BD/131386/2017 and Daniel Medeiros' by grant 9040/13-7 from CAPES Foundation, Ministry of Education of Brazil.

The authors thank Artur Gonçalves for his work on coding part of the interface and 3D functionalities. Thank you also the participants in the usability studies, especially the professional architects, for their time, interest and valuable inputs.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2019.03.009.

References

[1] R. Ibrahim, F. Pour Rahimian, Comparison of CAD and manual sketching tools for teaching architectural design, Autom. Constr. 19 (2010) 978–987, https://doi.org/10.1016/j.autcon.2010.09.003.

[2] F.P. Rahimian, R. Ibrahim, Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design, Des. Stud. 32 (2011) 255–291, https://doi.org/10.1016/j.destud.2010.10.003.

[3] A. Bridges, D. Charitos, On architectural design in virtual environments, Des. Stud. 18 (1997) 143–154, https://doi.org/10.1016/S0142-694X(97)85457-9.

[4] F.P. Brooks, What's real about virtual reality? IEEE Comput. Graph. Appl. 19 (1999) 16–27, https://doi.org/10.1109/38.799723.

[5] D. Donath, H. Regenbrecht, Using virtual reality aided design techniques for three-dimensional architectural sketching, Design Computation: Collaboration, Reasoning, Pedagogy - ACADIA Conference Proceedings, CUMINCAD, Tucson, Arizona, USA, 1996 1-880250-05-5, pp. 199–212 ISBN.

[6] G. Franz, M. von der Heyde, H.H. Bülthoff, An empirical approach to the experience of architectural space in virtual reality—exploring relations between features and affective appraisals of rectangular indoor spaces, Autom. Constr. 14 (2005) 165–172, https://doi.org/10.1016/j.autcon.2004.07.009.

[7] A. Heydarian, J.P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, W. Wood, Immersive virtual environments versus physical built environments: a benchmarking study for building design and user-built environment explorations, Autom. Constr. 54 (2015) 116–126, https://doi.org/10.1016/j.autcon.2015.03.020.

[8] T. Hilfert, M. König, Low-cost virtual reality environment for engineering and construction, Visualization in Engineering 4 (2016) 2, https://doi.org/10.1186/s40327-015-0031-5.

[9] Y. Hong, P. Michalatos, LumiSpace: A VR architectural daylighting design system, in: SIGGRAPH ASIA 2016 Virtual Reality Meets Physical Reality: Modelling and Simulating Virtual Humans and Environments, ACM, New York, NY, USA, 2016: pp. 10:1–10:2. doi:https://doi.org/10.1145/2992138.2992140.

[10] H. Ibayashi, Y. Sugiura, D. Sakamoto, N. Miyata, M. Tada, T. Okuma, T. Kurata, M. Mochimaru, T. Igarashi, Dollhouse VR: A Multi-view, Multi-user collaborative design workspace with VR technology, in: SIGGRAPH Asia 2015 Emerging Technologies, ACM, New York, NY, USA, 2015: pp. 8:1–8:2. doi:https://doi.org/10.1145/2818466.2818480.

[11] A.Z. Sampaio, M.M. Ferreira, D.P. Rosário, O.P. Martins, 3D and VR models in civil engineering education: construction, rehabilitation and maintenance, Autom. Constr. 19 (2010) 819–828, https://doi.org/10.1016/j.autcon.2010.05.006.

[12] R. Stark, J.H. Israel, T. Wöhler, Towards hybrid modelling environments—merging desktop-CAD and virtual reality-technologies, CIRP Ann. 59 (2010) 179–182, https://doi.org/10.1016/j.cirp.2010.03.102.

[13] B. Westerdahl, K. Suneson, C. Wernemyr, M. Roupé, M. Johansson, C. Martin Allwood, Users' evaluation of a virtual reality architectural model compared with the experience of the completed building, Autom. Constr. 15 (2006) 150–165, https://doi.org/10.1016/j.autcon.2005.02.010.

[14] Y.-J. Yoon, I.-K. Shin, Y. Jang, S.-M. Choi, Stereoscopic 3D exploration of freeform architecture, Autom. Constr. 46 (2014) 1–10, https://doi.org/10.1016/j.autcon.2014.06.002.

[15] A. Heydarian, B. Becerik-Gerber, Use of immersive virtual environments for occupant behaviour monitoring and data collection, J. Build. Perform. Simul. 10 (2017) 484–498, https://doi.org/10.1080/19401493.2016.1267801.

[16] A. Heydarian, E. Pantazis, A. Wang, D. Gerber, B. Becerik-Gerber, Towards user centered building design: identifying end-user lighting preferences via immersive virtual environments, Autom. Constr. 81 (2017) 56–66, https://doi.org/10.1016/j.autcon.2017.05.003.

[17] S.F. Kuliga, T. Thrash, R.C. Dalton, C. Hölscher, Virtual reality as an empirical research tool — exploring user experience in a real building and a corresponding virtual model, Comput. Environ. Urban. Syst. 54 (2015) 363–375, https://doi.org/10.1016/j.compenvurbsys.2015.09.006.

[18] D. Paes, E. Arantes, J. Irizarry, Immersive environment for improving the understanding of architectural 3D models: comparing user spatial perception between immersive and traditional virtual reality systems, Autom. Constr. 84 (2017) 292–303, https://doi.org/10.1016/j.autcon.2017.09.016.

[19] D. Paes, J. Irizarry, A Usability Study of an Immersive Virtual Reality Platform for Building Design Review: Considerations on Human Factors and User Interface, Construction Research Congress 2018, (2018), https://doi.org/10.1061/9780784481264.041.

[20] S. Lee, J. Yan, The impact of 3D CAD interfaces on user ideation: a comparative analysis using SketchUp and Silhouette modeler, Des. Stud. 44 (2016) 52–73, https://doi.org/10.1016/j.destud.2016.02.001.

[21] F. Braida, A.A. Rosa, I.F. Silva, D.M. Homem, A. da S. Jardim, A exploração do mundo projetual dos blocos de montar por meio do jogo digital interativo Minecraft, Blucher Design Proceedings 2, Editora Edgard Blücher, 2015, pp. 371–377, https://doi.org/10.5151/despro-sigradi2015-80192.

[22] J. Sanchez, Block'hood - developing an architectural simulation video game, Real Time - Real Time - Proceedings of the 33rd eCAADe Conference, Vienna University of Technology, Vienna, Austria, 2015 978-94-91207-08-2, pp. 89–97 ISBN.

[23] J. Sanchez, Gamescapes, Adaptive Architecture - Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Cambridge, Ontario, Canada, 2013 978-1-926724-22-5, pp. 207–216 ISBN.

[24] S. Kuan, T. Kvan, Supporting objects in voxel-based design environments, Proceedings of the 10th International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA), CAADRIA, New Delhi, India, 2005 89-7141-648-3, pp. 105–113 ISBN.

[25] S. Kuan, T. Kvan, CoBlocks: an improved voxel-based design tool by object structuring of voxel models, Int. J. Archit. Comput. 4 (2006) 35–55, https://doi.org/10.1260/147807706779399042.

[26] C. Fanning, R. Mir, Playthings, pedagogy, and punching trees: minecraft in the history of construction play, in: Decorative Arts and Design Session, 25th MAPACA Annual Conference, Baltimore, Maryland, USA, 2014. https://www.academia.edu/9406781/Playthings_Pedagogy_and_Punching_Trees_Minecraft_in_the_History_of_Construction_Play (accessed April 19, 2018).

[27] C. Fanning, R. Mir, Teaching tools: progressive pedagogy and the history of construction play, in: Understanding Minecraft: Essays on Play, Community and Possibilities, Garrelts, Nate (Ed.), McFarland & Company, Inc. Publishers, Jefferson, North Carolina, USA, 2014: pp. 38–56. ISBN: 978-0-7864-7974-0.

[28] J.J. Jirout, N.S. Newcombe, Building blocks for developing spatial skills: evidence from a large, representative U.S. sample, Psychol. Sci. 26 (2015) 302–310, https://doi.org/10.1177/0956797614563338.

[29] B. Vale, R. Vale, Architecture on the Carpet: The Curious Tale of Construction Toys and the Genesis of Modern Buildings, 01 Edition, Thames and Hudson Ltd, New York, New York, 978-0-500-34285-5, 2013.

[30] T. Alphin, The LEGO Architect, No Starch Press, 2015 (978-1-59327-706-2).

[31] J. Hegarty, B. Smith, J. Jebens, J.P. Molloy, Assembling Environments with LEGOscape, in: ACM SIGGRAPH 2014 Talks, ACM, New York, NY, USA, 2014: pp. 14:1–14:1. doi:https://doi.org/10.1145/2614106.2614180.

[32] D.J. French, B. Stone, T.T. Nysetvold, A. Hepworth, W. Edward Red, Collaborative design principles from Minecraft with applications to multi-user computer-aided design, J. Comput. Inf. Sci. Eng. 16 (2016) 021006–021006–9. doi:https://doi.org/10.1115/1.4032667.

[33] S. Bafna, S. Shah, The evolution of orthogonality in built space: an argument from space syntax, in: Proceedings Book, 6th International Space Syntax Symposium, KUBAT, Ayşe Sema, ERTEKIN, Özhan, INCE GÜNEY, Yasemin (Eds), TUBITAK & Istanbul Technical University, Faculty of Architecture, Cenkler, Istanbul, Turkey, 2007. ISBN: 978-975-561-304-8.

[34] P. Steadman, Architectural Morphology: An Introduction to the Geometry of Building Plans, Pion, 1983 (978-0-85086-086-3).

[35] P. Steadman, Why are most buildings rectangular? Archit. Res. Q. 10 (2006) 119–130, https://doi.org/10.1017/S1359135506000200.

[36] L. Olsen, F.F. Samavati, M.C. Sousa, J.A. Jorge, Sketch-based modeling: a survey, Comput. Graph. 33 (2009) 85–103, https://doi.org/10.1016/j.cag.2008.09.013.

[37] G. Conti, G. Ucelli, T. Maver, JCAD-VR: Java collaborative architectural design tool in virtual reality - a Java3D based scalable framework for real-time, multiplatform VR environments, Architectural Information Management - Proceedings of the 19th eCAADe Conference, CUMINCAD, Helsinki, Finland, 2001 0-9523687-8-1, pp. 454–459 ISBN.

[38] D. Donath, H. Regenbrecht, Using immersive virtual reality systems for spatial design in architecture, AVOCAAD Second International Conference Proceedings, Brussels, Belgium, 1999, pp. 307–318 ISBN: 90-76101-02-07.

[39] T. Dorta, P. LaLande, The impact of virtual reality on the design process, Digital Design Studios: Do Computers Make a Difference? - ACADIA Conference Proceedings., Québec City, Canada, 1998 1-880250-07-1, pp. 138–163 ISBN.

[40] H. Regenbrecht, E. Kruijff, D. Donath, H. Seichter, J. Beetz, VRAM - a virtual reality aided modeller, Promise and Reality: State of the Art Versus State of Practice in Computing for the Design and Planning Process - 18th eCAADe Conference Proceedings, eCAADe, Weimar, Germany, 2000 0-9523687-6-5, pp. 235–237 ISBN.

[41] B.R. De Araújo, G. Casiez, J.A. Jorge, M. Hachet, Mockup builder: 3D modeling on and above the surface, Comput. Graph. 37 (2013) 165–178, https://doi.org/10.1016/j.cag.2012.12.005.

[42] L. Anderson, J. Esser, V. Interrante, A virtual environment for conceptual design in architecture, in: Proceedings of the Workshop on Virtual Environments 2003, ACM, New York, NY, USA, 2003, pp. 57–63, https://doi.org/10.1145/769953.769960.

[43] G. Schubert, C. Anthes, D. Kranzlmüller, F. Petzold, From physical to virtual: real-time immersive visualisations from an Architect's working model, CONVR 2012: Proceedings of the 12th International Conference on Construction Applications of Virtual Reality, Taiwan Univ. Press, Taipei, Taiwan, 2012 978-986-03-4289-5, pp. 417–426 ISBN.

[44] B. de Vries, H.H. Achten, DDDoolz: designing with modular masses, Des. Stud. 23 (2002) 515–531, https://doi.org/10.1016/S0142-694X(02)00006-6.

[45] N. Sasaki, H.-T. Chen, D. Sakamoto, T. Igarashi, Facetons: face primitives with adaptive bounds for building 3D architectural models in virtual environment, Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology, ACM, New York, NY, USA, 2013, pp. 77–82 , https://doi.org/10.1145/2503713.2503718.

[46] B. Jackson, D.F. Keefe, Lift-off: using reference imagery and freehand sketching to create 3D models in VR, IEEE Trans. Vis. Comput. Graph. 22 (2016) 1442–1451,

https://doi.org/10.1109/TVCG.2016.2518099.
[47] R.L. Armstrong, The midpoint on a five-point Likert-type scale, Percept. Mot. Skills 64 (1987) 359–362, https://doi.org/10.2466/pms.1987.64.2.359.
[48] M. Sousa, D. Mendes, R.K.D. Anjos, D. Medeiros, A. Ferreira, A. Raposo, J.M. Pereira, J. Jorge, Creepy tracker toolkit for context-aware interfaces, Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces, ACM, New York, NY, USA, 2017, pp. 191–200, https://doi.org/10.1145/3132272.3134113.
[49] J. Nasman, B. Cutler, Evaluation of user interaction with daylighting simulation in a tangible user interface, Autom. Constr. 36 (2013) 117–127, https://doi.org/10.1016/j.autcon.2013.08.018.

Web references (last accessed 22/04/2018)

[50] Autodesk Autocad, http://www.autodesk.com/products/autocad.
[51] Autodesk Revit, http://www.autodesk.com/products/revit-family.
[52] B. Branit, World Builder (2007), http://www.imdb.com/title/tt1419113/.
[53] B. Schell, J.L. Esch, J.E. Ulmer, System and Method for Three-Dimensional Modeling, https://patents.google.com/patent/US6628279B1/en, (2000).
[54] Definition of Maquette: https://www.merriam-webster.com/dictionary/maquette
[55] Google Tiltbrush, https://www.tiltbrush.com.
[56] Maquetteer: http://web.tecnico.ulisboa.pt/daniel.s.lopes/maquetteer_video.avi
[57] McNeel Rhinoceros: https://www.rhino3d.com
[58] Minecraft: https://minecraft.net
[59] MinecraftEdu: https://education.minecraft.net/
[60] Nemetschek Vectorworks, http://www.vectorworks.net/.
[61] Results from laypeople evaluation forms: http://web.tecnico.ulisboa.pt/daniel.s.lopes/maquetteer-questionnaire-data.xlsx