Sketching in Virtual Space with Voxels

A CAD tool for the Early Stages of Architectural Design

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Abstract

Early scale modeling is an essential part of the architectural process. It consists on creating small rough sketches of the building being projected, which are used for spatial perception, testing shapes and volume distribution. The more traditional approaches to scale modeling consist on creating this maquettes using physical materials (e.g., styrofoam, balsa wood, cardboard). This limits the speed at which an architect can work and becomes increasingly complex, expensive and time consuming with the size of the project. On the other hand, CAD software uses mostly 2D interfaces that heavily rely on windows-icons-menus-pointer elements (WIMP) which are not suited for early stage scale modeling due to their complexity and because, as many papers show, they affect the architectural creative process by having a steep learning curve and more tedious tasks. This thesis explores the use of Virtual Reality as a medium for early stage scale modeling, at different scales, that will improve on analogue and 2D computer based approaches. A spatial user interaction system was created using a motion capture setup, a videogame controller for user input and a head mounted display (HMD) for creating a virtual reality environment. The application developed, Maquetteer, uses voxels, cubes constrained to an orthogonal grid, as a modeling unit to create early stage maquettes. The proposed system was tested by both laypeople and professional architects and results show that it is easier to use in comparison to a commonly used WIMP modeling application.

Keywords: Virtual Reality, 3DUI, CAD, 3D Sketching, Scale Modeling, Architecture
Resumo

A produção de modelos à escala nas fases iniciais do projeto arquitetónico é essencial para o mesmo. Esta consiste em criar esboços com baixo detalhe do edifício a ser construído de modo a conseguir visualizar melhor o produto final e poder testar diferentes formas e distribuições de volume. Os métodos tradicionais para a criação de modelos à escala consistem em criar maquetes físicas utilizando materiais como esferovite, cartão ou madeira. Isto limita a velocidade a que o arquiteto consegue trabalhar e é um processo que se torna exponencialmente mais complexo, dispendioso e demorado à medida que o projeto cresce em complexidade. Por outro lado, ferramentas CAD usam maioritariamente interfaces 2D que usam predominantemente janelas, ícones, menus e ponteiros que não são os mais indicados para modelação nas fases iniciais do projeto devido à sua complexidade e porque afetam o processo criativo devido à dificuldade de aprendizagem e a tarefas entediantes que fazem parte do processo. Esta tese explora o uso de Realidade Virtual como meio para a modelação a diferentes escalas nas fases iniciais do projeto, como uma alternativa melhor aos métodos tradicionais de maquetagem e ao software 2D. Foi desenvolvida uma aplicação para realidade virtual com uma interface espacial, que usa voxeis, cubos restringidos numa grelha ortogonal, como paradigma de modelação para criar modelos à escala. O sistema proposto foi testado por leigos e arquitetos profissionais e os resultados demonstram que é mais fácil de utilizar em relação a uma aplicação CAD 2D comercialmente disponível.

Palavras-chave: Realidade Virtual, 3DUI, CAD, Esboço, Modelos à escala, Arquitetura
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<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>AR</td>
<td>Augmented Reality</td>
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<td>CAAD</td>
<td>Computer Aided Architectural Design</td>
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<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CPU</td>
<td>Central Processing Unit</td>
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<td>HMD</td>
<td>Head Mounted Display</td>
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<td>OS</td>
<td>Operating System</td>
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<td>UI</td>
<td>User Interface</td>
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<td>GUI</td>
<td>Graphical User Interface</td>
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<td>VR</td>
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<td>VRE</td>
<td>Virtual Reality Environment</td>
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<td>Wii Remote Controller</td>
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<td>WIMP</td>
<td>Windows, Icons, Menus and Pointer</td>
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<td>CAVE</td>
<td>Cave Automatic Virtual Environment</td>
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<td>Mocap</td>
<td>Motion Capture</td>
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<tr>
<td>VIMMI</td>
<td>Visualization and Intelligent Multimodal Interfaces</td>
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<tr>
<td>3DUI</td>
<td>Three Dimensional User Interface</td>
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1. Introduction

1.1 Motivation

Sketching is essential to the creative process, it allows the designer to try and explore ideas quickly and to relay them to others. It is a task that is present in almost any project that involves some kind of creative thinking including architecture projects. There are analogue approaches to sketching in architecture such as pen and paper or scale modeling and digital ones that are called CAD software that can be used in computers, tablets and other electronical devices. Sketching, either by digital or analytical methods, are considered a good practice in architecture as it promotes the discovery of relevant concepts [1] [2].

Scale modeling consists on creating different size replicas of the final project as a way of knowing how will it look like, studying different topologies and knowing how the structure will interact with the environment. An architect produces many scale models (also known as maquettes) during the lifetime of a project. At the beginning of the project they have very few details attempting only to see how the overall shape of the construction will be, what volume will it occupy and how that volume can be arranged in the structure’s target location. As the project advances and the shape of the construction becomes well defined the scale model starts to have more details until the final prototype which is the one more similar to the end result. This collection of maquettes can be seen as a window to the architect’s creative process and help the architect relay its vision to the client and colleagues. Traditionally scale models are made by using materials such as cardboard, styrofoam or wood which are then cut and pieced together to create the desired shape. It is a laborious work that can take several hours to finish and is limited by the resources available, by the number of people working on it, the size of the room and the physical properties of the materials used. [3]
As computers evolved digital alternatives to analogue sketching began to appear such as AutoCAD [4], Revit [5] and Rhinoceros [6]. Although they are considered powerful tools in architectural design their interface relies heavily in WIMP elements and due to their complexity learning them is a very time consuming task. Furthermore, this kind of tools can have a negative impact on creative thinking [7] which is essential for the design process specially on early stages. These characteristics make this kind of applications unsuitable to be used in early stage sketching when the user wants to create content and test different approaches quickly without great detail. A software that differentiates from this norm and that tries to be more approachable is SketchUp [8] [9] which uses surface push-and-pull methods making it faster to use and easier to master. Finally another application worth mentioning regarding this topic is Minecraft [10] which, despite being a videogame, serves as proof of concept in using voxels as a modeling unit for buildings and another architectural structures [11][12]. Voxels are cubes that are constrained in position and size to a grid (much like their 2D equivalent, the pixel). Minecraft is one of the most successful games of all time [13], it is seen as a potential learning tool [14] and some really complex constructions were made with it only using a very simple 2D interface and voxels.

![Figure 2 - Picture of the Buckingham Palace modeled inside the game Minecraft [10]. Taken from the forum site http://www.minecraftforum.net/ and created by the forum user ShortsForTheWin.](image)

There is more evidence that voxels/cubes are very important modeling tools. A great number of toys use cubes as building blocks for improving spatial thinking [15] and creativity. That kind of toys may have influenced current architectural styles [16] and some of them, such as Minecraft [10] and Lego [17], can be used as modeling tools for early maquettes. The constraints of this kind of tools, where all the blocks have to be orthogonal to one another, is not as restrictive when applied to early stage maquettes and curiously enough roughly 90% of all modern buildings have orthogonal layouts [18].
Figure 3 - Lego [19] set made for Architects allowing them to build simple scale models using Lego pieces. Image taken from the Lego online store.

Figure 4 – A classic example of orthogonality in architecture. The Farnsworth House projected by the famous architect Mies van der Rohe

Despite Minecraft and SketchUp being easier to master they still rely on WIMP elements and on a 2D interface which is unsuitable for a task as dependent on spatial thinking and visualization as architectural design. A 3D interface would then be much more suitable and would feel more natural to architects. Adding to this the keyboard and mouse are as far as possible from tools used by architects for physical scale-modeling making the transition from one paradigm to the other time consuming.

With the recent growth in popularity of Virtual and Augmented Reality the number of VR devices have exponentially risen. Companies such as Facebook, Samsung, Microsoft, Valve and many others have built affordable HMD’s that provide VR/AR experiences that are truly immersive while being small in size and portable. These characteristics make them great tools to produce 3D interfaces for improving
the way we interact with digital content. Being architecture very dependent on spatial notions and reasoning this kind of interfaces can improve architectural practice in a way that 2D applications could not by allowing direct manipulation, on different scales, and to more rapidly build a maquette [20][21][22].

1.2 Problem Statement

The goal of this thesis is to propose a digital alternative to physical scale modeling that improves on current CAD software and stays true to the sketching paradigm, a paradigm that stands for fast creation of low detailed, and rough prototypes. Our focus will be on early stage maquettes because this are the kind of maquettes that are less suited for conventional methods especially in regard to digital approaches because of the fact that they are very simple, rough, and should not take too long to make, all of which are characteristics embodied in the sketching paradigm. This contrasts with applications such as AutoCAD that, as we mentioned before, are complex to master and are more oriented for highly detailed representations of the final product. The goal is to produce a tool that allows the user to create and share with others low detailed maquettes in a much quicker way than current digital and analogue methods.

The solution proposed is called Maquetteer and presents a modeling paradigm, very similar to Minecraft, based on voxels which are, as mentioned before, cubes that are constrained to a grid in terms of size and position. Because the cubes are very constrained (orthogonal orientation and snapped to a grid) the actions that the user can perform are very limited making this system very easy to learn. Those actions are mainly associated to creating and deleting cubes using a 3D pointer that mimic some of the actions normally associated with physical scale modeling such as cutting or gluing cardboard. The voxel paradigm can be used for translating 3D sketching gestures that are messy and have no precision in well-structured data and models which can be manipulated with ease. On the other hand, because our main focus is on early stage maquettes and most buildings are predominately orthogonal the limitations are not too restrictive because the architect can, in theory, create anything that he desires within that scope or at least not feel that the application is not burdening to much the creative process. This way we have a tool that is both powerful and easy to use. Despite Minecraft and Maquetteer having very similar approaches to modelling the 3D interface of Maquetteer and the integration with VR allows for a greater degree of freedom, added functionality and immersion for the user.

The application was tested in three phases. In the first one by laypeople, where the focus was on the interface, how difficult was to learn to use the application and how fast could content could be created in comparison to other applications. In the second phase the testers were professional architects and the objective was to infer if this tool could be used during the architectural process and what could be improved in that perspective. The final phase of tests was performed by students and professionals of architecture which tried to use Maquetteer in a collaborative setup.
1.3 Scopes and Objectives

This thesis focuses on the early stages of the architectural design because current CAAD solutions are not suitable for this phase of design. It takes advantage of the sudden popularity of Virtual Reality in today’s world and tries to figure out how it can improve CAAD tools in a phase of design where the architect wants to try different solutions for the same project and the focus is on speed and not on the details. Taking inspiration from pen and draw sketching and from low detailed scale modeling this thesis presents a spatial interface immersed in a VRE for 3D sketching.

The objectives of this thesis are as follows:

- Implement, on an immersive VRE, a CAAD tool for early stages of architectural design.
- Achieve a user friendly interface that can compete with commonly used CAAD tools in terms of learning curve and content creation speed.
- Compare the implemented solution with a similar CAAD tool that relies on a traditional WIMP paradigm and observe the differences regarding learning and content creation speed. The application chosen to create
- Determine if the proposed paradigm and the solution developed are useful on a professional context (architects’ studio) and, if not, what can be made to improve them.

1.4 Contributions

The contributions of this Thesis are both of scientific and architectural nature. They are as follows:

- A framework for spatial interfaces in Virtual Reality with a wireless HMD. This framework allows for a solo application or on a more collaborative mindset. It is not tailored to Maquetteer only and can be used in different projects that also require a spatial interface on a VRE.
- A modeling application that can compete with commercial CAAD software when used for early stage architectural design.
- Using VR in architecture. Not only a CAAD tool was developed but there also were conducted interviews with professional architects to reflect on the theme. The usability tests also allowed to understand to which degree, problems commonly associated with VR compromise the experience of modeling in a spatial interface.
- Extensive user studies that evaluate the application’s usability and the potential of the paradigm for use in professional architect studies.
- A first evaluation of the benefits and potential of Maquetteer in a collaborative setup.
1.5 Submitted Manuscript

2 Literature Review

This literature review will first give an overview on the most common techniques used to aid Architectural Design in current times. In the second part there will be a review the state of the art in regard to CAAD software and finally, in the third part, the focus will be on CAAD software that tries to improve on current solutions by taking advantage of virtual reality and 3DUIs. In the second and third parts of the Literature Review the focus will be on the early stages of the Architectural Design process, which is the stage that could benefit more from the solution proposed in this thesis.

2.1 Architectural Design Techniques

Design is a fundamental part of the architectural process. It is the planning of a building in terms of aesthetics, structure and also functionality. There are different techniques that help the architect in this process by allowing him to test and visualize different ideas and concepts without actually having to build something and understand the interaction between the structure he wants to build and the surrounding environment in terms of volume and lighting. Furthermore, they can help the architect convey his ideas to colleagues or to the client. These techniques have been evolving throughout history and they can be grouped in three categories: manual drawing, scale modeling and CAD tools.

Manual drawing can be divided in architectural drawing and sketching. Architectural draws are technical drawings of a building project from a certain perspective, scale and usually with precise measurements. The perspectives on these drawings can be from the overall building or sections of it, such as a top view from a specific floor. They can be either made as a way to understand, or to show to a client, how the final building will look like or as a record of the final work. This kind of drawing can be made using ink and paper, thus falling on the manual drawing category, but this practice has been rendered almost obsolete by CAD tools and most technical drawings are now made on the computer. [23]

On the other hand, sketching is rapidly executed freehand drawing with very low precision. The goal from this kind of drawing is to explore ideas rapidly without caring with measurements or details and focus primarily on the overall look and/or shape of the building or a section of it. It is much faster to do than technical drawings that can be very time consuming. It is used mainly on the early stages of the architectural design although it can be useful in any part of the process. Mainstream CAD tools do not provide yet a computer based substitute for sketching. [23]
While manual drawings consist in 2D representations of 3D buildings scale modeling moves to the realm of 3D. Scale modeling is the creation of a replica, a model, of a building at a fraction of its real size. These models are made using cardboard, wooden blocks, polystyrene, foam, foam boards and others. They can also be 3D printed using virtual maquettes made with CAD tools. There are also companies which are specialized in creating small objects like trees, cars, structural elements or even furniture that can be used to provide more detail to a scale model. The size and detail of this models vary depending on what the architect intention is, what aspects of the building he wants to study. At 1:2500 (2500 meters in real life correspond to 1 meter on the scale model) and 1:1000 scales the focus is not in a building itself but on an entire city or large landscapes, at 1:250 or 1:500 scales the target is still not a building but the general area where it will be built and at 1:200 or 1:100 the focus begins to shift to the building itself and its rough shape in terms of volume disposition. At this scales also or as the size of the scale model increases to 1:50 the architect usually starts to focus on the interior of the building and on the floor plans to which, at 1:25 scale, it begins to add furniture. Finally, the biggest models usually built at 1:2 and 1:1 are usually used to study more refined details. The level of details can also vary within the same scale depending on the phase of the design process varying from low detailed 3D sketches to highly detailed replicas of the final product. [3]
Scale models are a very powerful tool. They can be used to study almost any aspect of the building from structural to aesthetics allowing even the architect to study how much light it will have at different times of day and its distribution throughout the building. It is also better than drawings for spatial thinking as these are 3D representations. It is also a common practice for the architect to gaze at the model at really short distances as a way to see what a person inside the building will see from different angles and perspectives. Other functions that are also associated with drawings such as relaying ideas to colleagues and customers and experimenting with different concepts are also a part of scale modeling.

CAAD is a rather loose term because it refers to any kind of software that can be used to aid the architectural thinking. They have the same functions as manual drawing or scale modeling but a lot of advantages over these methods. CAAD tools only require a computer to work which means that they do not require the large amounts of space and materials that scale modeling requires and it is faster and easier to work with these tools. It is also more simple to define the dimensions of each component of the building and they are more flexible in regard to errors or making different solutions for the same project. Other advantages of CAAD tools is that they can easily change between 3D and 2D views of the same buildings.

One of the most successful and widely used CAD application is AutoCAD. It started as a 2D technical drawing software and it expanded with other functionalities such as 3D visualization and modeling. Another commercial hit was the software SolidWorks which focused on 3D solid modeling. There are many other alternatives to these softwares such as Rhinoceros and Revit which follows the BIM (Building Information Modeling) philosophy. BIM is the representation of not just the...
elements of a building but also spatial relationships, light analysis, geographic information, and quantities and properties of building components in a digital and structured way [26]. As it is discussed by Mateus [27] this CAD tools are not suited for the early stages of the architectural design, where sketching is often preferred, because they are too complicated to use and to learn to easily test different ideas rapidly. One software that tries to be faster to use and to have a smaller learning curve is SketchUp [27] which is a 3D modeling CAD tool. It is a step on allowing digital sketching to be as intuitive as its traditional alternatives but it still relies on a WIMP/2DUI making it slower to master and use while also hampering spatial thinking and creativity.

Figure 8 - CAD tools commonly used in Architectural Design. From left to right and top to bottom: Rhinoceros [6], Revit [5], AutoCAD [4] and Sketchup [28].

2.2 CAAD Software made for Sketching

As it was mentioned before all the CAD solutions that are presented here on forward were conceptualized for the early stages of design. It is commonly accepted that current CAD tools are not suited for the early stages of the design process [29][30][31][32][33][34] restraining creative thinking and not possessing the flexibility of pen and paper sketching. Not anyone can draw for certain but anyone can sketch, anyone can express themselves using images that in a more or less similar way, making it an almost universal skill. That is why all the papers reviewed in this section use sketching in a way or another as the user input. It is a clear trend in the state of the art in early stage CAD tools that possess 2DUIs.

Kiia Kallio [32] introduces the 3D6B editor with whom the user can create 3D sketches using an intuitive 2D interface. It does so by choosing a plane on the 3D environment using the mouse and
keyboard and drawing on a 2D surface. Everything drawn by the user is projected on the plane selected by him. By changing the position of this plane while sketching the result is a 3D sketch. The input strokes are represented in the 3D environment as if they were strokes of a pencil on paper with no kind of correction or smoothing that is normally associated with vector drawing. The sketching itself is a very straightforward operation but manipulating the plane and positioning in the right place is a much more complicated endeavor making this solution more time consuming that 2D sketching. That being said, there is no comparison made between this solution and pen and other forms of sketching because there was no user testing of this application.

Shtof [30] attempts to make a quicker translation between 2D sketches and 3D models. The user sketches solely in a 2D plane any perspective of the 3D object intended. Afterwards that sketch is interpreted by the software and converted in a 3D model. The authors recognize the complexity and ambiguity of this process and, because of that, they created a hybrid method where the computer is aided by the user in interpreting the sketches. They argue that some of the tasks in interpreting 2D drawings of 3D shapes are very simple to humans while too complex for computers and vice versa. The user is then in charge of decomposing the drawing in basic geometrical shapes, such as cylinders and spheres, and then telling the computer which part of the drawing corresponds to what shape. Finally, the computer deforms those shapes, orients and resizes them so they can fit the drawings. User tests showed that the interpretation of the sketching process is fast. However, the models that can be used are limited because the program only works with a few basic geometrical shapes and it does not handle well occlusions in the 2D drawings. The approach of Pranovich [31] is similar although the sketches are interpreted into 2D structures and not 3D models. The user tells the software what kind of shape, in this case referred to as a graphical unit, he is going to draw and using this as a guideline the program interprets the sketch made. The system is quite limited not allowing many different types of graphical units and not allowing the user to more freeform draws such as doodles.
A more suitable approach for architectural design early stages is the solution proposed by Oh [29]. The application is called SESAME which is the initials of the words Sketch, Extrude, Sculpt, and Manipulate Easily that sum up the core ideas of it. The user sketches figures on the ground plane or above solids and after that he is able to create extrusions based on that shape and editing, sculpting or forming new 3D shapes. Those shapes can then be moved, cloned or edited in other ways. All of this operations are made using a 2DUI, mouse and keyboard. The goal is to create low detailed models of buildings in a similar fashion to scale modeling using physical materials. User tests were made comparing SESAME with 3DS Max achieving good results, proving it to be a better alternative, and determining that even users with no experience with CAD software use this application.

Finally, in McKay’s proposed system [33] is based on shape grammars. A shape grammar consists of a set of shape rules and a generation engine that selects and processes those rules. a rule that is applied to a certain shape dictating how it will be transformed. Basic rules can be combined to create rules that are more complex. Because the system is not implemented and the authors only offer possible guidelines to an application the contribution to this thesis is very small. But it was included to show other forms of 3D modeling that can be applied to early stages of the architectural design.
There is a lot being done to improve CAD tools so they can be used in early stages of architectural design. These applications try to give more freedom to the user and simpler interfaces reducing the level of precision of the achieved models which is only logical since precision is not needed at this phase. One shortcoming common to all the solutions reviewed on this subchapter is that all of them rely on 2D interfaces and it is interesting to note that almost all of them \cite{29,30,31,32} try to translate 2D input or images to 3D which is a really complex problem with no perfect solution. 3DUIs are better to create 3D content because no translation or interpretation is needed from 2D to 3D shapes and it is even showed that this sort of interfaces improves creative thinking when compared to 2DUIs \cite{2,9}. In the next subchapter, the focus will be in early stage CAD tools that use 3DUIs, more specifically VREs.

2.3 CAAD Software in Virtual Reality Environments

As mentioned before the focus now will be in spatial interfaces implemented on VREs. They allow the user to sketch using the three dimensions and to be able to interact with content in an immersive environment.

One of the simplest ways of 3D sketching is painting in space. Typically, a user maneuvers a 3D pointer that it can use to paint the virtual space with strokes mimicking a pencil or a brush. Among the implementations of this kind of paradigm is the project “Sketching in Space” \cite{35} from The Constitute and the concept video “Step into the Page” from Disney \cite{36}. This are simple approaches and are not suited nor even produced to be used in architectural design but worth mentioning as a base line.

Okeil \cite{37} proposed a hybrid system with immersive and non-immersive tools. The non-immersive tool, Sketchup, would be used for modeling while the immersive environment application would only be used to visualize and navigate the building in 3D. The changes on the model in Sketchup would translate in real time to the model in the VRE. The framework used was composed by a computer with a mouse and keyboard connected to a CAVE system. A CAVE consists in between three to six projectors directed to different walls off a room, in this case three, that merge together to form a virtual environment. This solution to CAD for early stages of the architecture process allows the user to visualize in 3D and in an immersive environment what he is sketching, improving his perception of the final product. Despite that, this technique has a lot of shortcomings by being constrained to conventional 2DUI applications for modeling, the constant transition between the non-immersive and the immersive environment can be tiresome, confusing and breaks the immersion and for every 2D CAD tool used there must be a software associated that can translate the CAD format to a format suitable for display in an immersive which can lead to loss of information.
Another CAAD tool developed on a CAVE framework was the one proposed by Hughes [38]. CAVECAD is a fully immersive architectural modeling tool that allows the user to produce low detailed buildings. The modeling process consists on creating basic shapes by selecting them on a 3D widget and arrange them in the desired shapes. The user can also manipulate those geometric shapes, parallelepipeds, cylinders and cones, by moving or rescaling any of the solids faces and thus create new shapes. There are snapping conditions to improve object positioning and the interaction with the environments was done with a 3D wand. User tests were conducted and although the authors considered their results favorable the users reported difficulty in finishing the test’s task on time, even those with a lot of experience with the tool, and the user sample has poor quality since it was small, only four people, and two of them had experience and included the CAVECAD programmer. Despite their shortcomings this solution allows for a quicker modeling paradigm than current CAD tools by using a 3D interface and by sacrificing precision.
Sasaki [39] introduced the concept of “facetons” as a modeling paradigm for a spatial interface. Facetons are infinite planes that are represented by a small widget that indicates their position and orientation and is responsible for the interaction with the user. When different planes intersect with one another they create finite surfaces from those intersections. By creating and intersecting many facetons it is possible to rapidly make complex forms. The spatial interface and immersive environment allows for the user to place the facetons with a high degree of precision and to be able to better understand the intersections of facetons required to create the desired shape. The user is also able to inspect his creation as if he was inside of it which is something that is normally not possible on early stages of the design process. Sasaki [39] presents a very good example of a CAAD tool for immersive modeling in the early stages of design allowing the user to rapidly develop models and interact with them as if they were in real scale using only very simple operations of drag and drop. This is true even for users who have little to no experience with CAAD tools or other modeling tools. However, the solution proposed shows one major flaw: the intersection of the facetons can become ambiguous to the user. When the number of facetons increases the number of possible intersections between planes increases and there is more than one solution for the final shape, which is a problem, and caused the major complaint by the users during the tests to be that, a lot of the times, the expected result and the real result did not match.
The following two approaches [40][41] have the same basic modeling paradigm, constrained modeling using voxels using a spatial interface in a VRE. Assuming that the size of the voxel is big enough, which is true for the papers in question, it is possible to create content in a spatial interface with high precision and quickly although having to sacrifice the possibility of highly detailed models. This loss of details is not a shortcoming of the tools because they were meant for 3D sketching and the early stages of architectural design, a stage of design where details are not relevant. Vries [40] introduced the concept of voxel modeling in VR as an architectural tool and also tried to diminish the problems associated with the voxels restrictions while Kuan [41] improved on this concept by introducing grouping of voxels in more complex structures that could then be edited and moved as one. Although both tools were conceptualized to be used on a VRE they both display a 2DUI with WIMP elements that does not take advantage of the VRE. The user tests were made using a keyboard and a mouse. Another
shortcoming of this papers, in regard to validating this tools as useful CAAD software, is the non-existence of professional architects amongst the user testers which could provide valuable feedback.

Figure 16 - CoBlocks' [41] interface which is based on DDDoolz's one [40]. It is visible a structure made entirely of voxels.

Leaving the scope of VREs there are two other important works that show the potential of voxel paradigms as modeling tools in the architectural design. The first one is Minecraft [10] which was mentioned before as a game that allowed the user to construct entire cities using only voxels. The second one is Block'hood [42] which was presented in a paper by Sanchez where he describes a game where the objective is to build architectural structures that are sustainable using only voxels that would serve as cells, modules with a specific function within the building. The reason for using voxels was their very simple structure and easiness to model with and to position [40][41][42].

Figure 17 - Screenshot from Block’hood [42]. It can be clearly seen that the modeled building is divided in modules that are constrained in a voxel grid.
This literature review shows that there is a need for better CAAD tools in the early stages of architectural design. Solutions as those from Pranovich [31] and Shtof [30] tried to use 2D interfaces/sketching to solve this issue but their solutions were often limited to a restrictive set of shapes and limited the creativity of the architect while Kallio [32] provided a system that, although easy to learn, is much more slow to use than pen and paper sketching and, because of the simplicity of the data stored, it does not allow for the addition of more complex editing tools. Oh [29] showed the most promising approach to architectural sketching, SESAME, using 2D drawing and extrusions as a modeling paradigm. Still the 2D interface lacks the expressiveness of spatial interfaces [2] [9]. The solutions that presented spatial interfaces improved over their 2D counterparts by allowing the user to explore the space as if they were inside of it [37] [38] [39] [40]. Most of them, excluding Okeil [37], provided means to model buildings using 3D cursors in an immersive space allowing the user to see a 3D representation of the sketch and introduce changes in real time in this representation. Sasaki [39] allowed the user to swiftly model buildings in real scale even if they were bigger than the user. This was one of the better tools presented with a very simple yet powerful interface in a VRE but this simplicity caused the interface to be ambiguous and making difficult to the user to predict correctly the result of their actions. Another conclusion reached was that voxels are a powerful paradigm for low detailed architectural modeling [40][41][10][42] that was already integrated in some spatial interfaces [40][41].What Kuan [41] and Vries [40] lack is proof that they would work on an architect’s studio and they would improve the set of CAAD tools that currently exist. Both tools were tested using architect students which lack the knowledge and experience to make an informed judgement on whether if this kind of spatial interface can be a suitable CAAD tool for professional studios. That is why the interface proposed on this thesis was tested using professional architects. Another improvement of this thesis over the solutions proposed by Kuan [41] and Vries [40] is the fact that it presents a 3DUl that tries to break from the WIMP mindset.
3. Hardware Setup

The spatial interface developed works in a fully immersive VR environment. It allows the user to walk in the application space as if it was a physical space and to interact with objects through a 3D interface. In this section it is described in detail the hardware setup used for creating such environment. Besides the HMD for visualization the Maquetteer uses a videogame controller for user input, a motion tracking system and two computers. The instructions of how to use the Setup can be found on Appendix D.

3.1 GearVR

The HMD is the device that allows the user to see the application as if it was inside of it, in other words, it is what creates the VRE. For Maquetteer the HMD used was the GearVR produced by Samsung. This device works in conjunction with the Samsung Galaxy S6 smartphone that runs the GearVR applications and also displays them.

![GearVR](image)

Figure 18 - GearVR

The GearVR has two optical lens, one for each eye, that are responsible for creating a stereoscopic image of what is being displayed in the smartphone display giving the illusion of depth. They allow for a field of view of 96 degrees (the human field of view is 110 degrees). This HMD also has a physical user interface that encompasses a Touch pad, a dedicated back button, focus adjustment wheel, volume keys and the phone eject button. Besides this features the GearVR also possesses three sensors: an accelerometer and a Gyroscope for detecting the movements of the user’s head and a proximity sensor that indicates to the device if someone is using it.

In regard to the Galaxy S6 it’s specifications are as follows: Android OS version 5.1.1. (Lollipop), a Quad-Core 1.5GHz CPU, 3GB of RAM and a display of 5.1 inches with a resolution of 1440 x 2560 which means that for each eye, because the screen had to be divided by two for stereoscopic vision,
the resulting resolution is ~1440 x 1280. Stereoscopic vision is a fundamental feature because it is what allows the user to have a 3D and depth perception inside the VRE.

![Image](image-url)

*Figure 19 – The application displayed in stereoscopic vision through the smartphone’s screen.*

### 3.2 Wii Remote

![Image](image-url)

*Figure 20 – Image from a WiiMote with all the button’s names. The rotation axis that is indicated is used when editing content which will be discussed later on.*

The controller chosen was the Wii remote controller. As it was mentioned above, it works as an input device for the user. It can connect wirelessly with any Bluetooth device and it has an accelerometer and an infrared emitter, which are not used in this application. Besides this there are six buttons on the controller, a direction control (cross) and a trigger. The user interacts with the application using these controls.
3.3 Optitrack

Optitrack is a motion capture system that functions by placing infrared cameras around the desired capture area and putting markers, wooden spheres covered with a special reflective material, on the tracked objects. The cameras used were of the Flex 3 model which have a speed of 100 frames-per-second and a resolution of 0.3 megapixels.

The markers are detected by the cameras and by joining the data of different cameras the position of the marker relative to the capture area can be determined. Each object has multiple markers arranged in a specific and unique way which allows the system to distinguish between different objects and assess their position and rotation. This information is then broadcasted and received by the Maquetteer application. The objects that are being tracked in this case are the GearVR and the WiiMote. Tracking the GearVR allows the user to move inside the application as in real life, in other words, if the user takes one step forward in the real world he will move the same distance in the VRE. Although the system also being able to detect the user’s head rotation, to make it “rotate” inside Maquetteer, in this instance we do not use this data replacing it with the information coming from the GearVR’s accelerometer which is more smooth and constant. The WiiMote is tracked so the user can have a representation of the controller inside the VRE that will be in the same position and have the same orientation as in the real space.
3.4 Computers

Two computers are needed in addition to the hardware described. One of them is connected to the motion capture system, processing the camera’s information and sending it to the GearVR. The other one receives the input information from the WiiMote via Bluetooth and sends it through UDP to Maquetteteer. The reason why a second computer is needed is because in one hand the Galaxy S6 smartphone does not have a Bluetooth receiver and in the other hand the computer responsible for the motion capture system cannot have a Bluetooth receiver attached because it is connected to all the infrared camera’s by USB ports and does not allow for more USB connections.

The motion capture system computer has a 3.5GHz processor (intel i5-4690) and 3GB RAM and the Bluetooth computer has similar specifications.
3.5 Communication

Because we want the user to have total freedom of movement the communication between optitrack, computers, GearVR and WiiMote is all done wirelessly. The motion capture system, that tracks both GearVR’s and WiiMote’s location and orientation, broadcasts via UDP this information which is received by the GearVR. The WiiMote input information is sent to the computer by Bluetooth and then sent by UDP to the GearVR, which does not have a Bluetooth receptor.

3.6 Collaborative Setup

The collaborative setup is not very different from the non-collaborative one. The purpose of the collaborative setup is to allow multiple users to be able to see the same VRE at the same time. This means that more GearVR’s, running Maquetteer, were needed. Each user has his own GearVR with a unique pattern of infrared trackers allowing the optitrack system to distinguish between users. By relaying this information to the GearVR’s via UDP broadcasting, every instance of the application knows the users’ positions.

Another important aspect of the collaboration is the WiiMote. To simplify, there is only one WiiMote and only one person can model at a time, the user who has the WiiMote. The GearVR’s receive the same inputs from the WiiMote using the process already described allowing them all to see the exact same VRE.
4. CAAD Spatial Interface

The interface developed is 3D and tailored to be used in a VRE allowing users to make early stage scale models using voxels. It was inspired by Minecraft, a videogame which emphasizes building constructions using only of voxels. The platform used was Unity3D a game engine focused in 3D games/environments. In this chapter each of its elements are discussed from user input to graphical elements.

4.1. The Voxel structure

The voxel is, in practical terms, a parallelepiped that is constrained to a grid in size and position. The voxel structure was implemented in a way that would allow us to optimize creation, access and rendering of the voxels. Each voxel unit side has 25 centimeters. This measurement is really important because it determines the precision and detail to which the models can be draw. The smaller the voxel the more detailed the model can be but on the other hand the less precise the drawings become and the heavier the processing is with more voxels being created for the same volume. If the voxel is too small the advantages of working on a constrained grid are lost. This final measurement was reached taking in to account the fact that there is no need for highly detailed maquettes because this is a 3D sketching tool for early stages of the development process and also the feedback of users, especially the architects.

The application space is divided in what we call chunks that encompass the volume equivalent to a cube with a dimension of eight by eight by eight voxels (this value can be changed). Each voxel belongs to a chunk and if the zone where a voxel has been created has not been assigned to a chunk a new one is created. This chunks can then be accessed through a class called World which contains a Dictionary structure that maps the chunks by their position in space and every access to the voxels is made through this class. This mapping is described in more detail in Annex E.
In regard to the renderization of the voxels it is worth mentioning that it cannot be done by rendering them one by one. This would take too much computational time, especially in a smartphone which does not have the same processing power as a computer, and during a normal modeling session, with a reasonable number of voxels, it would have such an impact on the application that would make the user unable to use it. To solve this problem, it was necessary to optimize the number of triangles (triangles are the basic unit of any rendered object) of the modeled content. Due to the fact that all the modeled content is composed by voxels, it is more simple to work with quads instead of triangles which are nothing more than two triangles that form a rectangle.

The solution was to, by knowing where and how many voxels were created, to create a mesh with the same shape as the voxels created but with a lower number of quads. This reduction was done using different criteria: First, all the quads that corresponded to sections of the voxels that were not visible to the user would not be part of the optimized mesh. Furthermore, if two or more voxels are side by side, the faces that are coplanar are merged in to the minimum number of rectangles/quads possible.

The calculation of this mesh is made by chunk so it does not become too heavy and to do it each chunk only has to check the voxels contained in it and all the ones immediately adjacent in neighbor chunks. What makes this process efficient is the fact that a chunk only has to do this operation if any of the voxels inside of it were changed or voxels immediately adjacent to it. A similar process is used in

![Figure 25 – Images depicting the optimization process [43]. On top it is shown the removal of the inner quads, which are not visible, from the left image to the right image. On the bottom, it is shown the process of merging quads in bigger ones to reduce their number.](image)

Figure 25 – Images depicting the optimization process [43]. On top it is shown the removal of the inner quads, which are not visible, from the left image to the right image. On the bottom, it is shown the process of merging quads in bigger ones to reduce their number.
the popular game Minecraft [40]. By using this optimization method, wish is called meshing, the number of voxels that can be rendered without compromising the program’s frame rate increased significantly.

4.2. Modeling Operations

Next we describe in detail the actions that can be made in this application. All of them can be accessed using only the buttons on the WiiMote.

4.2.1 Create and Erase Content

Creating and erasing content are very simple and intuitive tasks and are associated respectively to the Create and the Delete Mode. In the Create mode the user generates voxels in space by pressing button A and/or B while in the Delete Mode, by pressing the same buttons, the user creates cubes that are called Delete Cubes and when both the A and B buttons are released the program will check if there are voxels intersecting with the Delete Cubes and it will erase them and the Delete Cubes. The coordinates in space where this changes will occur are determined by the WiiMote pointer which is a point slightly above the tip of the 3D virtual representation of it. This point is not constrained to the grid and because of that, to know to which point on the grid it corresponds, the following transformation is done:

\[
p_{\text{g}} = \text{Integer} \left( \frac{p_{\text{s}}}{g_{\text{s}}} \right) \times g_{\text{s}}
\]  

(1)

The point in the space \(p_{\text{s}}\) is snapped to the hypothetical grid \(p_{\text{g}}\). The grid’s size \(g_{\text{s}}\) is the same has the size of a side of the voxel.

![Figure 26 – The right image is the creation of content and the left image is the deletion of content. All content within the red gridded cube will be erased.](image)

Creating content and creating Delete Cubes (Erasing Content) can be done in three different ways:
• **Freeform:** If the A button is pressed a voxel/cube will appear in the pointer position snapped to the grid. If the button is pressed and dragged it will create a line of voxels/cubes that follow the trajectory of the pointer.

• **Box:** If the B button is pressed and then dragged a box (parallelepiped) of voxels will be created. Its diagonal is defined by the initial position of the pointer snapped to the grid, when the button was pressed, and the current position. The action is completed when the B button is released. While the B button is not released, if the tip of the box does not match the pointer’s position the program generates voxels or erases them until they match, while still maintaining the parallelepiped shape of the box. This process is iterative by only expanding or shrinking the box along a coordinate at a time and by one voxel’s length for iteration. This allows the update of the box to be made in multiple updates of the application improving the framerate. The pseudo code can be found on Appendix F.

• **Box with pattern:** This functionality is a combination of the box and freeform functionalities, it involves creating a drawing with the Freeform functionality and, while still holding the A button, hold the B button. The result is a “cube” but instead of being formed by voxels it is formed by replicas of the drawing created with Freeform. In technical terms what happens is that the program determines the dimensions of the drawing and uses the box functionality replacing the voxel, as the unit, by the drawing.

![Figure 27 – Illustration of the three ways to create content. Freeform (first image), box (second image) and box with pattern (third image). The delete content functionality follows the same logic.](image)

### 4.2.2 Other Operations

In addition to creating and erasing voxels there are other transformations that the user can do to a group of voxels. The transformations are as follows: Move, Rotate and Replicate. The first two involve creating an auxiliary grid or World class and apply transformations to it. Furthermore, all of them are dependent of the following process:

The application must be on the Select mode. In the select mode the user creates cubes to indicate which region of space will be affected by the transformations. This is done by using the same techniques described in the last section, Freeform, Box and Box with Pattern. In the moment the user releases the A and/or B buttons the applications immediately changes state in one of three transformations modes that can be switched by the user. All of this modes will operate with the voxels which intersect with the region created in the Select Mode.
The Transformation modes are as follows:

- **Move:** By pressing the button A and moving the WiiMote the user can move the selection. The application calculates the distance travelled by the WiiMote between updates and applies the same displacement to the selection.

- **Rotate:** The rotate function as three phases. First with the A button the user selects the center of rotation. After that the user has to align the WiiMote with one of the three Cartesian axis which will be the rotating axis. Finally, still with the WiiMote aligned, rotating it will make the selected region rotate to. Small rotations of the WiiMote will translate in 90º degree rotations of the region.

- **Replicate:** Pressing the A button will create a copy of the original selection.

4.3. **Visualizing Content in different Scales**

A method for visualizing content in different scales was also implemented. This tool allows the user to see its sketch in the following scales: 1:50, 1:20, 1:10 and in real scale. To access this functionality, the application must be on the respective mode (Scaling Mode).

**4.3.1 The Dummy**

Immediately after entering the Scaling Mode a Dummy, a representation of the human body made only with parallelepipeds, will appear. This Dummy helps addressing a problem that the application has: The voxel has no correspondence to real life measurements *a priori*. What this means is that the user can choose to make, for example, with three voxels of the same dimension, a chair or a tower which means completely different correspondences between application and real world measurements. The Dummy gives the user control over that relation by allowing him to change its size indicating to the program what
is the size relation between a medium height person (1.75 meters) and the voxels. This process is somewhat redundant when we introduce to the application a contextual environment to the user model on. In this case the "real" dimensions of the voxel are constrained to the measurements and scale of the contextual environment.

![Figure 29 – Dummy snapped to a voxel and with different sizes.](image)

### 4.3.2 Changing Scales and Navigating on Real Scale Mode

![Figure 30 - Content visualized at different sizes. 1:5, 1:10, 1:20 and 1:50](image)

After adjusting the Dummy size, the user has to position the Dummy on a voxel which will make it change color from red to green signaling that the user can begin visualizing the different scales by clicking the A button. This position is important because when the user enters in real scale mode this position will mark the place where the user will be positioned on the maquette. After this step the user can alternate between the different scales by clicking on the Left and Right arrows. The only exception is the Real scale mode where the user has to confirm that it wants to access that mode by clicking the A button. This choice is due to the fact that the change between the 1:1 scale and other scales is
particularly abrupt. When the user chooses the real scale mode the scenery where the user is placed in the application changes for an open space with a day/night cycle. Having this extra step to confirm the 1:1 scale prevents the user from changing sceneries too many times too fast.

![Figure 31 – Content visualized in Real Scale (1:1) mode. The texture of the voxels was chosen, despite not being esthetically appeasing, to be able to easily distinguish shapes at distance and differences of distances.](image)

When the 1:1 mode is active the modeled area becomes much larger than the physical space where the user is. Because of this the user can press the up and down arrows from the WiiMote to navigate on the VRE. What happens is that instead of the user walking in a direction, all the elements of the VRE move to the opposite direction of the intended one creating the sensation that the user is moving. If the user presses the up button he will navigate forward relatively to the position of the WiiMote and if he presses the down button he will navigate backwards. As a way of making this process more precise there is a maximum angle between the WiiMote and an axis, x, y or z, for which the user moves in that direction.
4.4. State Operations

The operations mentioned in this section were implemented as ways of retrieving past states of the application.

- **Undo/Redo**: The undo and redo functions are used through the minus and plus buttons of the WiiMote respectively. Undo allows the user to nullify the last action performed while Redo reverts the Undo operation. To be able to do these operations the application stores, for every action performed (creating, erasing, moving, etc.), the information of every voxel that was created and erased in a structure.

- **Clear**: The clear function accesses the world class that has a function that returns all the voxel objects which are erased.

- **Save**: The save function saves the position of all the voxels created at the time the user chooses to use it. That information is saved in permanent memory in a .txt file. Due to the fact that the voxels have no orientation and always have the same scale, because of their constraints, the only information that is required to save is their position. The application automatically attributes a name to the save file based on the date and time of day and appends this name to file that contains all save files names. The save function is accessed through the button one on the WiiMote.

- **Load**: This functionality allows the user to load one of the save files. The program accesses the file with all the save files names and displays them to the user. The user can then choose one and the application will automatically execute the Clear function and create voxels with the positions described in the respective save file. The user can access this functionality through the button two from the WiiMote.

The operation selection is managed by state machine which is described in the image below. All the buttons mentioned on it belong to the WiiMote.
4.5. Graphical Elements

A fundamental part of this application are the graphical elements. They communicate to the user how to use the application. In this section each of this graphical elements will be described one by one, with the exception of the voxel that was already described.

4.5.1. Wii Remote

When the WiiMote is mentioned as a UI element it is not the actual WiiMote that is being mentioned but the 3D virtual representation of the same inside the VRE. It is very similar to the real WiiMote although the level of detail is relatively low because the more detailed models decrease performance. Due to the Optitrack cameras, this representation of the WiiMote has the same position and orientation in the virtual world that its counterpart in the real world.
Every Button of the WiiMote has a Text texture associated with it that indicates what the button does. The text changes color when the correspondent button is pressed from purple to green and the button itself also emits a green light.

As it was mentioned before, slightly above the top tip of the WiiMote there is a point that serves as a pointer. Whenever it is relevant there is an object that marks this position. This object’s shape and texture varies according to the state of the program indicating the current mode of operation. When the object is a cube, representative of a voxel, it is not centered on the pointer position but snapped to the grid on the nearest point from it. This objects on the pointer helps increasing precision, by letting the user know exactly where he is creating, deleting or selecting content, and to make state of the application more visible. In addition to this object there is also a 3D axis (x, y, z), which is centered on the pointer’s position, that is represented by three lines colored red, green and blue that are big enough to traverse the VRE from one side to the other. The purpose of this lines is to improve distance measurements, for example, ascertaining if two constructions are at the same height.
4.5.2. Panels

The panels are positioned roughly in the same place as the walls from the real environment. They show a picture from the WiiMote from the front and back. As in the virtual WiiMote each button has an associated text that describes, in more detail than in the WiiMote, the buttons’ function for a determinate state. Also, similarly to the text on the WiiMote, the text changes color if the associated button has been pressed.
4.5.3. Environments

The Environment is the virtual space where the user is inserted. It is an important aspect of the application because it influences the user state of mind and it can convey information about the application and/or the real world. Three different solutions were developed:

- **Laboratory**: The laboratory scenery is an exact replica of the laboratory João Lourenço Fernandes, situated on the Taguspark’s campus, in which the solution was implemented. Each one of the most relevant objects in the room, walls, ceiling, floor, desks and so on were measured and attributed the same length in Unity. Because Unity works with dimensionless values it was considered that in this case one unit on Unity3D would be equivalent to one meter. This kind of environment was chosen to try to make the users more at ease, creating the illusion that they were seeing the real room, which would in turn make them walk more with the HMD on allowing them to take the most advantage of the spatial interface. However, this solution proved not to be ideal as it will be discussed in the user tests section.

![Figure 37 - Image of the Laboratory scenery.](image)

- **White Laboratory**: The White Laboratory is the same as the Laboratory with the exception that all the realistic textures were substituted by a white plain texture. This was meant to reduce distractions, created by the furniture, and highlight the more important aspects of the UI.
- **Open Space**: The Open Space was a less reality based approach to this problem. It offers an open space and takes advantage of one of VR’s strong points: to be able to transport the user to any environment in an immersive way. This scenery does not have any of the elements of the room except a white contour in the ground to indicate the work area where the user can walk freely.

Each of the environments have one thing in common: they are all surrounded by invisible walls that become visible, displaying stop signs, when the user approaches one of them. This is meant to indicate to the user the limits of the Opitrack system tracking area.
Besides from the environments described above there is another one which appears when the user enters the real scale mode. This environment is an open field with a day and night cycle and a grass field as ground, which is set up underneath the lowest voxel. The texture of the voxels in this context changes to a brick because otherwise it becomes difficult to evaluate distances between voxels.

4.5.4. Landscape Context

An important part of the design process in Architecture is the context where the building will be inserted in, in other words, the landscape surrounding it. Because of this in some versions of the application there were scaled versions of landscapes inserted into the VRE. It was not implemented any functionality to allow the insertion and positioning of landscapes inside the VRE and because of that the scaled environments had to be introduced in Unity3D editor before building the application. With this in mind it was still possible to understand how this kind of functionality would influence the application. Although there was not any kind of direct interaction between the context model and the user, editing or positioning of the model itself, and that the shape of this model is not formed by voxels, the user was still able to make use of this context creating voxels on top of it. One of the consequences of working with the scaled context is that the user no longer defines the scale of what he is modeling because that measure is constrained by the landscape scale. For example, if the landscape scale is 1:100 then each side of the voxel, which in the VRE measures 2.5cm, corresponds to 2.5 meters on 1:1 scale. When visualizing content at different scales the landscape also changes sizes.
4.7. Different Orientations and Layers

One of the problems with this system is that you can only create boxes in the world axis directions. You can model in different orientations creating voxels one by one but that can be cumbersome or outright impossible depending on the size of what is being modeled. This become even more apparent when scaled landscapes were introduced in the VRE and the design was constrained to the streets and other elements orientations. On the other hand, letting the user choose the orientation of the voxels while modeling would make the system less restrained and more complex undermining the advantages of modeling with voxels and the purpose of this tool.

The solution was to let the user define beforehand the orientation of the grid. A grid is how the constraints of voxels will be described. In terms of the implementation each of the grids is a Game Object called Voxel Grid with the grid’s orientation and all the scripts necessary to create and edit content associated to it plus the meshing scripts. All of this elements take the empty Voxel Grid’s orientation as a parameter to determine the orientation of the voxels. Using widgets and the WiiMote’s position and buttons it is possible to model in different orientations. Once an orientation is chosen it will remain the same, while content is being modeled, until it is changed again by the user.

When the user presses the home button of the WiiMote a widget is shown centered around the WiiMote’s position at that time. The widget is composed by a sphere on its center connected by a line to a sphere on the top of the WiiMote. Besides that, there are arrows directed away from the center that represent all the orientations/Voxel Grids previously created. If the button home is pressed again the voxels orientation will change to the one of the line that connects the two spheres of the widget.

Solving the orientation problem introduced another functionality: Layers. When a certain orientation is chosen the user can no longer create, edit or erase content in different orientations. To be able to do it again the user must change to one of those orientations again. Content modeled with different orientations can be seen as different layers. The user can only interact with one of them at a
time but can switch between them following the widget previously described. Furthermore, instead of switching to the same layer, the user can also create a new layer with a preexisting orientation, making it possible to create more than one layer with the same direction. When the user presses the home button to lock an orientation, if the WiiMote is intersecting with a widget’s arrow then the corresponding layer will become active, that means the content on it will become editable. But if it is not intersecting with it then a new layer will be created. The WiiMote can also be place on top of an arrow and by pressing the A button the corresponding layer can be hidden, making all the content associated with that layer invisible, or shown and by pressing the B button that layer can be erased.

![Image showing the different orientation's gizmo. It can be seen content generated with different orientations and the content associated with the layer/arrow that the WiiMote pointer is hovering is highlighted in a different color.](image)

This Layer functionality is very powerful because it allows the creation of different solutions for the same project that can be browsed rapidly without the need for saving and or loading. The user can also choose to separate different elements of a sketch on different layers and manipulate one of them without altering the others.

Besides the features already mentioned from this functionality it is relevant to mention that each arrow has a different color, randomly generated. And when the WiiMote correctly intersects with an arrow the arrow changes color and the layer's content is highlighted. These elements improve the transition and distinction between layers.

### 4.8. Collaborative Design

The last aspect addressed in this thesis was the collaborative design making it possible for more than one user to be in the same VRE and work together. In regard to the interface the only change was the
introduction of avatars that would indicate the position of all other users and the direction that their head was pointed to.

Figure 43 - Three users modeling together in a collaborative environment.
5. User Tests

The application undergone different stages of user testing. In this section we will present those different stages, talk about what was evaluated, how it was evaluated and what were the results.

5.1 Tests with Laypeople

In the first phase of testing the users were all people who had almost no knowledge of Architecture and the architectural design process. They were 18 in total with ages from 20 to 29 years old and all of them were Computer Engineering students who had at least one course on Person-Machine interfaces. In addition to this, they have watched 3D movies or IMAX but have not wear HMDs.

The test itself was meant to compare the prototype with a commercially used CAAD software, SketchUp. This software was chosen because it is very widespread and popular and on the other hand is more suitable for 3D sketching than its peers. The test had two different tasks, first the user would model some simple architectural elements to get used to the system. The elements chosen were a pillar, a beam, a slab, a wall with a window and a set of stairs which are elements that can be seen in any building. After that the task was to model some famous buildings. Those buildings were, in increasing order of modeling difficulty: Empire State Building, Farnsworth house and the Falling Water house. For each example, there was a picture (in Sketchup’s case) or a 3D model in the VRE (in proposed system’s case) of the intended final product. In spite of that, it was made clear that there was no need for much precision and that an approximate copy would suffice. This tasks were timed and repeated in both systems, Maquetteer and SketchUp, and were preceded by an explanation of their functionalities and an adjustment period of 15 minutes. The order in which the applications were used alternated from user to user so it would not influence the results. After the test was completed the user answered to a questionnaire, which can be found on Appendix A, about the usability of both systems and in addition to this they were asked to make a heuristic report about the interface. The questionnaire is very straightforward: The first part is a consent form for using images and footage recorded during the testing session and some profile questions to ascertain the user’s field of study and experience using Virtual Reality devices and similar technologies. The second part focus is about the Maquetteer app and the questions were about, in this order, Virtual Environment, WiiMote, modeling and overall appreciation of the application. On the last part, there was an evaluation of the SketchUp software which followed the topics GUI, modeling and overall appreciation.
The results of this user tests were not only useful for validating the modeling paradigm and the application’s interface but also provided important empirical feedback that helped us improve the application before the second testing phase. The most relevant change was the setting of the VRE from the realistic setting to the open space. This was done because the realistic approach created too much noise and had too many elements that were not relevant for the interface and diverted attention from those elements which were indeed relevant.

5.2 Tests with Professionals

Five internationally renowned architects were invited to test the system in the second phase. The purpose and methodology were different from the previous evaluation. The objective, in this case, was not to test and improve the interface but to understand if this was a tool that architects would use on the design process, given the chance. Because of this, the professionals were not required to model with SketchUp.

The testing session would begin by an explanation of the application’s hardware setup and the application’s functionalities. After that the user would model freely in space so it could become accustomed to it and also understand better its potential. When the architect was comfortable with the system a 3D scale model, from a real location, would be introduced on the VRE. The objective was for
the user to try to design a building in that location using the application and, by doing that, understand how this tool could be used in an architecture studio during the design process.

Once the session was over, the user would answer a questionnaire, shown on Appendix B, which began with a consent form and continued with profiling questions to ascertain the user’s familiarity with VR and similar technologies and their experience as professional architects. The last part of the questionnaire was about the Maquetteer application, how easy was to model with it and how did it contribute for their design process. After all the user tests were conducted a semi structured interview was conducted with all the professional architects so a more informal discussion about the application could happen. The questions that were used to steer this conversation can be seen on the Appendix C. They focused first on the user experience and then on the advantages of the system for the design process and has a creative tool. Even though there were no statistical results withdrawn from the interview important feedback was received and a more empirical evaluation of the application.

5.3 Collaborative Tests

The collaborative tests were a way to understand how the application would work in a collaborative context. Two teams of three people participated: one of which was composed by three professional architects and the other one by a teacher and two architecture students. The task was for each team to model in collaboration a building, switching the WiiMote between them, while all participants from that team were in the VRE. Before this task there was an introduction to the application where the controls were explained and a questionnaire and profile form was filled by the participants. In the end of each testing session there was a semi structured interview with the users to understand what were their difficulties on working together and if they had saw an improvement over other forms of design.

![Figure 46 – Building Modeled during the collaborative testing sessions.](image)
5.4 Results and Discussion

From the testing sessions, described in the earlier sections from this chapter, a lot of relevant feedback was received. Focusing on the statistical analysis of the questionnaires and test results and on the semi structured interviews the more relevant observations and results are discussed here. It is also worth mentioning that some of the feedback received in earlier phases of testing was used to improve the system for latter phases. The statistical analysis of the questionnaires was done, almost exclusively, using the Wilcoxon Signed Ranks Test. This tests allows to compare sets of data which do not have to be normalized.

5.4.1 Tests with Laypeople

The Laypeople tests addressed two key points: how well would it perform in comparison to similar software which already had commercial success and determining what parts of the interface needed most to be improved. The commercial software used was SketchUp produces voxel like models, although not as constrained as our solution, and also aims to simplify modeling exchanging precision for speed and a user friendly interface. The results of this comparison were favorable, the statistical analysis of the questionnaires indicates that our system was easier to use than SketchUp ($Z = -2.0, p = 0.046$) although in terms of learning curve they were very similar. The navigation on the virtual environment was also better ($Z = -2.176, p = 0.029$). One aspect where there was no statistical relevant difference was on the perception of the location of the cursor. Table 1 presents the results to the most relevant questions presented to the users about the core aspects of the interfaces which show a slight advantage to Maquetteer. Other positive aspect was the comparison between the examples and the scale-models modeled by the users. In almost every case the users agreed that the results were very similar in the two applications being the exceptions task 8 (“Falling Water House”) where the system proposed on this thesis was better and that in task 6 (“Farnsworth House”) SketchUp was better but not by a significant margin.

<table>
<thead>
<tr>
<th>How easy was it to ...</th>
<th>Maquetteer</th>
<th>SketchUp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use the system...</td>
<td>5(1)</td>
<td>4(2)</td>
</tr>
<tr>
<td>Select objects using...</td>
<td>5(2)</td>
<td>4(3)</td>
</tr>
<tr>
<td>Create objects using...</td>
<td>5(1)</td>
<td>5(1)</td>
</tr>
<tr>
<td>Erase objects using...</td>
<td>5(2)</td>
<td>5(3)</td>
</tr>
</tbody>
</table>
Table 1 - Participants opinions regarding the core aspects of the applications. Median (Inter-quartile Range) - indicates statistical significance.

<table>
<thead>
<tr>
<th></th>
<th>5(1)</th>
<th>4(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceive the system’s state using...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Navigate on the environment using...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When the task times were analyzed, the conclusion was that Maquetteer add consistently better times such as on the “Stairs” (Z=-3.174, p < 0.01). The ones who were significantly quicker than on SketchUp were the two most complex ones from each phase: tasks 1 (“Stairs”) and 8 (“Falling Water House”). The only case where SketchUp outperformed the proposed system in execution times was on task 7 (“Empire State Building”) although the difference was not very significant. This may have happened due to the fact that the constrained measures with which the users had to work with did not allow them to keep true to the relation between the proportion of the different elements of the building. For example, the buildings antenna is very thin and was usually the last part modeled by the users and when they reach that phase they would find that it was too big in relation to the rest of the building. Which led to them trying to fix the proportions between the antenna and the rest of the building. It is important to restate that this was only a problem on task 7. That being said, this need for adjustments due to miscalculated measurements may have been the cause for the widespread values of execution times that can be seen in the image bellow.

Another interesting aspect to mention was the fact that, although most of the users moved around the VRE to see what they were modeling and the examples from different perspectives, some of them were not able to do this remaining static on the VRE. There was even one instance where the user remained on the same place and modeled only a 2D perspective of the task. This resembles a lot the posture associated with WIMP interfaces.
Figure 47 – Representation of the average value and standard deviation of the tasks’ execution time (in minutes:seconds) for both systems. Task: 1 – set of stairs; 2 – pillar; 3 – beam; 4 – slab; 5 – wall with window; 6 – Farnsworth House; 7 – Empire State Building; 8 – Falling Water House.

Regarding the interface’s quality analysis, the main source of feedback was the heuristic reports that the users had to write. All users had written a report of sorts at least once before. The fails of the system pointed by the users were compiled to understand where there were the more serious problem and try to solve them. Some problems were not fixed because they had no easy solution. One example was the complaint that was hard to interact with the buttons of the WiiMote even with the digital representation. Another problem was the lack of proprioception, the ability to see one’s body, which is not a trivial matter. Some of the other faults that come up on the heuristics evaluation may have been originated by the lack of proprioception such as the sensation of floating, not being at the correct distance from the ground and difficulty in perceiving distances and proportions in general [44]. Other problems were addressed, such as the complaint about having too much information on the WiiMote’s virtual representation making it difficult to read. Instead of removing or changing the information on the WiiMote the problem was fixed by changing the VRE to something more simple and cleaner. What was happening was that the first VRE had too much unnecessary elements, such as tables and computers which were modeled to simulate the real environment, which added too much visual noise to the background and interfering with the more useful interface elements, like the WiiMote. This decision was also supported by the fact that the realistic setting was not having the intended effect of providing a familiar setting and was increasing the sensation of disproportionate measurements (which was also mentioned on the heuristic reports). Other flaws that were fixed was the cursor having the same color that the generated voxels and the fact that sometimes the cursor was shifted by one voxel from the position where the user was modeling. A positive conclusion withdrawn from the reports was that the system’s interface had no fatal problems and very few serious problems. The changes mentioned were made to this system before the tests with professional and the collaborative tests.
5.4.2. Tests with Professionals

In the second experience the subjects were, as mentioned before, professional architects. One advantage that was immediately identified on the interview by them was the fact that they were able to model completely immersed on the virtual space instead of looking at a screen. It helped them visualize things and have a better idea of the relation between the different elements. It also allowed them to model things in 1:1 scale with ease which is something that conventional methods do not allow. All of this was supported by the fact that, during the free modeling phase, the architects modeled around their bodies and many times at real scale. One problem they pointed out however, was the fact that they could not see their body which would have been useful for having a better notion of sizes and proportions by using it as a reference.

In regard to the system itself the general opinion was that it run really smoothly and that the response times were very good. The overall interface was easy to use and was particularly helpful having the virtual representation of the WiiMote with the text indicating the functionality of each button. The high level of satisfaction with the system may have been in part due to the fact that, at this point, the interface was already improved since the first round of tests using the feedback gotten from them.

There were two main complaints about the system. The first one was about the scale of the voxel, when the scale model of the environment was introduced, suddenly the architect was restrained to model at the same scale as it and was not able to change scales. This need was made even more obvious by the fact that, when using the scaling functionality was used, the user was restrained to visualization and navigation. They expected to be able to model at this scales and in fact “requested” that the possibility of modeling at this different scales was added. Despite this, they were very impressed with the visualization at different scales, especially at 1:1 scale, and pointed out that this feature was a very important aspect of the system because of the way it simulated a sense of scale and that it could be very useful in architectural education because students usually lack this and it is something which is not easy to convey.

The other complaint was that the restriction of the grid in terms of orientation was too severe. They approved the use of voxel as a modeling approach but noted that being able to change the orientation of the grid and size of it would be beneficial. The objective was not to work with a lot of different orientations or sizes but choose one that would suit better the topology of the site’s scale model. The problem of different orientations was solved and almost by chance another complaint, though a minor one, was also solved which was the urge to have different layers and different versions of the same project and the ability to switch between them.

From the two testing sessions conducted the conclusions were that the system is easy to use in terms of paradigm and interface to the point where it can compete with commercial software to a degree. Despite having almost no experience with this kind of concepts, users rapidly understood how to interact with the virtual reality and spatial interface. Regarding the possibility of this system being used in an architecture’s studio it showed a lot of potential with architects agreeing that they were willing to use it during the design process if the mentioned limitations were overcome.
5.4.3. Collaborative Tests

The collaborative tests were not as extensive due to the fact that it is not the main focus of this thesis. Despite this, the conclusions were positive and noteworthy. The users considered that the avatars were sufficient representation of the other users and that they were able to pass the WiiMote to one another, although with some degree of difficulty, and communicate efficiently. They found the interface intuitive and satisfactory, attributing most problems to the lack of experience and recognizing the potential for this new setup of Maquetteer. Overall the feedback was positive and indicated that there is potential enough to pursue this line of investigation and to continue to improve the application. The users also express this feeling and emphasized the remote collaboration as a valuable feature.
6. Conclusions and Future Work

6.1 Conclusions

The goal of this thesis was to combine voxel modeling paradigms, popularized in games such as Minecraft, and a spatial interface embed on a VRE to create a CAAD tool for the early stages of architectural design. Due to this, the goal was for it to be easy to learn, to use and to be able to generate content quickly, all qualities associated with traditional sketching. Not only that, but by making use of VRE based spatial interfaces, the goal was to improve over commercial software which generally relies on WIMP interfaces which are not as intuitive and restrain spatial thinking. But most important than all, we wanted to demonstrate that this approach can be useful to an architect's studio.

After the work done in this thesis it is clear that VR can improve the architectural design process. The feedback received shows that not only it provides more intuitive interfaces but also allows for the user to explore what is being designed in a more concrete way. This happens due to the immersion that it is felt and the ability to model all around our body. It remains unclear if these systems are suited for high precision work but for activities such as 3D sketching, where the user is not required to be precise on its movements, it is.

The system proposed was a success in many aspects and the voxel paradigm proved to be well suited for this kind of tool making it easy to model with. Because the focus was on sketching and not on detailed models the constraints of voxels were not seen as a problem. The only complaint regarding this was not being able to work with two or three different orientations chosen by the user instead of the default one.

User tests with laypeople showed that the system is easy to learn and works well as a modeling tool and most users felt comfortable in the VRE despite not having little to no experience with this kind of technologies. When looking at the production of simple models of buildings with low details, which is the target of this work, the system can compete in terms of learning curve and modeling speed with commercial software while having all the advantages of a spatial interface. Laypeople’s tests were also valuable due to the feedback received on the system’s interface so it could be improved to a more polished version, which is fundamental for this work, since its aim is usability. This feedback also led to the conclusion that our interface had no fatal flaw.

Regarding real world application, professional architects found the concept interesting and were eager to explore more of its potential. According to them, the system could be used in architect’s studios provided that some alterations were made. Not only this but it could also have additional benefits in other areas such as learning and become a powerful tool in architecture courses.

The VRE and the spatial interface were not just gimmicks but a key point for the success of the system. The users who took more advantage of this fact by walking around the VRE and changing their point of view of the content they were modeling had the best results. Professional architects, when given
the chance, would model around their body and try to make real size constructions instead of scaled ones. Being able to be on the same environment as the content that is being modeled not only made some tasks much more intuitive, such as positioning the cursor and changing the perspective on the modeled content, but it helped, as confirmed by professionals, to understand how the envisioned building or element would look like in real scale on the real world.

Despite the positive feedback there is a lot of room for improvement. The professionals do not consider that the system is yet ready for being used in an architect’s studio and on the other hand there are still some optimization issues when the number of voxels increases a lot, although this is only visible on extreme cases.

6.2 Future Work

As mentioned earlier, there is a lot of room for improvement. Two issues were brought up by professional architects and that were recognized as flaws of the system: being able to change the orientation of the grid and being able to switch back and forward between two or three different orientation and to be able to model at different scales and sizes. Some modifications already were made to the system, and were already described on this Thesis, to solve the first issue but they were not properly validated by user testing. In relation to the second issue, it would be interesting to understand better what are the benefits gained in modeling all around the body in real scale. Another aspect that requires more working and testing is the collaborative work and also, in a later stage, remote collaborative work.

Another direction that could be pursued is the integration of avatars, proprioception, in the system, and understand how that could improve the overall experience. It has been established that we use our own body to infer distances and dimensions of the environment around us. The collaborative experience could also be improved by this by making it easier to demonstrate intent and to interpret the actions of others without relying only on verbal interaction. Analyzing the walking patterns, gestures and posture of the users could also give valuable information on how people adapt to VRE and how to improve this kind of applications. And there is much more that can be explored regarding the interaction of the user with the VRE, for example, how it benefits from the ability of modeling in real scale and how can the body be a tool to improve that process.

Leaving the scope of spatial interfaces, there is much to improve in regard of the physical setup. It would be interesting to integrate the system in a more affordable setup that could be sold commercially. Another potential line of work would be to record the movement from the WiiMote and GearVR captured with the mocap cameras and analyze that data.

More important than improving the system however, would be to understand how it could benefit architecture and other similar fields. In the future there will be an attempt to integrate Maquetteer in the classroom on an architecture course and see if can improve the students learning process. But the main goal of this project is to be integrated as an important tool of the design process on architect’s studios.
replacing CAD software and/or traditional scale-modeling techniques on early stages of the design process by improving it.
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[36] https://www.youtube.com/watch?v=GSbkn6mClXE

Appendix A: Laypeoples’ Questionnaire

Consentimento informado

Caro participante,

Estamos a conduzir um estudo sobre criação de modelos 3D simples em ambiente de realidade virtual (RV) imersivo, utilizando uma aplicação desenvolvida especificamente para o efeito.

Para tal, necessitamos da sua contribuição!

A experiência deverá demorar aproximadamente 40 minutos, durante a qual terá a oportunidade de realizar várias experiências importantes num ambiente RV imersivo. No final de cada experiência será pedido que responda a um questionário sobre a mesma.

As sessões serão gravadas em vídeo e áudio. Todos os dados recolhidos serão mantidos em sigilo e serão analisados, exclusivamente, pelos investigadores deste projecto. Os dados poderão também ser utilizados para apresentação ou exibição de resultados em publicações científicas, conferências ou eventos semelhantes. Somente após a sua autorização específica para o fazer, poderão os dados recolhidos ser utilizados para divulgação on-line (por exemplo, no youtube, vimeo, etc.).

A sua participação é voluntária e poderá sempre desistir a qualquer momento sem qualquer penalização ou consequência.

Para participar nesta experiência, pedimos-lhe que preencha o consentimento presente neste questionário, concordando com as frases escritas abaixo.

Obrigado pela sua colaboração!

1. Li e compreendi o significado deste estudo. Tive a oportunidade de colocar questões, caso necessário, e recolher as respectivas respostas.
   • “Concordo”

2. Compreendo que a participação neste estudo é voluntária e que posso desistir a qualquer momento, sem apresentar qualquer explicação. Caso tal aconteça, não serei alvo de qualquer penalização e os dados relativos à minha experiência serão removidos e destruídos.
   • “Concordo”

3. Autorizo o uso das gravações audio e vídeo recolhidas durante a sessão.
   • “Concordo”

4. Autorizo o processamento dos dados audiovisuais no âmbito deste projecto para fins de análise, investigação e disseminação de resultados em publicações científicas ou conferências na área do projecto, pelos investigadores deste projecto.
   • “Concordo”
5. Compreendi que os dados recolhidos neste estudo serão utilizados como mencionado anteriormente.
   • “Concordo”

6. De acordo com o descrito acima, autorizo a minha participação neste estudo e aceito as suas condições.
   • “Concordo”

7. Disseminação on-line
   • “Autorizo a disseminação dos dados audiovisuais recolhidos durante a sessão em plataformas on-line (por exemplo: youtube, vimeo, etc.)”

8. Número do teste
   • Inserir Número

**Perfil do Utilizador**

9. Idade
   • Inserir Número

10. Sexo
    • “Masculino” / “Feminino”

11. Qual é a sua mão dominante?
    • “Esquerda” / “Direita”

12. Habilitações
    • “Ensino Secundário” / “Licenciatura” / “Mestrado” / “Doutoramento” / “Pós-Graduação”

13. Área de formação
    • “Arquitectura” / “Design” / “Engenharia” / “Other:”

14. Com que frequência Joga videojogos?
    • “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

15. Com que frequência Utiliza sistemas de modelação 3D digital (CAD)?
    • “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

16. Com que frequência Utiliza o comando Wii
    • “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

17. Com que frequência Assiste a cinema 3D
    • “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

18. Com que frequência Utiliza sistemas de Realidade Virtual Imersivos?
    • “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

19. Costuma sentir algum dos efeitos descritos abaixo no cinema 3D?
“Nunca senti desconforto” / “Enjoo” / “Vertigens” / “Dor de cabeça” / “Dores oculares” / “N/A” / “Other:"

Maqueteer App

1. Número do teste
   - Inserir Número

Head-Mounted Display

2. Sentiu algum dos efeitos descritos abaixo durante a utilização do sistema de realidade virtual?
   - “Nunca senti desconforto” / “Enjoo” / “Vertigens” / “Dor de cabeça” / “Dores oculares” / “N/A” / “Other:"

3. De um modo geral, considero que foi fácil a Navegação entre modos.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

4. De um modo geral, considero que foi fácil a Identificação do modo corrente.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

5. De um modo geral, considero que foi fácil a Leitura do nome dos modos.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

6. De um modo geral, considero que foi fácil a Execução das tarefas.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

7. Considero que foram úteis as informações projetadas na parede sobre as funções dos botões do comando.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

Comando

8. Sobre o comando, considero que é confortável de se manusear.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

9. Sobre o comando, considero que é fácil localizar os botões de controlo.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

10. A escolha do botão do comando estava adequada à função:
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

11. A escolha do botão do comando estava adequada à função: Create (clique-a-clique)
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

12. A escolha do botão do comando estava adequada à função: Create Box (clique + arrasto)
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

13. A escolha do botão do comando estava adequada à função: Navegação entre modos (Create, Select, Delete, Scale)
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

14. A escolha do botão do comando estava adequada à função: Undo
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

15. A escolha do botão do comando estava adequada à função: Redo
16. A escolha do botão do comando estava adequada à função: Mudar de modelo
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

17. Considere que a representação do comando foi fundamental para perceber exactamente onde estava a modelar.
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

18. Notas sobre o comando de controlo.
- Resposta Aberta

Modelação

19. Considere que é fácil: Criar objectos "clique-a-clique"
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

20. Considere que é fácil: Criar objectos por "clique + arrasto"
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

21. Considere que é fácil: Selecionar objectos "clique-a-clique"
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

22. Considere que é fácil: Selecionar objectos por "clique + arrasto"
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

23. Considere que é fácil: Apagar objectos "clique-a-clique"
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

24. Considere que é fácil: Apagar objectos por "clique + arrasto"
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

25. Considere que o sistema é preciso na: Colocação do cursor
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

26. Considere que o sistema é preciso na: Criação de paralelepípedos
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

27. Considere que o sistema é preciso na: Criação de um paralelepípedo sobre outro existente
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

28. Considere que o sistema é preciso na: Seleção de objectos
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

29. Em geral, como avalia a sua percepção do tempo despendido na criação dos modelos?
- “1 - Muito longo” / “2” / “3” / “4” / “5” / “6 - Muito curto”

Apreciação global da aplicação

30. Em geral, considero que é fácil: Criar modelos 3D
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

31. Em geral, considero que é fácil: Orientar-me no espaço virtual
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

32. Em geral, considero que é fácil: Perceber onde estão os limites da sala
- “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
33. Em geral, considero que é confortável o uso do: Head-Mounted Display (HMD)
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
34. Em geral, considero que é confortável o uso do: Comando
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
35. Em geral, considero que é fácil criar modelos simples com voxels:
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
36. Como classifica o nível de liberdade permitido pelo sistema na criação de formas 3D simplificadas? *
   • “1 - Nenhuma liberdade” / “2” / “3” / “4” / “5” / “6 - Muita liberdade”
37. Senti falta de ver uma representação do meu corpo no ambiente RV (propriocepção):
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
38. Considero que esta aplicação tem utilidade na produção de maquetas/modelos simples para:
40. Como classifica o nível de dificuldade na aprendizagem do uso do sistema? *
   • “1 - Muito difícil” / “2” / “3” / “4” / “5” / “6 - Muito fácil”
41. Como classifica o nível de dificuldade geral no uso do sistema? *
   • “1 - Muito difícil” / “2” / “3” / “4” / “5” / “6 - Muito fácil”
42. Comentários sobre a aplicação global da aplicação (pontos positivos / pontos negativos)
   • Resposta Aberta

**Sketchup**

1. Número do teste
   • Inserir Número

**GUI**

2. O que sente em relação à quantidade de botões na interface?
   • “1 – Poucos” / “2” / “3 - Número adequado” / “4” / “5 – Muitos”
3. A interface tem um aspecto/disposição dos botões coerente?
   • “1 – Confuso” / “2” / “3” / “4 – Coerente”
4. Em geral, considero que foi fácil: Identificar a função pretendida
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
5. Em geral, considero que foi fácil: Navegar na área de trabalho
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

**Modelação**

6. Considero que foi fácil: Criar rectângulos
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
7. Considero que foi fácil: Extrudir rectângulos
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
8. Considero que foi fácil: Selecionar paralelepípedos
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
9. Considero que foi fácil: Apagar paralelepípedos
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
10. Considero que foi fácil: Redimensionar paralelepípedos
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
11. Considero que o sistema é preciso na: Colocação do cursor
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
12. Considero que o sistema é preciso na: Criação de paralelepípedos
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
13. Considero que o sistema é preciso na: Criação de um paralelepípedos sobre outro existente
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
14. Considero que o sistema é preciso na: Seleccção de objectos
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
15. Considero que é fácil utilizar o rato na criação de paralelepípedos:
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
16. Como avalia a sua percepção do tempo dispendido na criação dos modelos? *
    - “1 - Muito longo” / “2” / “3” / “4” / “5” / “6 - Muito curto”

Apreciação global da aplicação

17. Em geral, considero que é fácil: Criar modelos 3D
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
18. Em geral, considero que é fácil: Orientar-me no ambiente de trabalho
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
19. Como classifica o nível de liberdade permitido pelo sistema na criação de formas 3D simplificadas?
    - “1 - Nenhuma liberdade” / “2” / “3” / “4” / “5” / “6 - Muita liberdade”
20. Considero que esta aplicação tem utilidade na produção de maquetas/modelos simples para:
    - “Arquitectura” / “Design de mobiliário” / “Design de equipamento” / “Desenho Urbano” /
      “Criação de cenários (jogos)” / “Não tem utilidade” / “Other: “ Resposta aberta
21. Como classifica o nível de dificuldade na aprendizagem do uso do sistema?
    - “1 - Muito difícil” / “2” / “3” / “4” / “5” / “6 - Muito fácil”
22. Como classifica o nível de dificuldade geral no uso do sistema?
    - “1 - Muito difícil” / “2” / “3” / “4” / “5” / “6 - Muito fácil”
23. Comentários sobre a aplicação global da aplicação (pontos positivos / pontos negativos)
    - Resposta Aberta
Appendix B: Professionals’ Questionnaire

Consentimento informado

This work is partially supported by national funds through FCT with reference UID/CEC/50021/2013 and TECTON-3D PTDC/EEI-SII/3154/2012.

Caro participante,

Estamos a conduzir um estudo sobre criação de modelos 3D simples em ambiente de realidade virtual (RV) imersivo, utilizando uma aplicação desenvolvida especificamente para o efeito.

Para tal, necessitamos da sua contribuição!

A experiência deverá demorar aproximadamente 60 minutos, estando dividida em duas partes:

1ª parte - habituação ao sistema (modelação livre);
2ª parte - desenvolvimento projectual com um contexto (modelação com a envolvente do projecto).

Após a realização da experiência, ser-lhe-á pedido que preencha um breve questionário.

As sessões serão gravadas em vídeo e audio. Todos os dados recolhidos serão mantidos em sigilo e serão analisados, exclusivamente, pelos investigadores deste projecto. Os dados poderão também ser utilizados para apresentação ou exibição de resultados em publicações científicas, conferências ou eventos semelhantes. Somente após a sua autorização específica para o fazer, poderão os dados recolhidos ser utilizados para divulgação on-line (por exemplo, no youtube, vimeo, etc.).

A sua participação é voluntária e poderá sempre desistir a qualquer momento sem qualquer penalização ou consequência.

Para participar nesta experiência, pedimos-lhe que preencha o consentimento presente neste questionário, concordando com as frases escritas abaixo.

Obrigado pela sua colaboração!

1. Li e compreendi o significado deste estudo. Tive a oportunidade de colocar questões, caso necessário, e recolher as respetivas respostas.
   • “Concordo”

2. Compreendo que a participação neste estudo é voluntária e que posso desistir a qualquer momento, sem apresentar qualquer explicação. Caso tal aconteça, não serei alvo de qualquer penalização e os dados relativos à minha experiência serão removidos e destruídos.
   • “Concordo”

3. Autorizo o uso das gravações áudio e vídeo para fins científicos.
   • “Concordo”
4. Autorizo o processamento dos dados audiovisuais no âmbito deste projecto para fins de análise, investigação e disseminação de resultados em publicações científicas ou conferências na área do projecto, pelos investigadores deste projecto.
   - “Concordo”

5. Compreendi que os dados recolhidos neste estudo serão utilizados como mencionado anteriormente.
   - “Concordo”

6. De acordo com o descrito acima, autorizo a minha participação neste estudo e aceito as suas condições.
   - “Concordo”

7. Disseminação on-line
   - “Autorizo a disseminação de excertos dos dados audiovisuais recolhidos durante a sessão em plataformas on-line (por exemplo: youtube, vimeo, etc.), para divulgação do projecto.”

8. Nome completo:
   - Resposta Aberta

9. Sigilo do participante: não autorizo que seja utilizado o meu nome na divulgação dos resultados da experiência ou em qualquer comunicação sobre a mesma.

Perfil do Utilizador

10. Atelier
   - Nome do Atelier

11. Arquitecto/a profissional à
   - Número

12. Idade
   - Número

13. Sexo
   - “Masculino” / “Feminino”

14. Qual é a sua mão dominante?
   - “Esquerda” / “Direita”

15. Habilitações
   - “Licenciatura” / “Mestrado” / “Doutoramento” / “Pós-Graduação”

16. Com que frequência: Joga videojogos?
   - “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

17. Com que frequência: Utiliza sistemas de modelação 3D digital (CAD)?
   - “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

18. Com que frequência: Utiliza o comando Wii?
19. Com que frequência: Assistiu a cinema 3D?
   - “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

20. Com que frequência: Utiliza sistemas de Realidade Virtual Imersivos?
   - “Nunca” / “< 1 vez por mês” / “< 1 vez por semana” / “1 - 5 vezes por semana” / “1 vez por dia” / “> 1 vez por dia”

21. Costuma sentir algum dos efeitos descritos abaixo no cinema 3D?
   - “Nunca senti desconforto” / “Enjoo” / “Vertigens” / “Dor de cabeça” / “Dores oculares” / “N/A” / “Other:”

**Projecto com contexto**

22. Sobre o projecto em que vai trabalhar, já tem alguma ideia do que irá fazer na aplicação? *
   - “Sim” / “Não”

23. Em caso de resposta afirmativa, por favor desenvolva:
   - Resposta Aberta

24. Tipo de projecto:
   - Resposta Aberta

25. Fase de desenvolvimento do projecto (atelier):
   - “Programa preliminar” / “Estudo prévio” / “Projecto base” / “Projecto de execução” / “Concluído”

26. Material produzido sobre o projecto, até à data, no atelier:
   - “Nenhum, o projecto está no início.” / “Esquiços” / “Maqueta(s) conceptuais” / “Desenhos técnicos” / “Maqueta(s) do projecto” / “Modelo 3D” / “Ilustração do projecto (desenhos, fotomontagens, renders, etc.)” / “Other:”
   - Resposta Aberta

27. Caso tenha respondido “Maqueta(s) do projecto” na pergunta anterior, por favor indique quantas e a que escala:
   - Resposta Aberta

**Maqueteer App**

This work is partially supported by national funds through FCT with reference UID/CEC/50021/2013 and TECTON-3D PTDC/EEI-SII/3154/2012.

Muito Obrigado por nos ajudar a incrementar o estado da arte em RV para Arquitectura. O seu contributo é fundamental para desenvolvermos algo de realmente inovador. As resposta a este questionário são importantíssimas para o próximo desenvolvimento.

Por favor ajude-nos pormenorizando todos os aspectos que mais o impressionaram na experiência.
1. Nome completo
   - Resposta Aberta

**Head-Mounted Display**

2. Indique se sentiu algum dos efeitos descritos abaixo durante a utilização do sistema de realidade virtual?
   - “Nunca senti desconforto” / “Enjoo” / “Vertigens” / “Dor de cabeça” / “Dores oculares” / “N/A” / “Other:” Resposta Aberta

3. De um modo geral, considero que foi fácil a: Navegação entre modos.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

4. De um modo geral, considero que foi fácil a: Identificação do modo corrente.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

5. De um modo geral, considero que foi fácil a: Leitura do nome dos modos.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

6. De um modo geral, considero que foi fácil a: Execução das tarefas.
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

7. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   - Resposta Aberta

8. Considero que foram úteis as informações projectadas na parede sobre as funções dos botões do comando:
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

9. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   - Resposta Aberta

**Comando**

10. Sobre o comando, considero que: É confortável de se manusear.
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

11. Sobre o comando, considero que: É fácil localizar os botões de controlo.
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”

12. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
    - Resposta Aberta

13. A escolha do botão do comando estava adequada à função: Create (clique-a-clique)
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

14. A escolha do botão do comando estava adequada à função: Create Box (clique + arrasto)
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

15. A escolha do botão do comando estava adequada à função: Navegação entre modos (Create, Select, Delete, Scale)
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”

16. A escolha do botão do comando estava adequada à função: Undo
    - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
17. A escolha do botão do comando estava adequada à função: Redo
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
18. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   • Resposta Aberta
19. Considere que a representação do comando foi fundamental para perceber exatamente onde estava a modelar:
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
20. Notas sobre o comando de controlo:
   • Resposta Aberta

Modelação (geral)

21. Considere que é fácil: Criar objectos "clique-a-clique"
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
22. Considere que é fácil: Criar objectos por "clique + arrasto"
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
23. Considere que é fácil: Selecionar objectos "clique-a-clique"
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
24. Considere que é fácil: Selecionar objectos por "clique + arrasto"
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
25. Considere que é fácil: Apagar objectos "clique-a-clique"
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
26. Considere que é fácil: Apagar objectos por "clique + arrasto"
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
27. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   • Resposta Aberta
28. Considere que o sistema é preciso na: Colocação do cursor
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
29. Considere que o sistema é preciso na: Criação de paralelepípedos
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
30. Considere que o sistema é preciso na: Criação de um paralelepípedo sobre outro existente
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
31. Considere que o sistema é preciso na: Seleção de objectos
   • “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente” / “N/A”
32. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   • Resposta Aberta
33. Em geral, como avalia a sua percepção do tempo despendido na criação dos modelos? *
   • “1 - Muito longo” / “2” / “3” / “4” / “5” / “6 - Muito curto”

Projecto com contexto

34. A aplicação foi utilizada, principalmente, para:
35. Considero que a aplicação ajudou a: abordar o projecto de uma perspectiva diferente
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
36. Considero que a aplicação ajudou a: compreender melhor a envolvente
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
37. Considero que a aplicação ajudou a: estudar melhor a relação do projecto com a envolvente
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
38. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   - Resposta Aberta
39. Considero que a utilização do sistema modificou a percepção do problema de projecto. *
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
40. Se sim, em que sentido? Se não, indique-nos o que pode ser melhorado.
   - Resposta Aberta
41. Considero que a utilização do sistema estimulou novas ideias sobre o projecto. *
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
42. Se sim, em que sentido? Se não, indique-nos o que pode ser melhorado.
   - Resposta Aberta

**Apreciação global da aplicação**

43. Em geral, considero que é fácil: Criar modelos 3D
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
44. Em geral, considero que é fácil: Orientar-me no espaço virtual
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
45. Em geral, considero que é fácil: Perceber onde estão os limites da sala
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
46. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   - Resposta Aberta
47. Em geral, considero que é confortável o uso do: Head-Mounted Display (HMD)
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
48. Em geral, considero que é confortável o uso do: Comando
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
49. Em geral, considero que é fácil criar modelos simples com voxels:
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
50. Como classifica o nível de liberdade permitido pelo sistema na criação de formas 3D simplificadas?
   - “1 - Nenhuma liberdade” / “2” / “3” / “4” / “5” / “6 - Muita liberdade”
51. Senti falta de ver uma representação do meu corpo no ambiente RV (propriocepção):
   - “1 - Discordo totalmente” / “2” / “3” / “4” / “5” / “6 - Concordo totalmente”
52. Caso tenha discordado totalmente de algum ponto, indique-nos o que pode ser melhorado.
   - Resposta Aberta
53. Considero que esta aplicação tem utilidade na produção de maquetas/modelos simples para:
- “Arquitectura” / “Design de mobiliário” / “Design de equipamento” / “Desenho Urbano” /
  “Criação de cenários (jogos)” / “Não tem utilidade” / “Other:” Resposta Aberta

54. Como classifica o nível de dificuldade na aprendizagem do uso do sistema?
- “1 - Muito difícil” / “2” / “3” / “4” / “5” / “6 - Muito fácil”

55. Como classifica o nível de dificuldade geral no uso do sistema? *
- “1 - Muito difícil” / “2” / “3” / “4” / “5” / “6 - Muito fácil”

56. Comentários sobre a usabilidade global da aplicação (pontos positivos / pontos negativos)
- Resposta Aberta
Appendix C: Semi Structured Interview

ENTREVISTA

1. Qual é a vossa primeira impressão sobre a aplicação que estiveram a experimentar?

QUESTÕES SOBRE O SISTEMA

2. As vossas experiências foram bastante longas, com tempos de imersão em ambiente RV superiores a 30 minutos. Sentiram algum desconforto ou enjoo durante a sessão?

3. Sobre o sistema, sentiram que o Head Mounted Display – ou seja, os óculos do Gear VR - e o comando foram, de alguma forma, intrusivos na vossa experiência?

4. Relativamente à interface RV, consideram-no adequado às experiências que desempenharam?

5. Sobre a utilização dos voxels na realização de modelos 3D simplificados, ou seja, na realização de maquetas de esboço de forma rápida, o que é que acharam?

6. Sentiram necessidade de, a determinado momento, mudar a dimensão do voxel?

7. Mas que esse tamanho fosse variável durante toda a experiência ou fixando uma dimensão logo de início e ficava aquela?

8. No seguimento da parte de modelação, sentiram que os modelos que criaram foram, de alguma forma, condicionados pelo sistema? (positiva ou negativamente)

9. Em que medida é que o que modelaram correspondeu ao que pretendiam modelar?

10. E sentiram que aqueles eixos a verde, a vermelho e a azul ajudavam a relacionar a geometria?

11. Vocês já falaram um bocadinho sobre isto, mas pedia-vos para elaborar mais uma vez: quais foram as vossas principais dificuldades na utilização do sistema? (em geral, em tudo – desde constrangimentos físicos até constrangimentos do processo)

12. Que tipo de funcionalidades ou ferramentas esperavam encontrar, mas que não estão disponíveis na aplicação? (array / layers / adicionar geometria a uma selecção / outras)

QUESTÕES SOBRE O USO DA APLICAÇÃO NA PRÁTICA PROFISSIONAL

13. Na segunda parte da experiência, foi-vos pedido que trabalhassem com a envolvente de um projecto real – que referiram estar no início. Sentiram que o sistema vos ajudou a compreender melhor o contexto do projecto?

14. Já tinham alguma ideia (para esse projecto) que pretendiam testar na aplicação ou exploraram ideias novas, tirando partido do potencial criativo do sistema?

15. O sistema promoveu, de alguma maneira, a emergência de novas ideias para o projecto, de outros pontos de vista?

16. De que modo é que o sistema poderia ter utilização prática, em contexto profissional?

17. Um dos pontos referidos foi a possibilidade de utilizar o sistema no ensino de projecto em arquitectura, nomeadamente nos primeiros anos. De que modo poderia contribuir?
Appendix D: Maquetteer’s Setup Guide

This guide is a step-by-step guide for running Maquetter, specifically, on VIMMI’s Lab:

- Mocap markers:
  1. If the WiiMote and the GearVR do not already have markers, wooden spheres covered in a highly infrared radiation reflective tape, they have to be positioned so the Mocap system works. Put three or more markers in each of them. These markers cannot have the same pattern in both rigid bodies, cannot be all collinear in a rigid body and they have to be positioned in places where the Optitrack cameras can see them.

- Mocap system:
  1. Open the Motive software [45] and make sure all cameras are recognized by checking if a number appears in all of them.
  2. Calibrate the Optitrack cameras using the Motive software. This process is the same for any mocap system who uses Motive.
  3. Define the rigid bodies for the WiiMote and for the GearVR (in this order) and choose the option of broadcasting the rigid bodies position and orientation information (which will happen via UDP).

Figure 48 – Position that both the GearVR and WiiMote should be during the process of creating the rigid bodies on Motive.
4. After that, save these changes unto a file. While this changes are still valid, instead of opening the motive software directly, open the saved file so steps 1, 2 and 3 are not needed. When the calibration loses accuracy repeat steps 1, 2 and 3. Either way, it is always needed to check if the cameras are being recognized by the system.

- WiiMote:
  1. Open TouchMote [46].
  2. Connect the WiiMote following the instructions on TouchMote.
  3. Open an executable called WiiMote UDP GearVR which is located in a folder with the same name on Desktop to initiate a program called WiiMote Tester.
  4. Insert the GearVR's smartphone’s IP address on the WiiMote Tester’s field named “Destination IP”.

- GearVR:
  1. If the Maquetteer application is not in the smartphone it must be installed.
  2. Open the Maquetteer application.
  3. Put the smartphone on the GearVR
  4. Adjust the focal point using a wheel in the top of GearVR.

“Streaming to the Computer”

The computer will not actually be streaming the smartphone’s screen image but the effect is similar. Two additional steps are required for this:

1. Press the Home button from the WiiMote long enough for the button layout’s menu appear. Then choose the Maquetteer layout. If the layout is not defined it needs to be created by using the control mapping defined on “InputManager.cs” which is located on the project folder.
2. Open and run the application on computer and place the mouse somewhere on the application screen.

**Collaborative Setup**

In the collaborative setup, place markers on multiple GearVR’s following the restrictions mentioned before. Create a rigid body for each of the GearVR’s and place the smartphone with the respective application on it (for example, if the GearVR corresponds to the first rigid body created on Motive after the WiiMote then place in it the smartphone with the application “Maquetteer_user1”). Finally, instead of opening only one instance of the WiiMote Tester, open one for each smartphone.
Appendix E: Pseudo Code from Class World

class World

    DictionaryStructure<ChunkPosition, StoredChunk> world;

    SnapPositionToGrid(point)
        point = Integer (point / gridSize) * gridSize;

    SpacePositionToGridPosition(point)
        point = SnapPointToGrid(point);
        point = point / voxelSize;

    SpacePositionToChunkPositionConversion(point)
        point = SpacePositionToGridPosition(point);
        point = point / chunkSize;

    SpacePositionToInsideChunkCoordinates(point)
        BeginninOfChunkInVoxels = SpacePositionToChunkPositionConversion(position) * chunkSize;
        gridCoordinates = SpacePositionToGridPosition(point);
        insideChunkCoordinates = gridCoordinates - BeginninOfChunkInVoxels;

    InsertVoxel(voxel)

        If(ChunkExists)
            GetChunkFromDictionary();
            If VoxelExistsInTheSamePosition
                EraseVoxelInChunk();
                InsertVoxelInChunk(voxel);
            Else
                CreateChunk();
                InsertChunkInDictionary();
        Else
            CreateChunk();
            InsertChunkInDictionary();

        End If

    End If

    End InsertVoxel

End class World
InsertVoxelInChunk(voxel);

DestroyVoxel(point)
    If VoxelExists
        Destroy Voxel;
    End if
end class

class Chunk
    VoxelFromChunk[chunksize][chunksize][chunksize];
end of class
Appendix F: Pseudo Code for the Creation of Boxes of Voxels

Update()

If WiiMotePointerPosition != TipOfTheBox:

For a maximum of 10 iterations:

For each dimension (x,y,z):

If WiiMotePointerPosition[dimension] not in the Box’s range

ExpandBoxInOneDimension(dimension);

Else If (WiiMotePointerPosition[dimension] is within the Box’s rang and not at the TipOfTheBox:

DecreaseBoxInOneDimension(dimension);

End if

Update TipOfTheBox;

End for

End if

ExpandBoxInOneDimension(dimension)

dim1 and dim2 = x,y,z except dimension;

Create a parallelepiped of voxels which:

In dimension: has one voxel of length and positioned right next to the end of the Box.
In dim1 and dim2: spreads from the beginning to the end of the Box.

DecreaseBoxInOneDimension(dimension)

dim1 and dim2 = x,y,z except dimension;

Delete a chunk of voxels with the shape of a parallelepiped which:

In dimension: has one voxel of length which corresponds to the voxel on the surface of the Box.
In dim1 and dim2: spreads from the beginning to the end of the Box.