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LEONARDO PAVANATTO SOARES

3D MODELING OF LARGE STRUCTURES IN AUGMENTED REALITY

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3D MODELING OF LARGE STRUCTURES IN AUGMENTED REALITY

LEONARDO PAVANATTO SOARES

This Thesis has been submitted in partial fulfillment of the requirements for the degree of Master of Computer Science, of the Computer Science Graduate Program, School of Technology of the Pontifical Catholic University of Rio Grande do Sul.

Advisor: Prof. Márcio Sarroglia Pinho
Co-Advisor: Prof. Doug A. Bowman

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Sanctioned on ………, 2019.

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“Imagination will often carry us to worlds that never were. But without it we go nowhere.” (Carl Sagan)

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MODELAGEM 3D DE GRANDES ESTRUTURAS EM REALIDADE AUMENTADA

RESUMO

Modelagem tridimensional em realidade aumentada permite ao usuário criar ou modificar a geometria de conteúdo virtual enquanto registrado no mundo real, possibilitando a verificação da correspondência entre ambos *on-the-fly*. Nós propomos uma nova abordagem para a modelagem em realidade aumentada em ambientes onde a geometria é desconhecida que utiliza uma técnica de marcação de pontos para definir a posição de características presentes no mundo real, como edificações e caminhos próximos. Algumas ferramentas foram desenvolvidas para amplificar a utilidade dessas características e permitir o ato de modelagem, que geralmente ocorre sobre terrenos vazios mas deve considerar estruturas próximas. Nós desenvolvemos uma aplicação no domínio da arquitetura, direcionada a permitir o projeto de modelos volumétricos *in-situ*. Um modelo volumétrico é uma representação simplificada da ideia do arquiteto para a construção, definindo o tamanho geral e localização no terreno, enquanto *in-situ* diz respeito a estar no local onde a edificação será feita. Eles têm como objetivo entender a edificação, as características do ambiente, e como elas se relacionam. Nossa aplicação permite ao arquiteto criar o seu modelo enquanto ele pode visualizar o mundo real e fazer modificações adequadas. Nós analisamos os problemas relacionados a essa abordagem e suas soluções, e avaliamos a aplicação através de estudos com usuários. Os resultados indicaram que é uma abordagem adequada para a modelagem de volumes *in-situ*. Nós também avaliamos técnicas de marcação de pontos com diferentes níveis de precisão e o uso de percepção para o alinhamento de linhas, e concluímos que técnicas de marcação com pouca precisão e o uso de percepção para alinhamentos têm um impacto negativo na acurácia do modelo, e na facilidade uso e na utilidade da aplicação.

Palavras-chave: realidade aumentada, modelagem 3d, técnicas de marcação de ponto, estudos de volumetria

3D MODELING OF LARGE STRUCTURES IN AUGMENTED REALITY

ABSTRACT

Three-dimensional modeling in augmented reality allows the user to create or modify the geometry of virtual content while it is registered to the real world, enabling the verification of the correspondence between the model and the real world on-the-fly. We propose a new approach for modeling in augmented reality on environments with unknown geometry that uses point marking techniques to define the position of features present in the real world, such as neighboring buildings and pathways. Some tools were designed to increase the usefulness of these features and to allow the act of modeling, that usually takes place over empty terrains but must consider the surrounding structures. We developed a use case application for the architecture domain, aimed at allowing the design of a massing model in-situ. A massing model is a simplified representation of the architect's idea for the building, defining its general size and location in the terrain, while in-situ refers to being at the place where the building will be made. It aims at understanding the building, the characteristics of the environment, and how they related. Our application allows the architect to create this model while they can visualize the real world and make modifications accordingly. We analyze the problems regarding the approach and propose solutions and evaluated the application under formal user studies. Results indicated it is a reasonable approach for modeling a mass in-situ. We also evaluated point marking techniques with different levels of precision and the use of perception to align lines, and concluded that low precision marking techniques and the use of perception to perform alignments impact the accuracy of the model, and the ease of use, and usefulness of the application.

Keywords: augmented reality, 3d modeling, point marking techniques, massing studies

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1. INTRODUCTION

The reality-virtuality continuum proposed by Milgram [25], sometimes called the mixed reality continuum, indicates how much virtual an environment is. An environment at one extremity only contains content from the real world and is the most common type of environment since people live it daily. An environment at the other extremity only contains content from a synthetic spatial environment, usually viewed from a first-person point of view. The latter is usually called a virtual environment or virtual reality. Between both ends, environments can combine different levels of real and virtual content.

Augmented reality is an approach that enhances a person's view of the real world with virtual content by using displays, tracking, and other technologies [24]. We can place augmented reality in the continuum as having a predominance of the real environment with the addition of virtual content over it, as Figure 1 illustrates. An example could be rendering a virtual mug at a specific point over a real table. We should perform this combination in a spatially and cognitive manner, allowing the user to perceive the virtual information as a part of the real world [38].

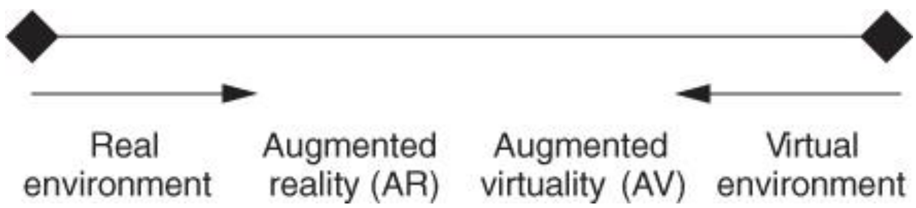

Figure 1 - Reality-virtuality continuum. Augmented reality presents a predominance of the real environment with some virtual information overlaid.

Source: Billinghurst et al. [5]

In the past years, researchers and companies have proposed many augmented reality applications aimed at solving or simplifying real-world problems on a wide range of topics, as outlined by some surveys [1], [20], [44]. In the maintenance field, Schall et al. [37] designed an application for handheld devices that displays virtual illustrations of underground infrastructure, that field workers can use to improve their understanding of the area. Henderson and Feiner [14] developed an application that shows visual guidelines for mechanics while they are performing maintenance on military vehicles.

In the medical field, Bichlmeier et al. [4] overlaid 3D information over a patient's body, to aid surgeons in visualizing data about the patient. Other studies explore overlaying information from Computer Tomography (CT) and Magnetic Resonance Image (MRI) [10],

[12]. In the entertainment industry, augmented reality has been adopted for some time, from sports broadcasting [6] to games [13], [31]. There are also applications for training and education, like the Construct3D application [19], that teaches geometry and math. In architecture, there are commercially available applications that provide the functionality of visualizing 3D models in augmented reality, like Trimble's Sketchup Viewer [46]. Figure 2 illustrates the application.

Figure 2 - Trimble's Sketchup Viewer for mixed reality.

Source: Trimble [46]

AR found space among these applications due to the need of mixing real and virtual information. Having the content showing in a handheld display or a head-worn display, which is a display attached to the user's head like glasses, presents advantages in terms of time, by having the information ready to be seen, and gives extra information about localization, since the system registers the content over the real world [38]. Schmalstieg and Höllerer [38] define registration as the alignment between the coordinate systems of the real and virtual worlds.

We believe that designing large structures could also have a positive impact by incorporating augmented reality in its early phases. Designing large structures is an essential task in our society. We construct new buildings, bridges, and pathways every day. Before defining a project and getting to the point of starting their construction, however, the design ideas for the structure must be explored and their problems addressed. An architect or engineer usually represents these early ideas through a massing model, a simplified representation of how they envision their creation [26].

Ching [8] defines **massing** as “a unified composition of two-dimensional shapes or three-dimensional volumes, especially one that has or gives the impression of weight, density and bulk.” Thompson [43] adds that primary geometric shapes are used, like a cube, cylinder, prism, and pyramid. He stresses, however, that the composition can be an aggregate of any number of primary forms, as long as it defines a strong, definite shape. Massing models can be physical mockups made of cardboard or clay or be entirely digital. Jacoby [17] presents a massing model of an architecture case, which is illustrated in Figure 3.

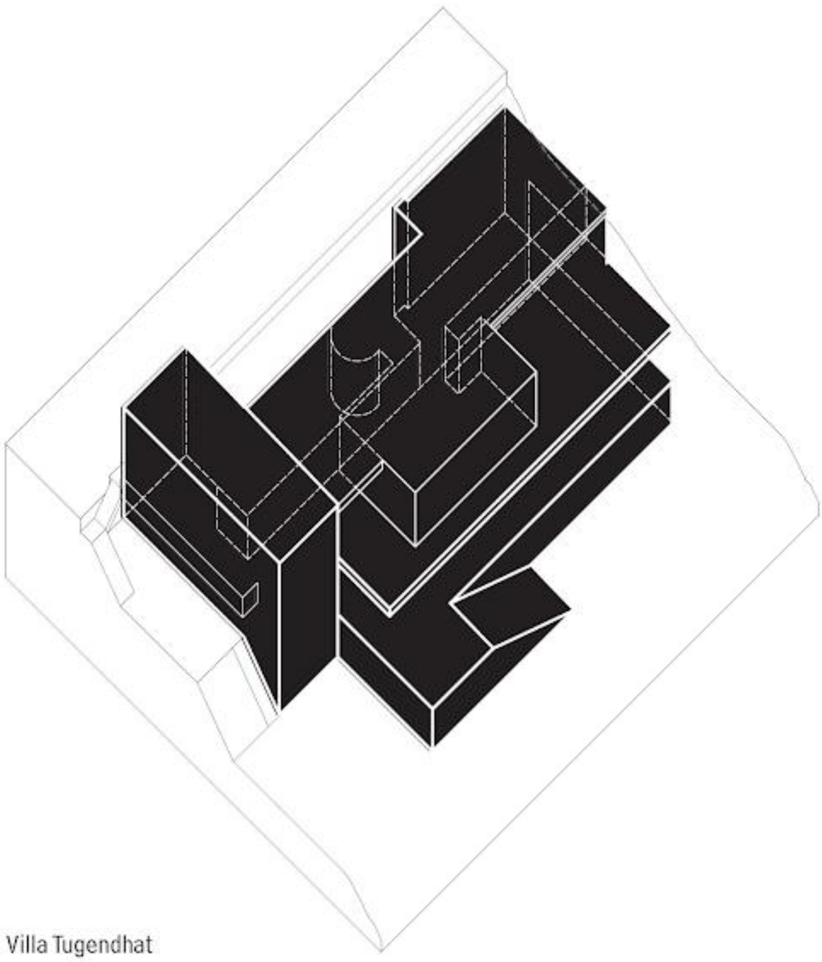

Figure 3 – Digital massing model of the Villa Tugendhat building. The black blocks define the building, while the white surfaces define the terrain.

Source: Jacoby [17]

Many times, these structures are tied to a couple of constraints. The massing model should be modified to comply with the uniqueness of each project’s necessities and characteristics. The surrounding environment plays an essential role in defining ideas for the project by giving the designer some clues on how the structure should behave. For instance, an important step is defining the position and orientation of the structure on the terrain [26], and the negotiation of their heights and setbacks with neighboring structures.

AR allows us to blend the complexity of the real world with the simplicity of a virtual massing model. Instead of just visualizing the model, we argue that the user should be able to create and modify this model in real-time and in-situ. Here we define in-situ as the place where the structure would be constructed. This would make the process less time consuming since the understanding of the environment, and the construction of the model would happen at the same time and place. Moreover, this could provide an improved and more immersive perspective of how the final structure would look like in the environment.

Modeling techniques that allow the creation and modification of geometric primitives, such as points, lines, planes, and volumes, are required to allow the design of a 3D model in AR. Some solutions have been proposed in the past to deal with modeling in augmented reality [2], [30], [38]. Baillot et al. [2], proposed a couple of techniques to define points in space. Among other traditional techniques, they proposed a point marking technique that casts two rays from distinct perspectives and triangulates the closest point on their intersection, as illustrated in Figure 4. Another solution to this problem is to place the point in the location where the user is standing, as described by Piekarski et al. [32].

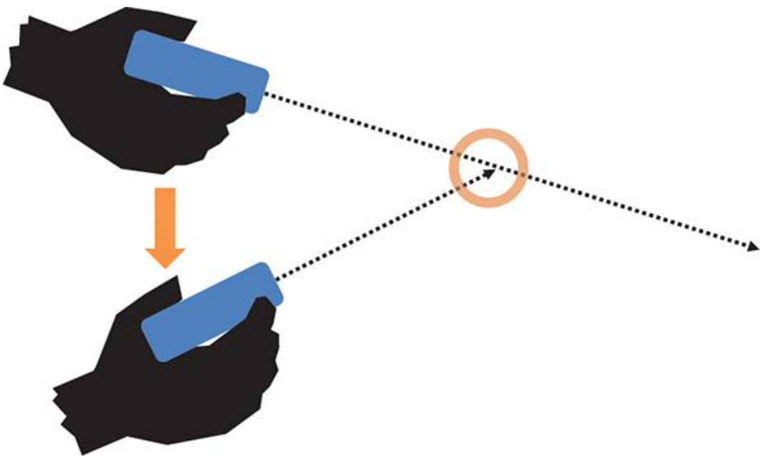

Figure 4 – Defining a point by triangulating two rays. User marks point from one perspective; moves to another perspective and marks the same point again.

Source: Schmalstieg and Höllerer [38]

Defining a plane requires three points. By knowing the user gaze and tracking the user's hand, one could define a plane positioned at the user’s hand or a given distance from the user’s position, as the Augmented Reality Working Plane technique described by Piekarski et al. [33]. By using the Landmarks approach, users could visually align their view to the side of an existing structure and create a plane parallel to it. This technique relies on the visual perception of the user to align their head with the existing structure correctly. Figure 5 illustrates some options on how to create planes.

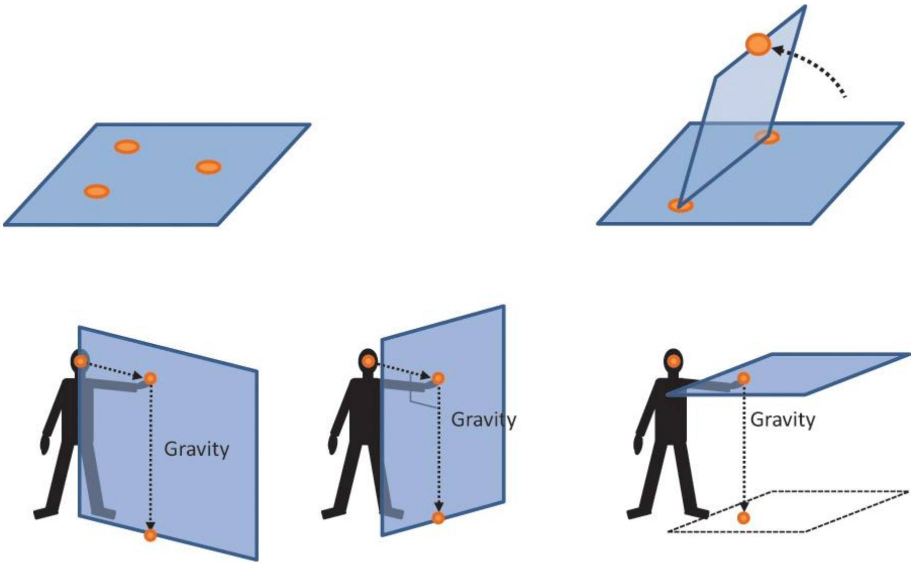

Figure 5 – Multiple ways of defining a plane in augmented reality by defining three points.

Source: Schmalstieg and Höllerer [38]

Piekarski et al. [28] proposed the creation of volumes using the intersection of multiple planes, called the Infinite-Planes technique. The space inside the intersection becomes the volume, as illustrated in Figure 6. Extrusion is another way of achieving a volume [2]. After the user specifies a surface, they choose a value of height and extrude it.

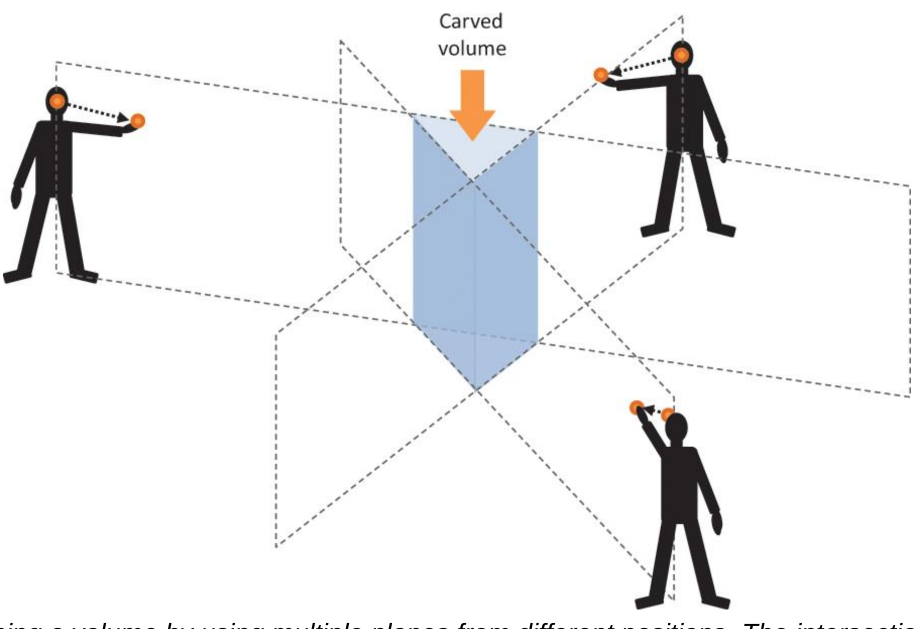

Figure 6 - Defining a volume by using multiple planes from different positions. The intersection of the planes creates the volume.

Source: Schmalstieg and Höllerer [38]

In practice, some difficulties and uncertainties are still present in these approaches. First, these approaches were not evaluated under formal quantitative user studies, making it difficult to understand how they perform related to each other and their optimal uses. Most works presented an analysis of their prototype based on a subjective self-evaluation or informal feedback. Therefore, we know these approaches work to some extent, but we cannot elaborate on when they should be used or get a clear picture of problems to be improved.

For instance, the point marking technique proposed by Baillot et al. [2] might create points with accuracy errors, and we do not know how this error propagates through the model. If the errors are frequent, does the user have to keep redoing steps of the modeling process? Do they understand that errors exist at all? On the other hand, the point creation technique proposed by Piekarski et al. [32] requires the user to walk around the space, which for a large structure might be a big area, relying on the accuracy of the tracking. If the tracking is not good, how does it impact the quality of the model or even the usability of the system? Finally, defining planes or volumes based on the user’s head may be imprecise, because the smallest angular error might create an oblique plane, turning a positional error into a cumulative error. How much imprecision there is to this technique? Is the Landmarks approach enough to guarantee the alignment?

The terms precision and accuracy are extensively used in this work. We can define **precision** as a description of the repeatability, spread or variance of a result when gathering many samples, while **accuracy** is the absolute error of one or many samples. Therefore, having an imprecise technique may eventually result in a very accurate sample, but across many samples, the results will be very spread out. Consider the case of an archer throwing many arrows at a target hoping that they will hit as close to the center as possible. In the end, we can see in Figure 7 four possible outcomes depending on where the arrows hit the target. Each outcome has a different combination of precision and accuracy levels. Notice how precision is about how much the error varies, while accuracy is about how big the error is.

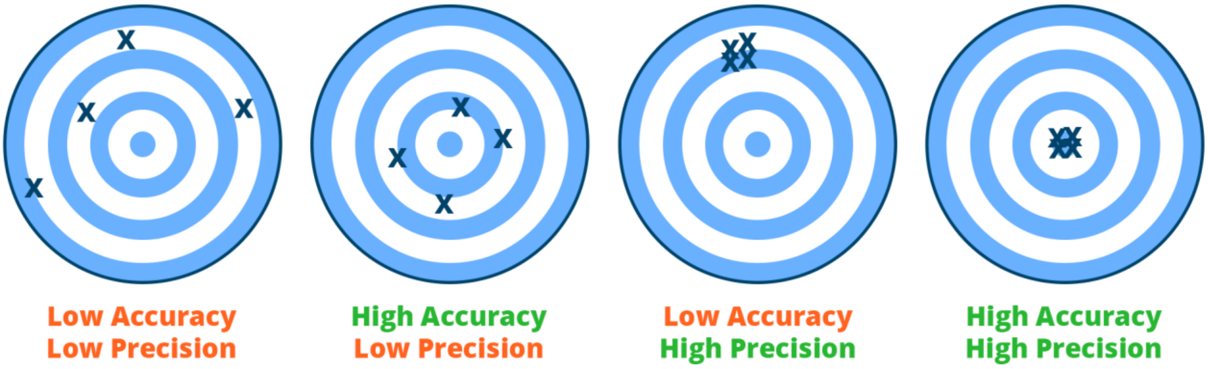

Figure 7 – Four different cases of combinations of low and high accuracy and precision.

1.1. Challenges

There still some open challenges that must be faced when developing applications for modeling in-situ using augmented reality. **Tracking** technologies for outdoor tracking are usually based on the Global Positioning System (GPS) and inertial sensors, which are not very precise into defining their location [2]. Approaches like differential GPS minimize these errors but require special equipment and are not straightforward to configure. Computer vision methods also mitigate this problem [38], but they are still prone to error in uncontrolled spaces such as the outdoor areas, where brightness and shadows change, and spaces are too large to reconstruct the 3D geometry.

Visual displays still present some limitations. Video see-through head-worn displays, which are opaque and captures the real world through a camera, strongly relies on the quality of the camera and the resolution of the display. If they are low, we lose information about the real world [14, p. 97], making it hard to visualize distant points and understand the environment. Optical see-through head-worn displays, which are semi-transparent and the user combines the real world and virtual content optically, has problems with the brightness of the sun and small fields of view [24], making it hard to visualize large virtual structures.

Interaction has some constraints. While direct manipulation techniques, in which the mapping between the user's hand and a virtual hand is 1:1, possesses higher precision, it cannot be used to interact with objects that are too far away [33]. In virtual reality, this could be fixed with a navigation technique, moving the user to a position closer to the target that they want to interact. In the context of modeling large structures in augmented reality, however, this might require them to walk through a big area.

While using at-a-distance techniques, like the point marking technique proposed by Baillot et al. [2], there is the difficulty of finding real-world features good enough to be marked. Since the process requires the user to mark from two different perspectives, the feature needs to be clearly distinguishable [22]. Since large structures usually are built over empty spaces, such as grass fields of parking lots, finding these features might be a challenge.

Human perception also plays an important role. The understanding of distances is a problem in both virtual and augmented reality [16], and this estimation gets worse on vast distances [22], [33]. Some visual cues can be added to diminish the error predominance, like shadows and colors. Adding shadows in an augmented reality system might be confusing though because they would be overlaid to real-world shadows, and differences in positioning might confuse the user.

1.2. Problem Statement

Early phases of the design process of large structures could benefit from augmented reality by allowing architects to visualize the real world and modify the virtual model at the same time. By having the model registered at the correct location, the architect could have a clear view of how it would fit in the environment, optimizing the process of understanding and modifying the massing model.

Today an approach specifically aimed at solving this problem does not exist. It is not clear how precise or challenging to use the modeling techniques proposed in the past are, due to the lack of summative studies. It is not clear how successive errors in registration impact the quality of the model, and how the precision of the techniques themselves impact those errors. Moreover, some techniques are impractical because they require the user to walk over large areas, or rely on human perception, which may be imprecise.

1.3. Research Goals and Scope

We propose a novel approach for the process of designing large structures at outdoor locations using Augmented Reality. It relies on defining points over features already present on the real-world as the basis upon to build. Such features can be anything distinguishable by the user and relevant for the type of modeling which they are performing, such as corners of buildings or pathways. By using such features, this approach can present the user with the capacity to make the new structure fit the environment quickly, by allowing the new geometry to be made parallel to, perpendicular to, or at a certain distance from existing geometry. Moreover, by defining these points at-a-distance, we can minimize how much the user needs to walk on the environment.

We developed an application which explores the use case of early phases of architectural design to experiment on our approach. These phases do not require detailed modeling, but rather a fast and prototypical way to visualize and modify ideas for the new building. We conducted formal experiments with the goal of analyzing how the accuracy errors of these points extrapolate to errors in the rest of the model, and how tools that rely on visual perception may deteriorate these results.

1.4. Research Questions and Hypotheses

We have two high-level research questions that we aim to answer within the scope of this work:

RQ1 - How can we provide usable and useful 3D modeling tools for large scale modeling in outdoor AR?

As we described before, there are a couple of constraints and challenges for modeling large scale structures in the outdoors. We want to investigate how these problems can be overthrown or minimized to provide a usable and useful approach.

H1. *Providing point marking techniques that allow users to use existing real-world geometric features as a basis for 3D modeling will result in a usable and useful augmented reality modeling tool.*

We consider the real-world to be the protagonist of this approach, and therefore if we can use it reliably, the tool will be more usable and useful. By using a point marking technique, we minimize how much the user must walk, while also being able to explore different types of point marking technique that have a higher precision.

RQ2 - How does the level of precision of point marking techniques affect the user experience of 3D modeling tools for outdoor AR?

Different types of point marking techniques present different levels of precision, which influences the accuracy of the marked point. Since we plan on using such techniques in our approach, we also aim to investigate how these differences of precision modify the result of the modeling process.

H2. *The precision of the point marking techniques is a critical factor affecting the user experience; high-precision point marking is required for acceptable results.*

We hypothesize that a point marking technique with bad precision will influence the user experience, because they may lead to bad accuracy of the marked point, which will propagate to through the modeling process, and may even alter the understanding of the model.

H3. *The precision of the point marking technique would not be a critical factor if translation operations performed later rely on the visual perception of the user.*

While we hypothesize that higher precision point marking techniques are essential in the modeling process, their importance diminishes if the operation of translation performed over a line of the model is based on perception. Translation is the process of moving an object along a straight line while keeping it rotation the same. We believe that operations based on visual perception would perform much worse and that the point marking precision would not show significant differences.

1.5. Methodology

This work obeyed the following methodology: at first, we performed interviews with stakeholders, such as architects and urban planners, to understand the specific use case of architecture modeling that we want to explore; after understanding the domain and involved tasks, we designed the modeling tools needed for the approach and implemented an AR application; we conducted two preliminary studies to understand, detect and correct problems with the techniques and application; finally, we conducted a summative user study to compare different ways of defining points and aligning lines in the environment, to test our hypotheses. A diagram can be seen in Figure 8.

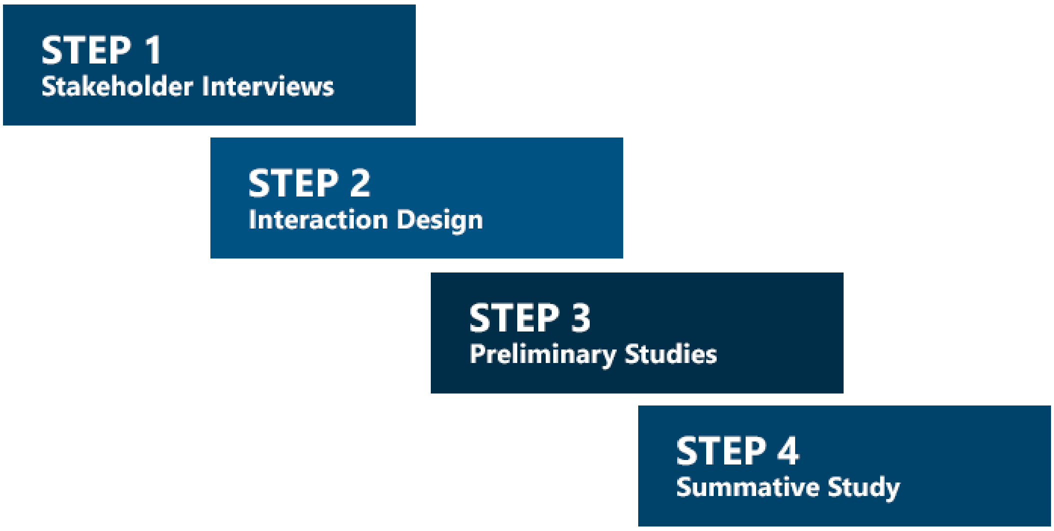

Figure 8 - Diagram of methodology followed by this work.

1.6. Contributions

This work makes some contributions to the state-of-the-art of modeling in augmented reality and future researches in the area:

- Proposed a new approach for modeling that relies on real-world features and model-free marking techniques while reducing how much the user must walk on the environment;
- Described the design and implementation of an augmented reality application for architectural massing studies;
- Defined tools to be used in a system for modeling in augmented reality, exploring their pros and cons;
- Described the problems faced with using head-worn displays in an outdoor environment;
- Formally evaluated the impacts of registration errors of marked points in the final model;
- Formally evaluated the impacts of aligning virtual lines based on perception in the final model;
- Delineated ideas for future work and the next steps for the area.

1.7. Structure

This document is organized as follows: this current Chapter 1, presented an introduction to our research; Chapter 2 presents the related work; Chapter 3 introduces and describes in the detail MASS, our use case application that explores modeling with architecture purposes; Chapter 4 presents our two preliminary user studies; Chapter 5 presents our summative user study; and Chapter 6 presents our conclusions and ideas for future work.

2. RELATED WORK

In this section we review related work divide into four groups. First, we discuss augmented reality applications that were developed for outdoor use in Section 2.1. Then, we review mixed reality applications that were focused on dealing with modeling and architecture in Section 2.2. We review the existing techniques for point marking in Section 2.3. Finally, we review work that aimed at performing modeling of structure in-situ using AR in Section 2.4, and summarize the state of the field on Section 2.5.

2.1. Outdoor Applications of Augmented Reality

Feiner et al. [11, p. 97] created the first augmented reality application for outdoor use. Called a Touring Machine, this application combined the concepts of augmented reality with the freedom of mobile computing. The authors' goal was to support ordinary users while they perform interactions with the real world. At that time, such a system required a backpack with a computer and many sensors. A see-through head-worn display coupled with a 3D graphics-ready computer displayed the name of the buildings and landmarks as the user walked around the Columbia University campus (Figure 6). It had a tracking based on a compass, inclinometer, and differential GPS. They also provided the user with a stylus-based hand-held device to be used in parallel with the HWD, which displayed more detailed information about the environment. Later, this system was expanded to display 3D models of buildings that used to exist in the campus, while also displaying paths to be followed by users [15, p. 99].

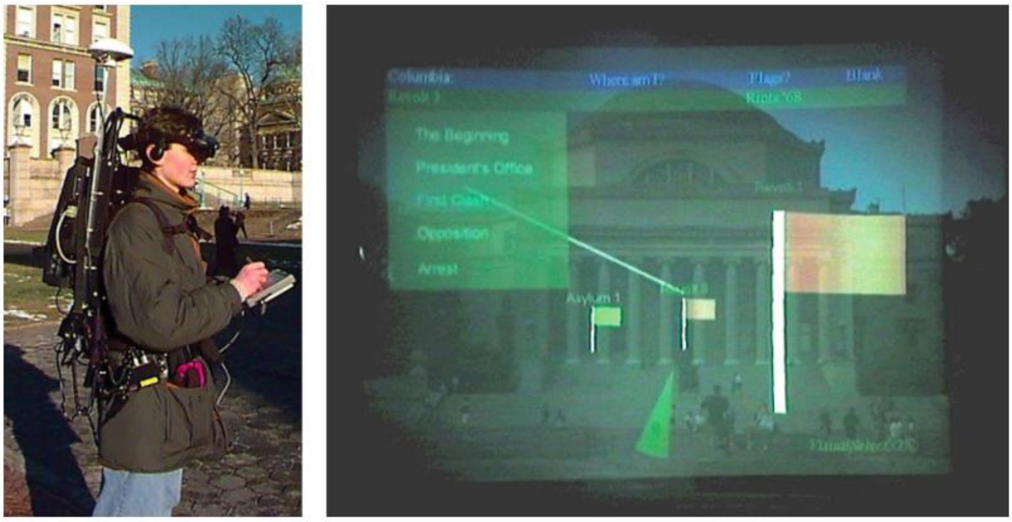

Figure 9 - A Touring Machine: backpack (left); the head-worn display showed information about buildings and landmarks (right)

Source: Adapted from Feiner et al. [11, p. 97]

Another system, called Battlefield Augmented Reality System [18], was built by the Naval Research Lab (NRL) for raising situation awareness in situations of military operations in urban environments. They investigated how multiple users on foot could cooperate between themselves and with remote personnel in a combat operation center, who could have access to more resources. The system was able to show goals and hazards dynamically, while the user moved throughout the environment.

Thomas et al. [41, p. 98] investigated handsfree terrestrial navigation on the outdoors while providing visual navigation aids. A wearable computer system used a see-through head-worn display, a compass, and a differential GPS. An application called “map-in-the-hat,” drew information on the screen, such as a diamond target for the user to follow. Many successors of this platform were developed under the name of Tinmith [30].

Piekarski and Thomas [31] used the original Tinmith system to develop an augmented reality version of the classic game Quake, a first-person shooter game from 1996. The game allowed users to walk in the real world freely. The position and orientation of the user's head defined their viewpoint related to virtual content. The system output the content to an optical see-through head-worn display and most of the interaction happened using real-world props. Lighter colors were used to draw the elements of the game, to increase their brightness in the outside. A complete map with the geometry of real-world buildings had to be created before using the game — this map allowed for occlusion of game elements, although alignment problems were likely due to tracking accuracy.

Figure 10 - ARQuake application. The tinmith system (left) was used to recreate the classic game Quake in augmented reality. The displayed showed the game overlaid to the real world (right).

Source: Adapted from Piekarski and Thomas [31]

2.2. Modeling and Architecture Applications of Mixed Reality

Some works explored how augmented reality could be used for urban planning and architecture. Thomas et al. [42] used the Tinmith system to visualize modifications of buildings in augmented reality in-situ. They modeled the original buildings and the new modifications using a computer-aided design tool and registered the content to the environment using GPS.

Kurmann [21] created a computer program called ‘Sculptor,’ which allowed for 3D virtual modeling in architecture. It focuses on the early stages of the design process, namely massing studies, and in the development of natural, intuitive and direct user interfaces for virtual reality. The author argued that the user should be able to see an object and perform an operation, rather than selecting an object and entering a value in a dialogue box. Sculptor allows for the specification of attributes like form, geometry, color, material, and texture.

Sareika and Schmalstieg [36] designed an application aimed at encouraging and improving communication over urban design. A live video feed sends images of the site to a tent where people are gathered to discuss potential modifications to the area. The interaction happens over a projection screen that everyone can see. Augmented reality is used to allow users to make sketches over this video feed on real-time. It proposes the use of a canvas billboard approach, where users can draw over the images at a given depth and get a correct occlusion.

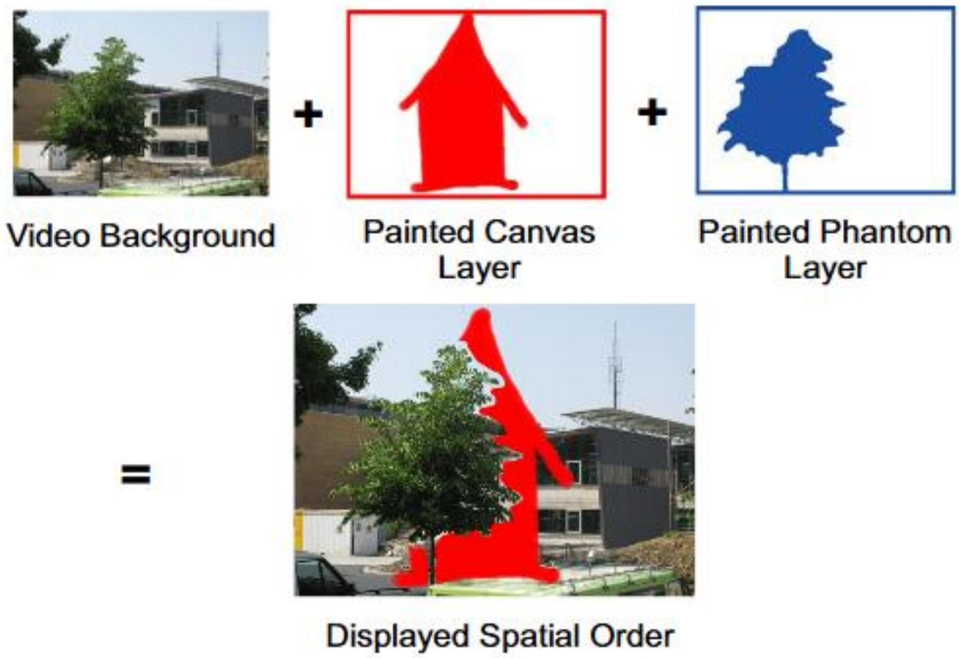

Figure 11 - Canvas billboard approach. Users draw over the video background in different layers. A phantom layer can also create occlusion on real elements.

Source: Sareika and Schmalstieg [36]

Belcher and Johnson [3] designed a mixed reality interface to support early design phases. The system allows people to gather around a table and test modifications to a building in real-time. The model is aligned over a platform with fiducial markers, and all users visualize the model with a video see-through head-worn display. The application can operate in augmented reality mode, or virtual reality mode, from a first-person viewpoint. The system also allows users to modify objects, and to simulate time and environment conditions, such as sunlight. They divided the tasks of the design process into four categories: **communication**, the process of exchanging ideas; **visualization**, the process of generating images; **simulation**, the activity of computationally forecasting the results of a given design choice; and **form generation**, the activity of shaping objects.

Chen et al. [7] proposed a hybrid virtual reality user interface specifically designed for massing studies. It combines two types of views (closer and an overview) and a table-prop for direct manipulation. A tracked pinch glove and stylus pen are also used to give a finely detailed input.

Figure 12 - Massing study environment using a projector (left) and a CAVE (right)

Source: Chen et al. [7]

Cirulis and Brigmanis [9] developed a mobile system aimed at improving urban planning processes by using augmented reality to visualize the content registered to the environment. Their application would allow the user to load a model from a database and place it on the environment automatically. The location of the models was hardcoded beforehand. They used GPS, gyroscopic, compass and inertial sensors for tracking the user.

Simon [39] developed a method for in-situ 3D sketching of polyhedral scenes, where a video camera is used for interaction and tracking. A fixed cursor is used to interact with the environment by having users rotate the camera. Some tools enable the creation of rectangles, extraction of textures and SIFT features, extrusion, translation, subdivision of a face and deletion. Camera poses are computed using image content.

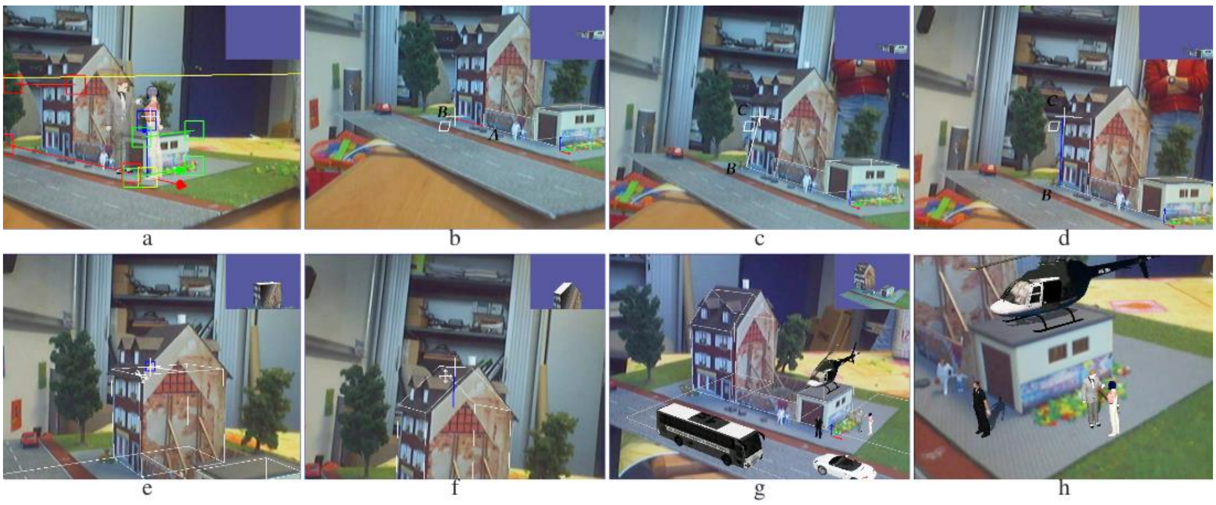

Figure 13 - Usage of the system.

Source: Simon [39]

Langlotz et al. [23] presented a novel system that allows content creation for mobile Augmented Reality in unprepared environments. They proposed approaches for small environments and large environments.

2.3. Model-Free Point Marking

Lages et al. [22] proposed and evaluated a few techniques for placing 3D points in environments where the geometry is unknown. These techniques are called: Perceptual, Geometric, and Vector Cloud.

In the **Perceptual** technique, a ray emanates from the forward vector of the user's head, allowing the user to define a line to the point of interest. The user can hold buttons to slide a cube back and forward over this line until they think that it is in the correct position. In the evaluation, this technique performed worst when compared to the others, possibly due to human perception limitations.

In the **Geometric** technique, the user casts a ray from each of two different perspectives. These rays originate from the user's head forward and are combined to define the point of interest. This combination is done by triangulating the intersection or closest point between them (Figure 14). This technique performed well for points close to the user but had much noise at higher distances, mainly due to precision errors of both orientation tracking of the device, and oscillation on the user's head.

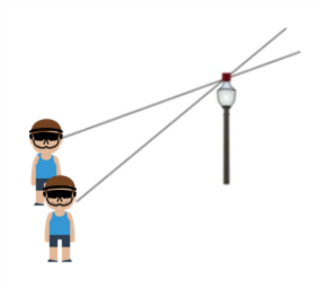

*Figure 14 - **Geometric technique**: user places two rays pointing to the same object from different perspectives, which are triangulated.*

Source: Adapted from Lages et al. [22]

In the **Vector Cloud** technique, the user casts multiple rays from each of the different perspectives. These rays originate from the user's head forward and go towards the point that the user wants to mark, forming a "cloud of vectors." The technique will pair all the rays among themselves and find the ones where the intersection is closest (Figure 15). The marked point is chosen as the geometric midpoint of that group. This technique performed the best, although it required the user to get multiple points, and thus, took more time. Accuracy was much higher than any of the previous techniques even for distant targets.

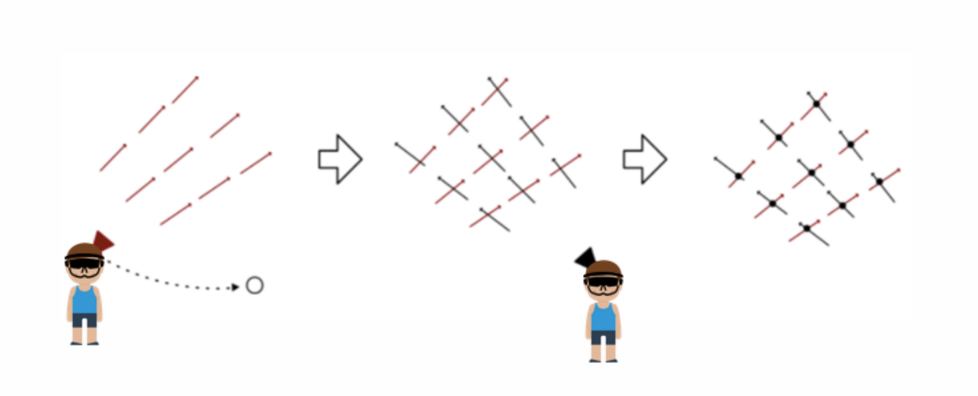

*Figure 15 - **Vector Cloud technique**: a point is selected based on intersections between multiple pairs of rays; first the user cast rays from one position; then, it casts rays from a second position; then, the system finds the points with closest intersections; finally, the geometric midpoint is selected as the point.*

Source: Adapted from Lages et al. [22]

Since GPS and inertial sensors have poor accuracy [38] and given the impracticality to put markers on outside environments, Lages used a markerless tracking approach to estimate the user position. Markerless inside-out tracking systems make use of the physical environment to determine position, orientation or motion [24]. One markerless tracking technique is visual odometry [27]. It performs tracking of 6 degrees of freedom of a camera relative to a starting point. It computes a 3D reconstruction of the environment, but to be used only for tracking.

2.4. Modeling of Structures in-Situ in Augmented Reality

In 2001, Baillot et al. [2] expanded the original B.A.R.S. system to provide tools for authoring the environment. They proposed techniques for large-scale design of 2D and 3D geometry aimed at reconstructing the existing environment and providing high fidelity maps to the B.A.R.S. system. The authoring techniques were divided into three groups: locating points in the environment to act as anchors, composing primitives by using the previously defined anchors and modifying those primitives. A traditional device, like a mouse or trackpad, was used to select points by moving a cursor over the model, while a virtual keyboard was used for entering values. Two visualizations were available: a first-person viewpoint, which can be combined with the real world and is shown in Figure 16, and a map viewpoint, which shows a top view of the virtual model.

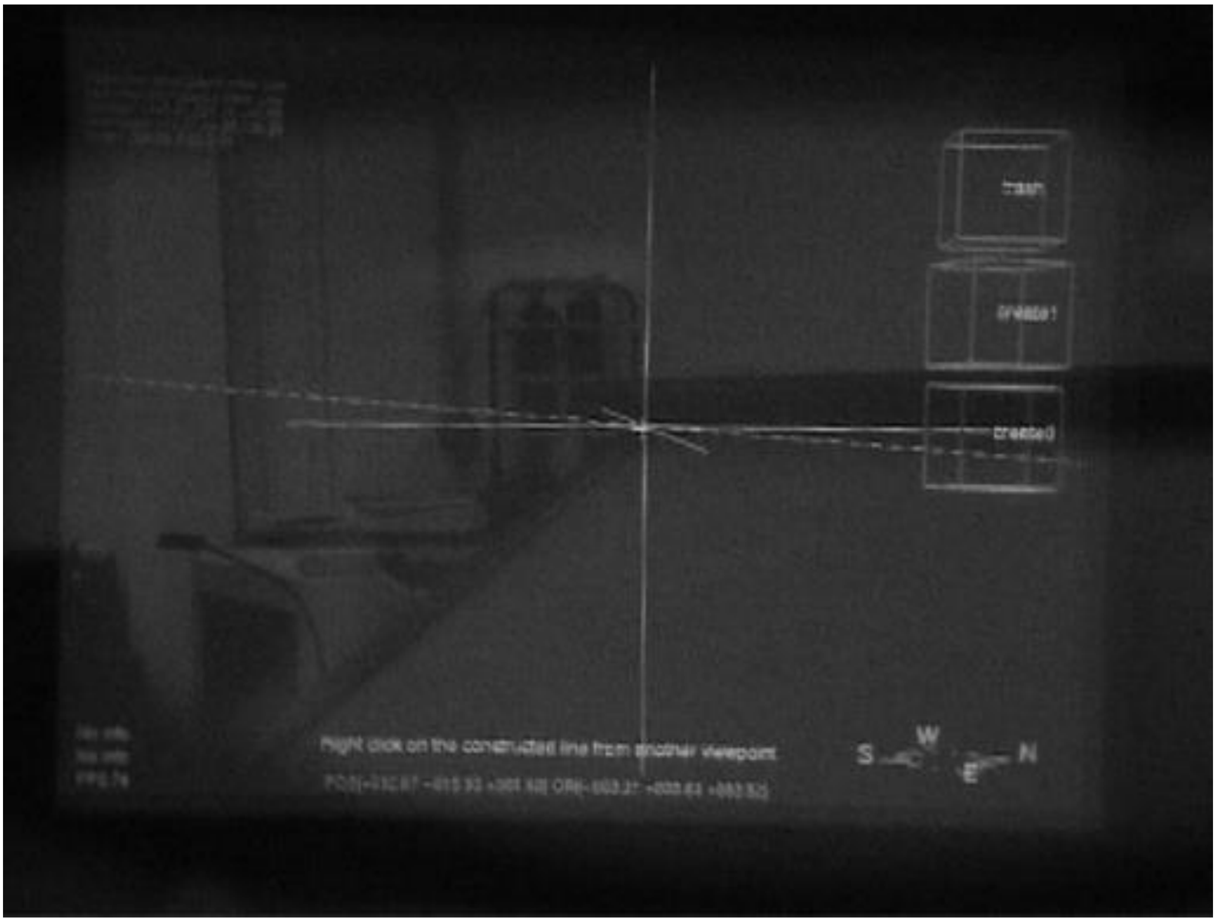

Figure 16 – First-person virtual information being displayed in the head-worn display.

Source: Baillot et al. [2]

The following techniques were defined for constructing points in the environment: direct coordinates entry, where values are entered using the keyboard; surface intersection, where a vertex can be created at the intersection between a raycasting and a surface; line intersection, where a vertex can be created at the intersection between two raycasting from different perspectives; distance from two or three points, where the user defines a radius and the intersection of a circle created on each point defines the new point.

After the anchors were defined, primitives could be built using them. The system supported the creation of lines, which is defined by two anchor vertices ad its endpoints; contour extrusion, where the user enters a height value in a keyboard, and a vertical extrusion takes place, as shown in Figure 17; a quad, which is created by selecting three points, and the fourth point is created in the opposite corner from the first point; and a box, which is created by selecting four points, three will define a quad, and the forth will define the height.

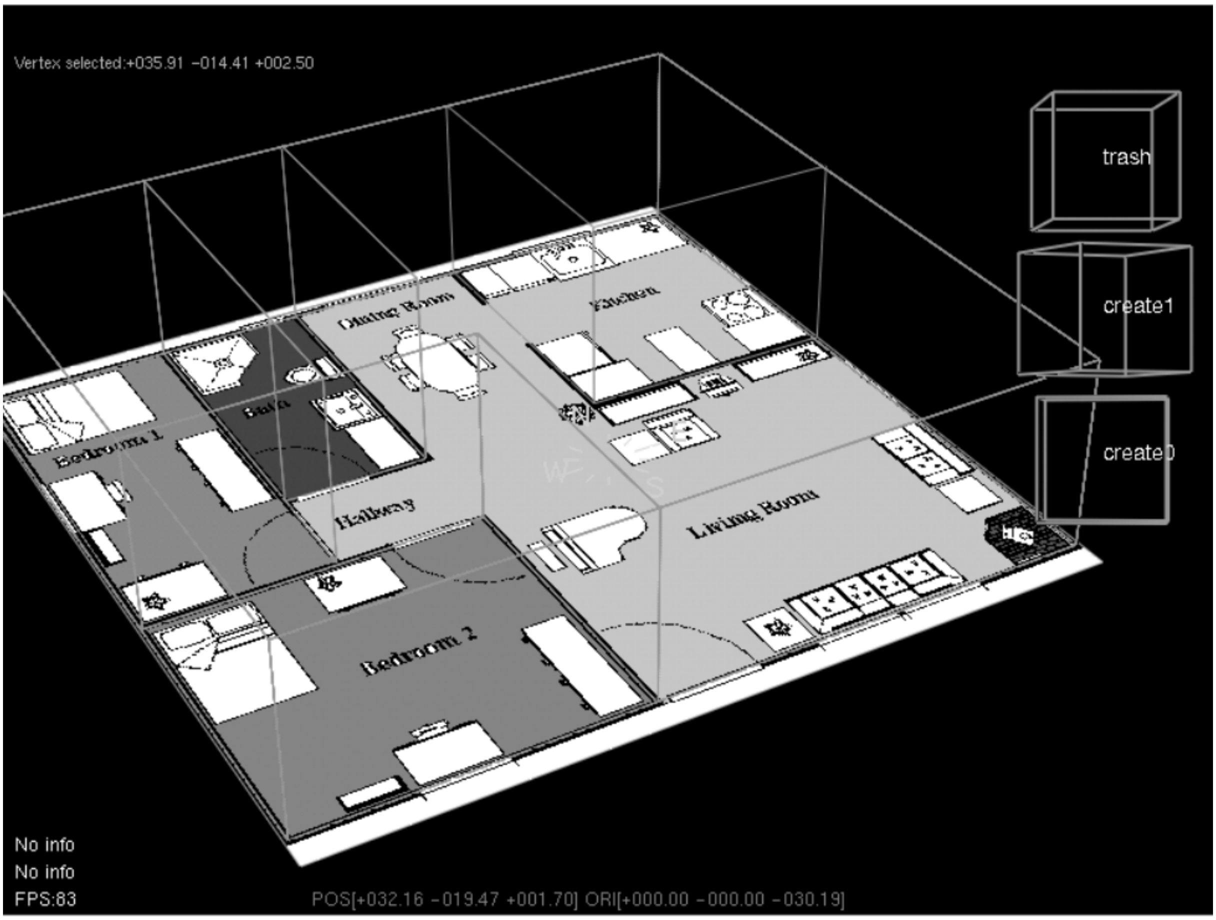

Figure 17 – A user can draw geometry from a floorplan bitmap placed on the ground. The black region is transparent when an optical see-through display is used.

Source: Baillot et al. [2]

Finally, the attributed of each primitive could be modified, such as color, label, type, and geometry, namely scale, position, and orientation. A bitmap mapping could also be performed to apply a texture over a polygon.

Piekarski and Thomas [30] developed the TINMITH system, a hand-gestures and GPS based experimental platform. It was used for a wide range of applications, from the placement of objects in the real world to a first-person mobile augmented reality game [31]. Using this platform, they proposed multiple techniques for the modeling of structures outdoors [34].

They developed the concept of **augmented reality working planes** [33], which is based on the working planes concept already in use in traditional Computer Aided Design (CAD) applications. It defines a plane positioned at a 3D point and orientation, which can be created relative to the user or other objects. The projection of 2D inputs over it allows the manipulation or creation of geometry in a 3D space. They argue that constraining the degrees of freedom that the user can manipulate would yield a higher accuracy. Figure 18 shows a user defining points over an augmented reality working plane.

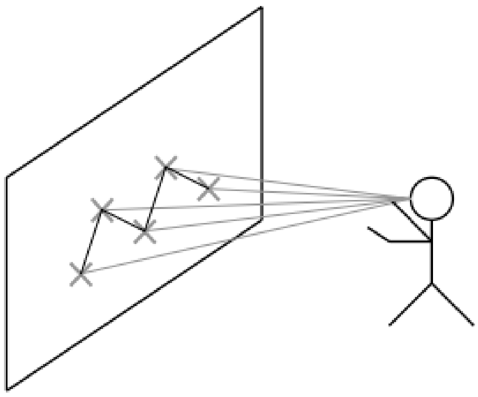

Figure 18 – Augmented Reality Working Planes. A plane is defined in the 3D environment and allows the user to more easily perform operations, such as defining points and drawing line segments.

Source: Piekarski and Thomas [33]

An augmented reality working plane could be created from the user's head direction and position, the user's head normal and an offset position, the user's head normal and an object's position, an object's position and normal orientation, and by using one object's position and another object's normal orientation. Defining augmented reality working planes that consider real-world objects requires an alignment strategy. To create vertices over an existing building, for instance, they needed to define the position and normal orientation of the building to align the working plane. To solve this problem, they explored the concept of aligning landmarks [29], a strategy used by sailors to understand their location on the sea, and also to navigate narrow channels. The latter is done by observing range lights, which is shown in Figure 19. In their application, the user would position themselves looking perpendicular to the wall where they wanted to create the working plane and visually align two landmarks that defined where the plane should stay, which in this case, would be the corners of the building.

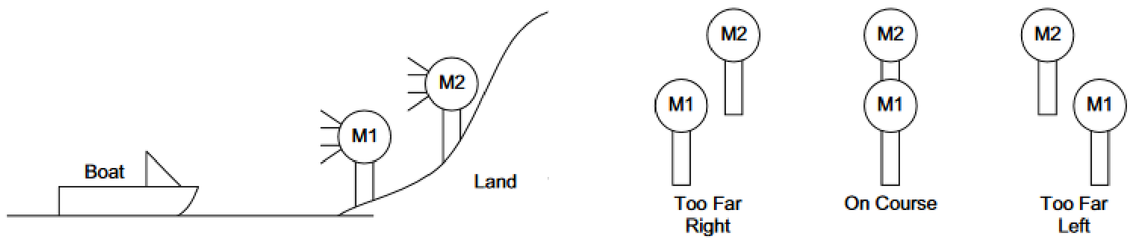

Figure 19 - Boat navigating a channel could watch range lights. Two lights are placed together, one behind the other. If they are not aligned, it means the position of the boat is wrong, and the side of the error indicates the to which side the boat should correct.

Ref: [29]

They proposed many techniques involving working planes which were named *interaction at-a-distance*. In the **infinite-planes technique** [34], they allowed the users to create planes using the same strategies described before and would carve a volume based on the intersection of those planes. The process is shown step-by-step in Figure 20.

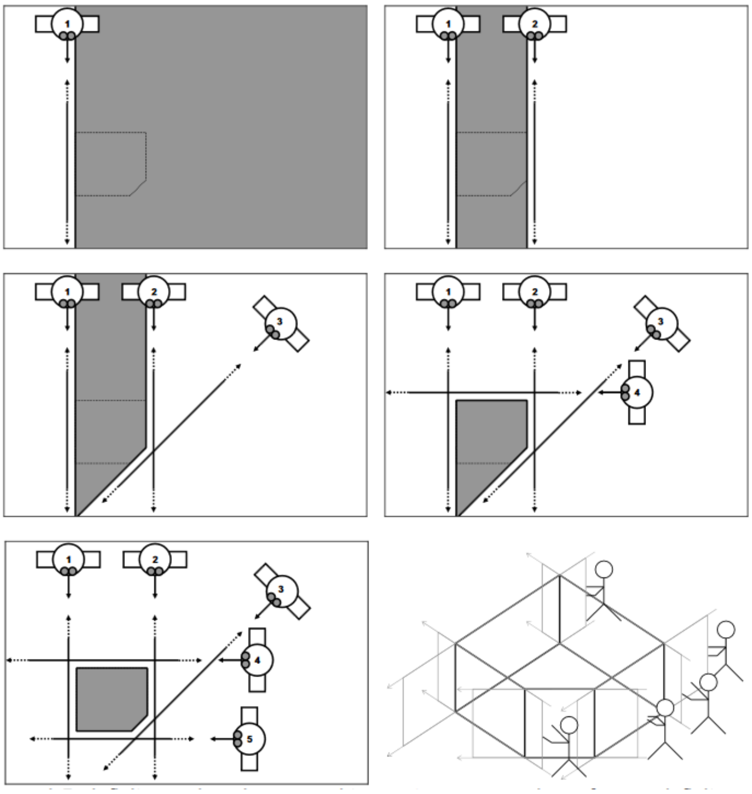

Figure 20 - Infinite-planes technique: planes were created by the user moving to different positions, the polygon inside their intersections form a volume with a chosen height;

Source: Piekarski and Thomas [29]

Many of the techniques were related to modifying volumes after they have been created. In the **laser carving technique** [34], parts of a volume could be cropped out of the model (by using the working planes) and deleted (Figure 21). The l**aser coloring technique** is a modification of the laser carving technique where instead of removing the selected part, it is separated from the primary volume and painted with another color, allowing details to be defined.

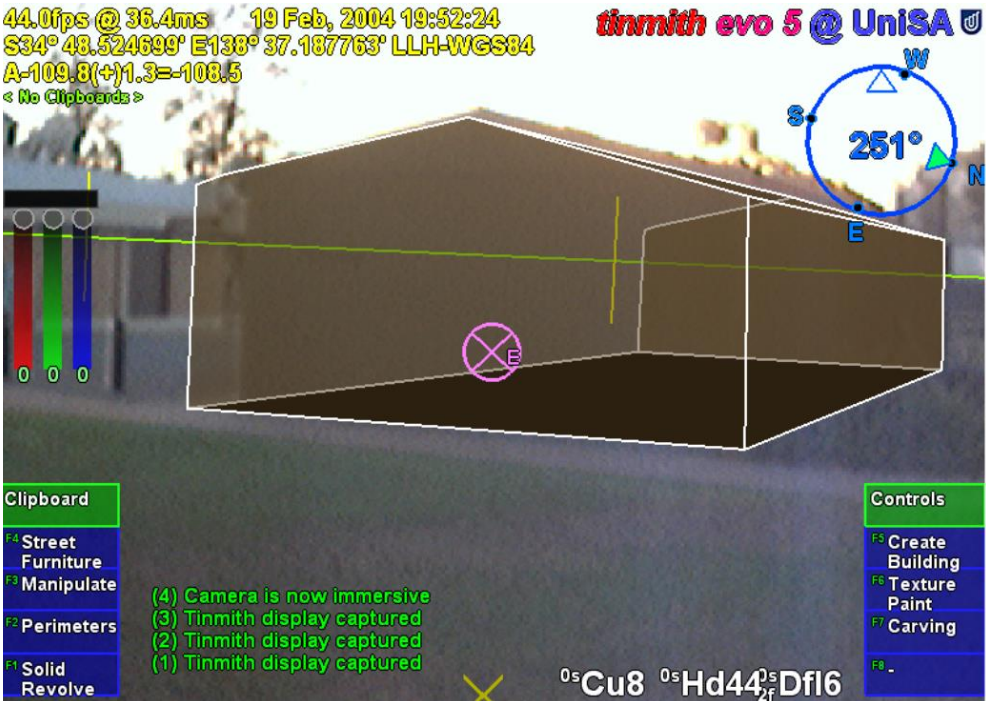

Figure 21 - ***Laser-carving technique****: lines are used to define where the volume will be cut; in this case, the top was removed to create an inclined roof.*

Source: Piekarski and Thomas [33]

The **texture map capture technique** [34] took advantage of the fact that the TINMITH used a video see-through head-worn display. It captured bitmaps of texture from objects by using its camera and allowed this texture to be applied to planes and volumes. Using the **surface of revolution technique** [34], objects that have curved features and cannot be approximated by boxes or polygons can be defined by drawing the shape of the objects in a working plane and performing a revolution of it. Figure 22 shows an object created using this technique.

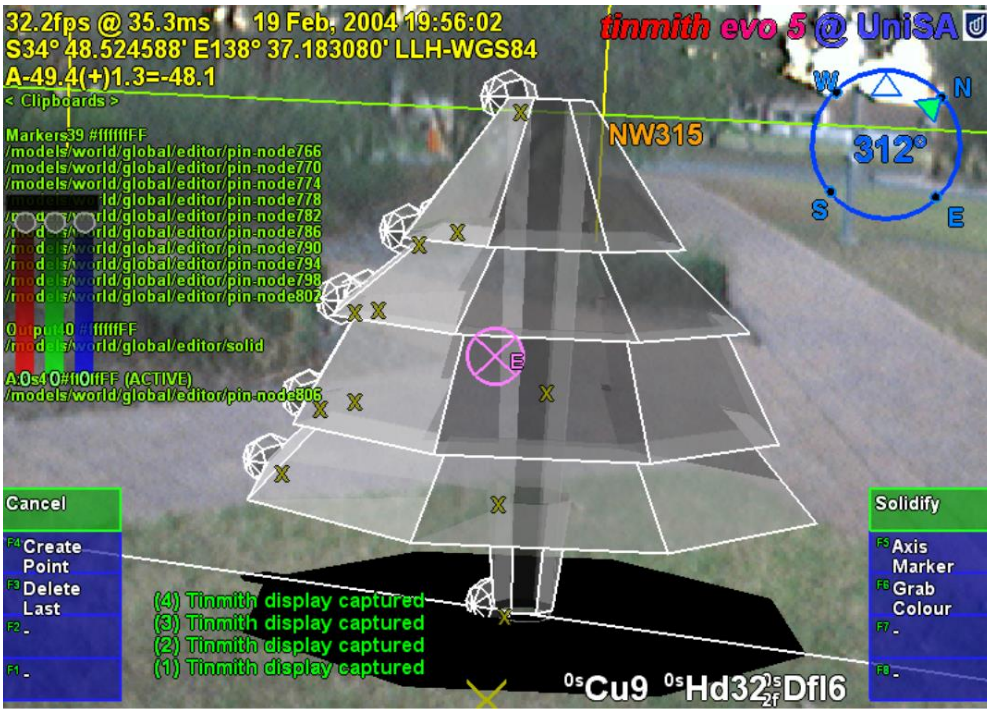

Figure 22 – Surface of revolution technique allows the creation of volumes with radial symmetry.

Source: Piekarski and Thomas [29]

The **bread crumbs technique** [32] allowed the definition of points in the environment by using the user's position as the place where to create the point. This technique requires the user to walk through the path that they want to define points. Later these points can define surfaces, as shown in Figure 23.

Figure 23 - Bread crumbs technique allows the definition of points based on the position of the user. These points can be connected to create surfaces.

Source: Piekarski and Thomas [29]

2.5. Summary

We could see from these papers that augmented reality has been used in the outdoors with success for some time [11], [15], [18], [41]. While some problems may present themselves in such environments, such as tracking and not knowing the geometry of the environment, there are approaches and mechanisms to minimize them. We could also understand some important uses that mixed reality systems found in architecture, from the visualization of designs to immersive modeling, while also considering the importance of collaboration in defining design choices.

We learned that the 3D position of real-world features could be discovered at-a-distance by using the model-free marking techniques [22]. The Perception technique used the visual perception of the user to define the depth of a point marked from a single position, while the Geometric and Vector Cloud techniques performed a triangulation between markings from two perspectives to define the point. The Vector Cloud used multiple samples in each perspective, raising the precision of the tool, especially at larger distances.

The papers related to modeling of structures in-situ have shown successful techniques performing such tasks [2], [30], [32]–[34]. We could observe that they mostly focused on making 3D models of already existing buildings and did not further explore the problem of designing new buildings over an empty space, or how using real-world features could benefit this process. While the augmented reality working planes [33] definition can use real-world features through the landmark's alignment strategy, the use is somewhat constrained to the problem of defining a line or plane. This strategy, along with the bread crumbs technique [32], also required the user to walk a lot in the environment to define the planes and points. We could also observe that there is a lack of formal user studies regarding this problem, whereas most of the work was informally tested for improvements, with some mathematical proves or derivations from other studies.

3. MASS APPLICATION

We propose a novel approach for the process of designing large structures at outdoor locations using Augmented Reality. It uses features already present on the real-world as the basis upon to build. Such features can be anything distinguishable by the user and relevant for the type of modeling which they are performing. Consider the case of architectural modeling. Early phases of the design process require architects to define the general geometry and location of a new building in an empty terrain. For this case, such features can be the corners of neighboring buildings or pathways, which may be of vital importance when trying to fit the new structure inside a defined environment.

Defining the interaction for designing large structures with such an approach relies on two premises. First, the immediate terrain will be somewhat empty since the structure would require space. Because of this, defining the correct place to register the content might not be trivial to be done perceptually, especially considering the limitations of human depth estimation. Second, there should be a relationship between the content designed by the user and the surrounding environment; otherwise, they could use a traditional modeling tool without any loss. Therefore, the environment may influence the shape of the model, or at least be able to support it.

Naturally, such an approach requires some mechanism for obtaining the location of these features for registering the content. Different approaches could be used to achieve this result, including scanning the environment to recreate the geometry or defining points based on the current user location. The former would require several sensors and would grow on complexity as structures get larger or are located farther away, while the latter might require the user to move considerably and is constrained by the precision of the user's tracking.

In this work, we consider the geometry of the real world to be unknown, and we do not attempt to recreate it. Our focus here is modeling at-a-distance, and therefore, such an approach would be computationally expensive. The only information we obtain is the location and orientation of the user's head at every frame. While we are still prone to tracking errors, we decided on using model-free marking techniques, as presented in Section 3.4, to obtain estimates of point locations. Using those marking techniques minimize how much the user must move around the environment because all marking process can happen at-a-distance. Given that tracking is not always precise at outdoors environments, it also reduces the amount of cumulative error when coupled with tracking based on video odometry [27]. Reducing tracking error is vital to yield fewer registration errors.

Given these conditions, we claim that modeling new large structures in-situ that are relative to real-world content is affected by the precision of the technique used to mark the points regarding accuracy, ease of use, usefulness, and performance. This effect would happen due to their necessity of extrapolating the positioning of those existing features and therefore amplifying the actual errors.

To investigate such a claim, we designed a system called ***Modeling Architectural Structures in-Situ (MASS)*** which is based on the case mentioned earlier of architectural modeling. We conducted interviews with experts on the field and defined a general concept of how we believe the interaction workflow should occur. The results from these interviews are explored in Section 3.1. The design process to achieve our application is described in Section 3.2. Following a couple of pilot experiments and preliminary studies, we designed a summative user study that analyzed the impacts of using point marking techniques with different levels of precision on the modeling process.

3.1. Stakeholders Interviews

We informally interviewed seven stakeholders. Five of them were architecture professors, one was a campus planner, and one was an augmented reality researcher. At this point in our research, we were still trying to understand how the idea of modeling structures in-situ would fit and be useful inside the architecture domain. Therefore, we tried to understand how the design process workflow usually happens and tried to locate which point of this process would benefit the most from our approach. For each interview, some slides were presented to make the interviewees aware of our goals before asking the questions, as shown in Appendix A – Presentation to Stakeholders. The answers were audio-recorded, and critical aspects were written down, to maximize the correct understanding of the gathered data. Given the different areas of expertise of our interviewees, the questions were slightly different on each interview.

3.1.1 Identifying the Design Process

At first, we tried to understand if the process of deciding the location and dimensions of this new building could benefit from our approach, with questions such as:

1. Can you take me through the process of deciding where the building will be constructed in general?
2. How does the surrounding environment influence this decision?
3. Can you take me through the process of defining the general size of the building?
4. How does the required size of the building influence how the location is chosen?

We learned that this step is related to defining a program for the building, by getting together all the stakeholders and defining some requirements. Architects define the location of the building based on outside factors, such as the proximity of the new building to existing related facilities. Each project is unique in this aspect, and at this point, the environment does not have much influence. Following this, the architects will create early design models and improve them iteratively until we get to a detailed project.

It became clear that this first step of defining the location and size of the building would not benefit much from our approach. We continued our interviews with questions more focused on the design of the early model. We asked questions such as:

5. Can you take me through the steps of the design process?
6. Who would be involved in each phase and what are their roles?
7. How do people communicate, are there procedures to mitigate miscommunications?
8. Does the team travel to the proposed building site? When and why?

From this, we learned that the design process of a new building is flexible and depends on the architect, architecture firm, or the characteristics of the new building itself. It is composed of consecutive phases, where each grows in detail and scope, as illustrated in Figure 24.

The first step can be called an **information-gathering phase**. The program for the building is defined in this phase. This program can contain information such as required square footage, the purpose of the building, location of the site, maximum budget, and specific design elements. At this point, the architects must visit the site to perform an assessment. Identifying positive and negative attributes of the environment is essential. For example, some part of the terrain could be a wetland, where it is too expensive or not possible to construct.

Then, an **ideation phase** follows. At this point, the environment is analyzed to understand how the dynamics of the site work, and how the ideas for the new building can fit. It is essential that the environment and the new building be harmonious. Architects try to follow one of two options: or the environment supplies the design idea, for instance the widespread use of Hokie Stones around the Virginia Tech campus suggests that new buildings should also use them; or the idea must fit into the environment, for instance making a 20-floors building at the middle of Virginia Tech, between existing 3-4 floor buildings does not seem appropriate.

The **representation phase** applies what was learned in the previous phases into an early model, called a massing model. Architects can perform massing studies in multiple ways, and each architect will have its favorite. Doing a massing model tends to have a higher importance in urban sites, where the relationship with the environment is more evident than in rural areas.

Finally, an **iterative phase** follows. The flow returns to the ideation phase to modify the design. Structure engineer might be consulted to make a few modifications at the project before sending it for approval. All the phases up to this point compose the early phases of prototypal design and the massing studies.

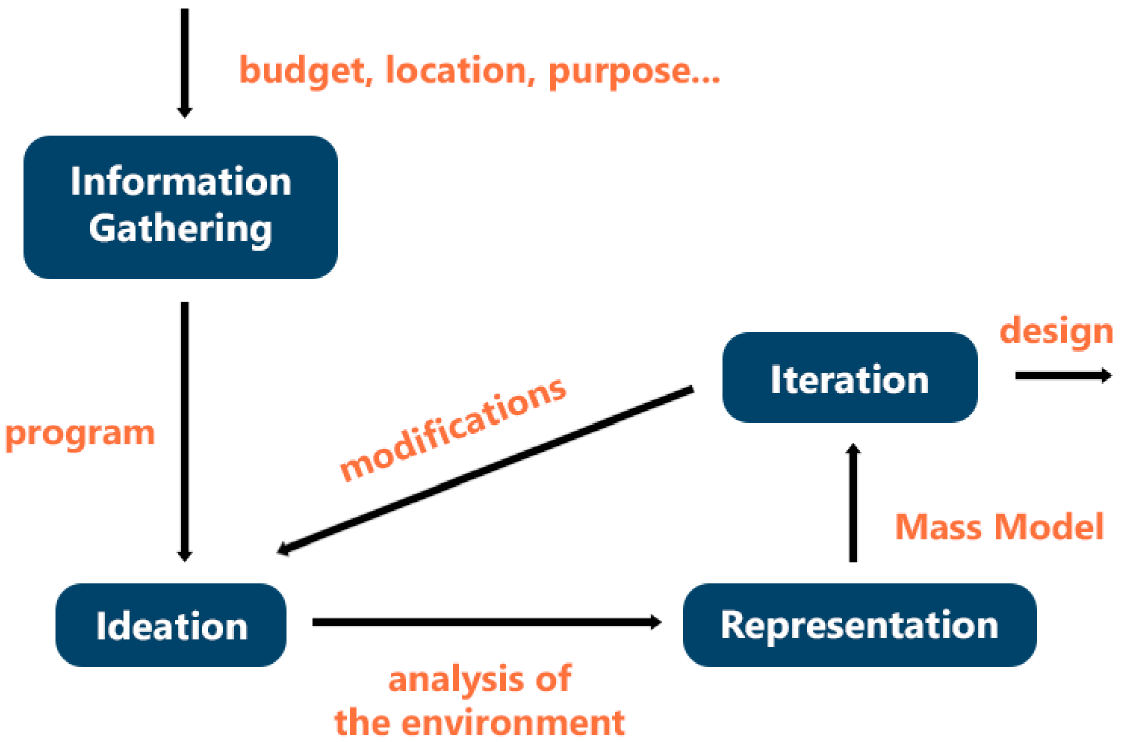

Figure 24 - Schematic showing the relationship between the phases of the design process. The phases are represented in blue and the inputs/output for each stage in orange.

3.1.2 Identifying the Relationship Between the Model and the Environment

We also made a couple of questions focusing on the aspect of the relationship between the model and the environment. We asked questions such as:

9. How is information about the existing environment and the surrounding area taken into account during the early design phases?
10. How do you analyze how the new building would fit the existing environment?
11. What is difficult about understanding how the new building will fit in its surrounding environment?

Generally, the existing environment surrounding the area is essential for the design. Many aspects should be analyzed to understand the environment, such as how the flow of people and cars work in the space, the height, disposition and materials of the surrounding buildings, the position of the sun and shadow effect, the direction of the wind, the layout of the site, existence of nearby historical or touristic elements, the topography, and possibilities for using alternative energy technologies.

Some difficulties in this phase might include understanding the scale of the new building in the environmental context, as well as the dynamics of the site, such as differences in specific moments in time, and understanding how the design choices made during this phase will impact the project as it becomes increasingly detailed. Moreover, our brains tend to think flat, while the terrain is usually not. Although architects do not decide these things during this phase, the geometry will influence how they can negotiate levels, and how people will be able to move around the space.

Municipal legislation can also take an essential role in some cities. For example, it can determine that the maximum height allowed of the new building needs to be relative to the size of the terrain (e.g., Chicago, New York). Alternatively, it can forbid construction on specific regions because of landscape choices (e.g., you cannot construct tall buildings on the north side of the Prices Fork Road in Blacksburg, VA, because that would block the view of the mountains), or due to laws to protect the environment (e.g., you cannot construct buildings close to rivers or native forests in Brazil).

3.1.3 Identifying Features of 3D Modeling Tools

We also did questions focused on the technical side of 3D modeling, along with their experience with Virtual and Augmented Reality. We asked questions such as:

12. What tools and techniques are used to study massing in the environmental context?
    a. Which steps are taken to create the building? Do you define a footprint and then create a 3D model?
    b. Which capabilities or features are required for defining the structure? Defining points, lines, volumes?
    c. What are the limitations of these tools and techniques?
13. How are the results presented? 3D models? Are they plotted over real images?
14. Have you worked with any Augmented Reality or Virtual Reality technology before? For visualization or modeling? How was the experience?

From these questions, we learned that architects could create massing models in several different ways. Some examples are hand sketching, volumetric mock-ups (clay, paper), photographic panoramas, digital modeling tools such as SketchUp and Rhino. Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools are not used at this early model phase since it requires a fast and less detailed approach. In digital modeling tools, the general step is to create a volume, by defining a rectangle footprint and applying an extrusion. Then define sub-faces and use “pushes and pulls” to modify the mass. Figure 25 illustrates this iterative process.

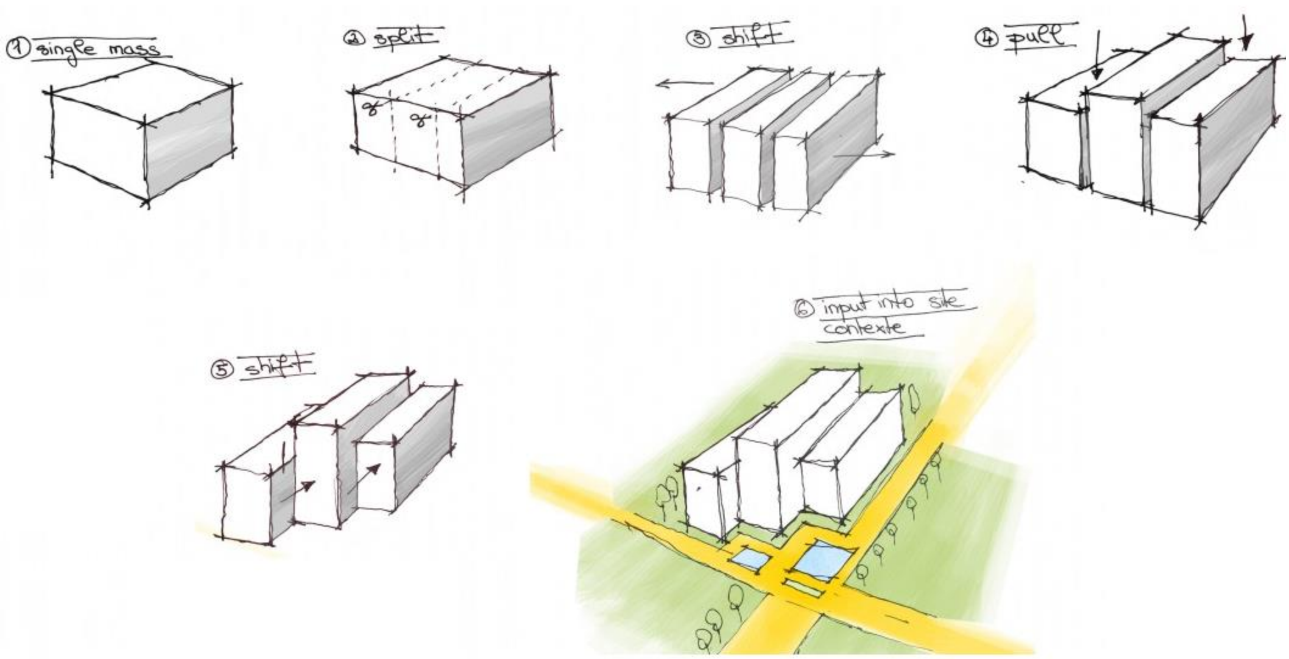

Figure 25 - Example of defining a massing model using push and pull operations. The architect defines a base mass by pushing a surface (1) and iterates upon it, dividing it (2), moving it (3), pulling it (4), and shifting it (5). Finally, it is inserted into the context (6).

Source: Adapted from Sokolowska [40]

Many architects prefer to build volumetric mock-ups instead of digital models because of perception factors. One stakeholder even expressed the existence of an open question of how the perception would influence the thought process of the architect and influence their design decisions. Architects can use renders when showing the project to clients, and the important thing is to give a sense of how it feels like to be next to the building. People or trees are an essential way to show the scale. Architects, clients, and construction workers have manly used augmented or virtual reality for the visualization of models. Some cases discussed were the visualization of interiors and the visualization of construction instructions (e.g., workers could use an HWD in-situ and visualize where to install plumbing).

In the interview with the augmented reality researcher, the most discussed aspect was tracking, and how it could be reliable. We concluded that the main challenges would be sensor inaccuracy (primary positional, but also rotational), the influence of the sunlight on the device, and human depth perception limitations.

Completing our interviews, it became clear that the ideation and representation phases of the design process would benefit the most from our approach. The user would be able to create and modify his massing model in a fast and preliminary way in-situ while observing how it relates to the surrounding environment.

3.2. Interaction Design

Upon completion of the interviews, we defined the workflow that our application would follow for this use case. The first step is to define the footprint. Considering our two constraints, architects could consider the neighboring pathways or buildings' setbacks to align the footprint of the new building since they would support modeling over the empty terrain and are meaningful to the use case. After the definition of the footprint, the height of the building could be defined by measuring the height of a neighboring building and applying an extrusion. Figure 26 illustrates the conceptual workflow for the application.

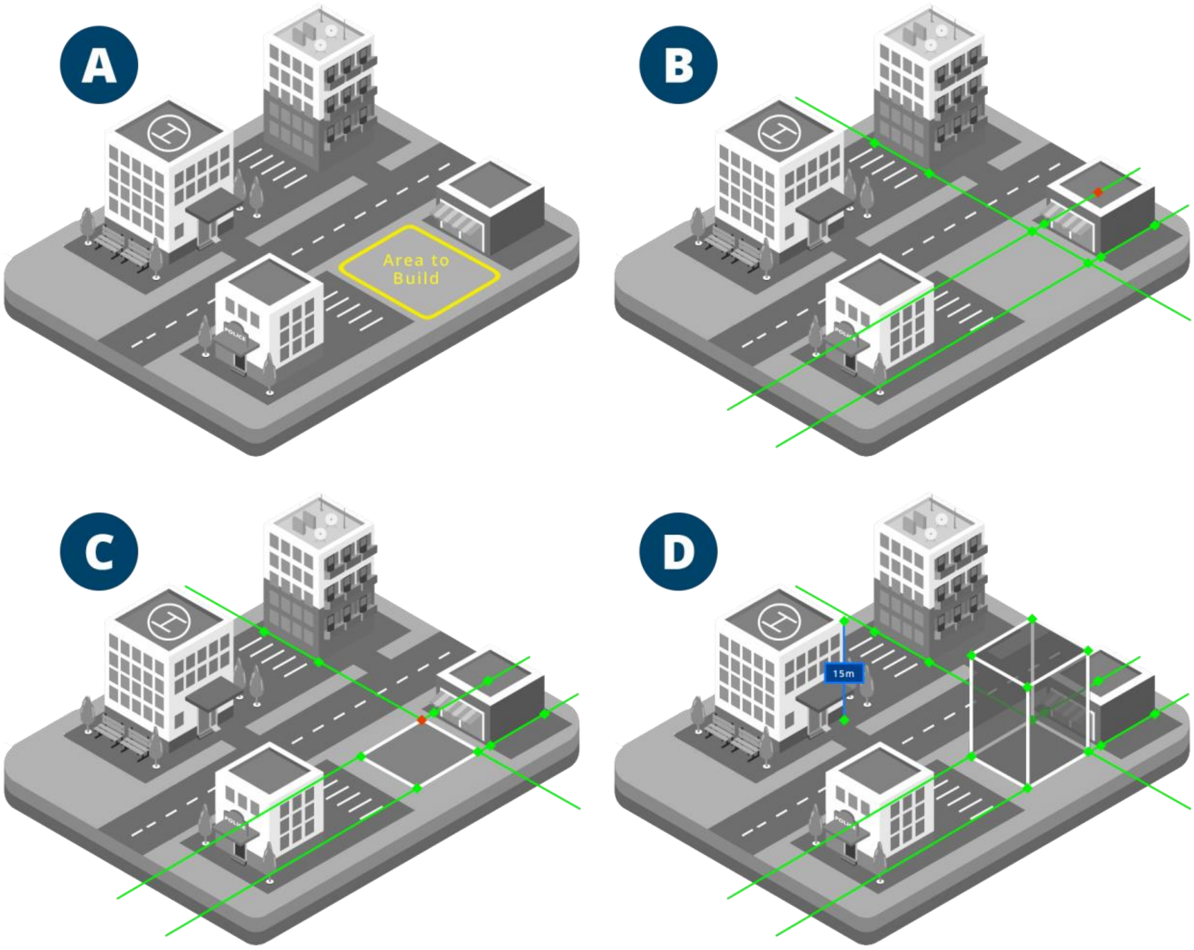

Figure 26 - Workflow concept. (A) locate the site of the new building. (B) define reference lines using objects and buildings surrounding the site. (C) draw line segments that define the footprint of the model over the reference lines (D) measure the height of another building and extrude

Source: Designed with elements from Freepik.com [47]

Given the complexity of a system for 3D modeling, we decided on dividing the interaction design process into two steps. First, we developed an application using simulated augmented reality [35]. Simulated augmented reality is an artifice used by researchers to design or evaluate the 3D interaction of an augmented reality system in a virtual environment. While the geometry of a virtual environment is usually known, for our application this knowledge is ignored, to mimic the real situation. Most of the development took place inside this environment. Then, after the interaction was stable enough, the final augmented reality application was developed for refining the interaction.

Both applications were developed using the Unity Engine [48], a cross-platform game engine that is commonly used in the fields of virtual reality and augmented reality due to its flexibility and ease of use. Unity is responsible for handling the physics simulation, the rendering, and the I/O operations. Unity uses a scene graph data structure, by hierarchically arranging objects, as a tree structure. Therefore, a given object can have many children but can only have a single parent. By applying a transformation to an object, the transformation propagates to its children, allowing us to modify multiple objects as quickly as one.

3.2.1 Simulated Augmented Reality Application

We created a small virtual town as the base scene for this application. As in an augmented reality system, the user interaction techniques disregarded the geometric information. This application was designed to be used on a virtual reality head-worn display (HTC Vive Pro), along with a tracking system with a walking area of around 5 square meters (Steam Lighthouse 2.0). Since we had decided that we would be using model-free marking techniques due to their ability to register points at-a-distance, we also added a visual target on the center of the screen. This target stays in a fixed position relative to the user's head position and orientation since the forward of the user's head indicates the point that we want to mark. The environment and interface can be seen in Figure 27.

Figure 27 - Simulated augmented reality environment. Digital models were used to create a small town, and the geometry was unknown to the application. The interface elements include the tool's name, the tool's tip on usage, and a blue cross-hair, which defines the point of interaction.

We also decided on using a handheld controller (Microsoft Xbox One Wireless Controller, shown in Figure 28) as another input device. While interacting with primitives is based on the orientation of the user's head, we chose to perform the confirmation of actions and selection of tools using buttons of the controller. Given that we would need multiple commands for the interaction, gesture or voice commands could demand a higher cognitive effort by the user, which is not the focus of our work.

Figure 28 - Xbox One S Wireless Controller. This controller can connect with devices using Bluetooth.

Source: Xbox [49]

The first step for designing the interaction was to define which model-free marking techniques would be appropriated for use to use. Following Lages et al. study [22], we decided on using their Geometric and Vector Cloud techniques, in which the user casts rays from two distinct perspectives, and the intersection of those rays defines a point. By their study, we know that Vector Cloud has proved to be much more accurate than Geometric in distant settings by obtaining multiple rays in each perspective. However, we would like to explore how this influences the interaction with our application.

As our approach would require the user to mark a significant number of points, we defined a derived technique that we called Multipoint Marking. In this technique, the user can mark multiple points from the first perspective of the triangulation, and then mark those same points again from the second perspective, in the same order. In that way, the user had to walk much less to obtain many points. When the user moves to the second perspective, a virtual ray emanates from the first perspective towards they were marking, as can be seen in Figure 29. The system displays one ray at a time, and it follows the order they were marked, helping the user to remember the ordering that they marked the points. After marking from the second perspective, a virtual point appears, as shown in Figure 30.

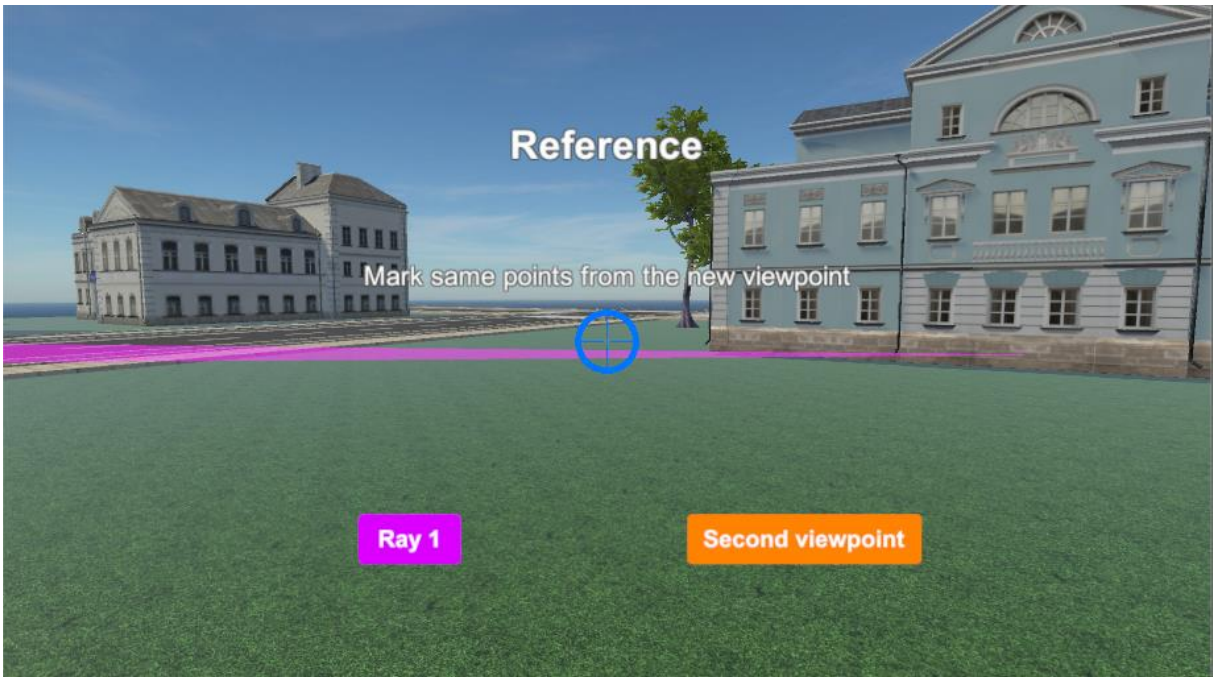

Figure 29 – User view from the second perspective. The user sees a virtual ray showing where they marked previously. Since this is a simulated augmented reality environment, the ray does not occlude when it touches the building.

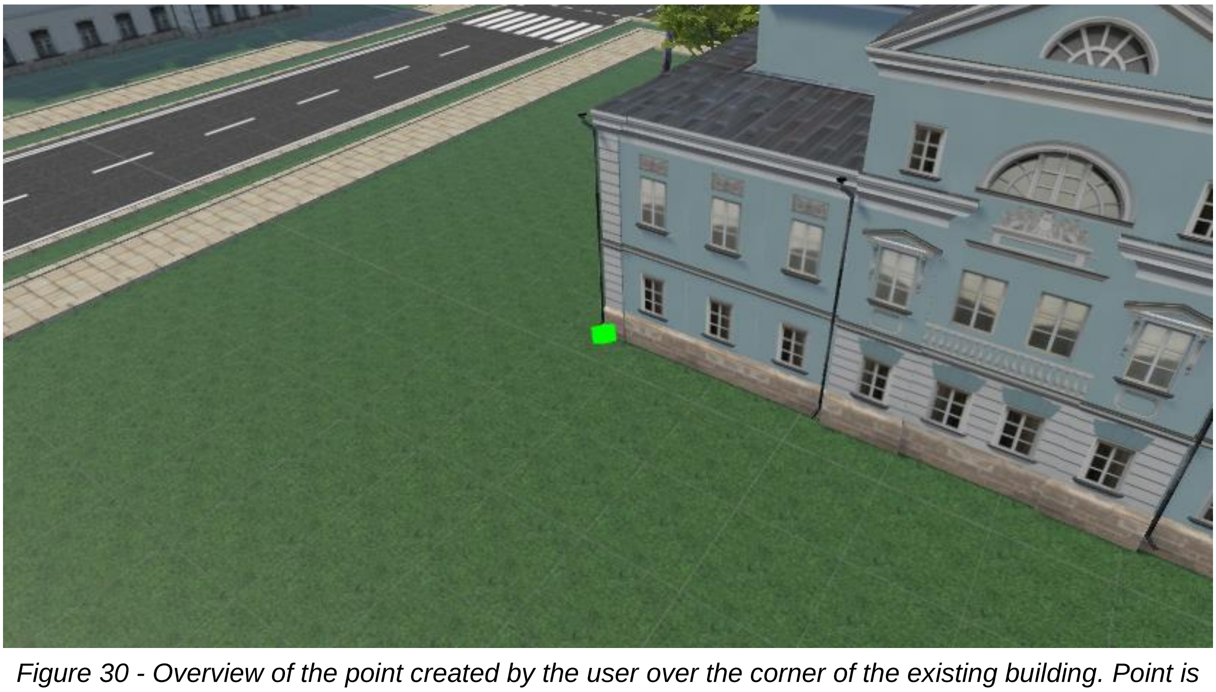

Figure 30 - Overview of the point created by the user over the corner of the existing building. Point is expressed as a green cube rotated 45 degrees.

3.2.2 Modeling Tools

Following this, we started working on modeling tools. We designed the following tools to create content:

- the **polyline tool**, which connects points to create line segments;

- the **rectangle tool**, which creates a parallelogram from three points, by defining the fourth point automatically. Since this is a parallelogram, the angles are not necessarily straight;
- and the **reference tool**, which creates an infinite green line based on the positions of two points.

The first two tools define the model, while the last one is used to create guidelines for the other tools. In all the tools from this category, the user can mark new points using Multipoint Marking, create new points over already existing line segments or references, or select already existing points, the last two using a ray-casting on the forward of the user's head. An example of polyline and reference can be seen in Figure 31.

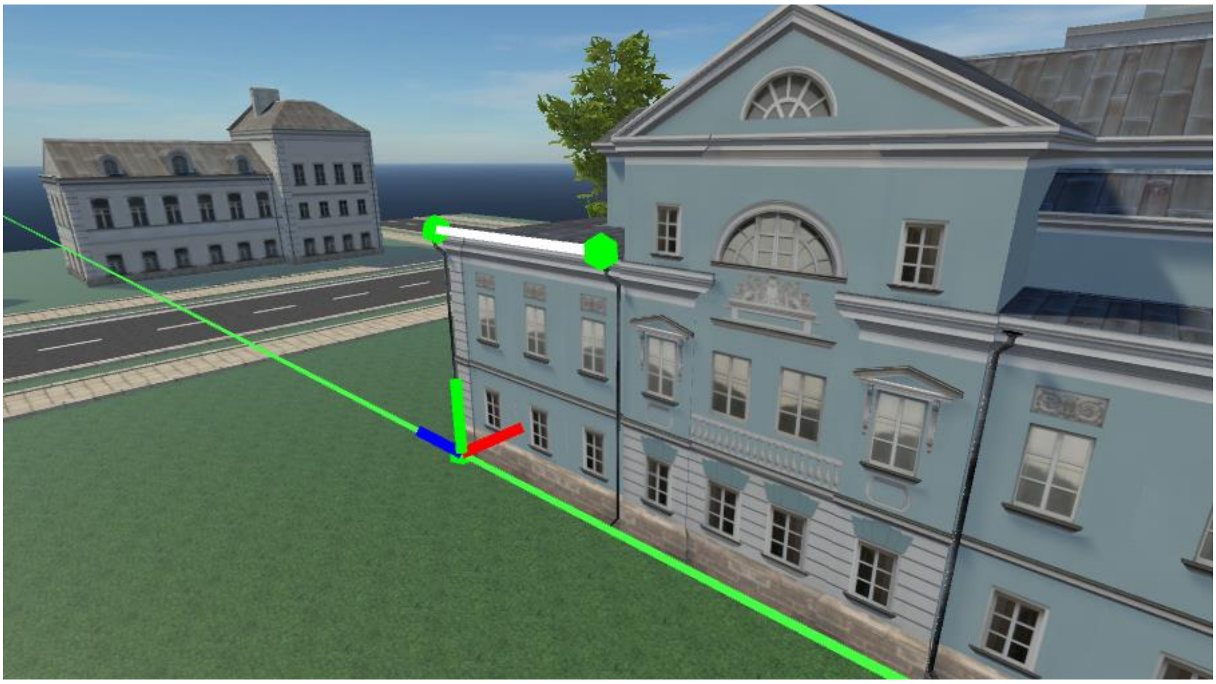

Figure 31 – Overview of a polyline and a reference. The line segment in the top of the building is a polyline; the green line in the bottom of the building is a reference line; the colorful axes are the coordinate system of the model.

After the user creates the basic primitives (points, lines, and surfaces), they can modify these primitives using the following tools:

- the **translation tool**, which moves the primitive relative to the coordinate system that the first reference line defined. The controls are mapped to the axes based on the user's orientation, meaning that the system will match the axes closest to the user's coordination system;
- the **rotation tool**, which performs a 45-degree rotation around the point of a line or surface where it was selected;

- the **clone tool**, which creates a copy of the primitive and allows for its translation, working similarly to the translation tool. However, the translation of lines is done perpendicular to the line, instead of using the coordinate system;
- and the **extrusion tool**, which creates a manual extrusion from a surface selected by the user. The direction is up/down in cases where the angle of the face is smaller than 45 degrees; otherwise, the direction is the face's forward while ignoring the "up" component;

There also some specialized tools, that make it easier to use the surrounding environment:

- the **extrusion to point tool**, which creates an automatic extrusion based on a point marked by the user. The surface will be extruded until it is co-planar to that point. This point can be defined by the same process of the tools from the tools to create content. The usage of the tool is illustrated in Figure 32, and the result in Figure 33;
- And the **clone to point tool**, which creates a clone of a reference line that is aligned with a point marked by the user. This point can be defined by the same process of the tools from the tools to create content. This tool was created later, as described in Section 5.5.

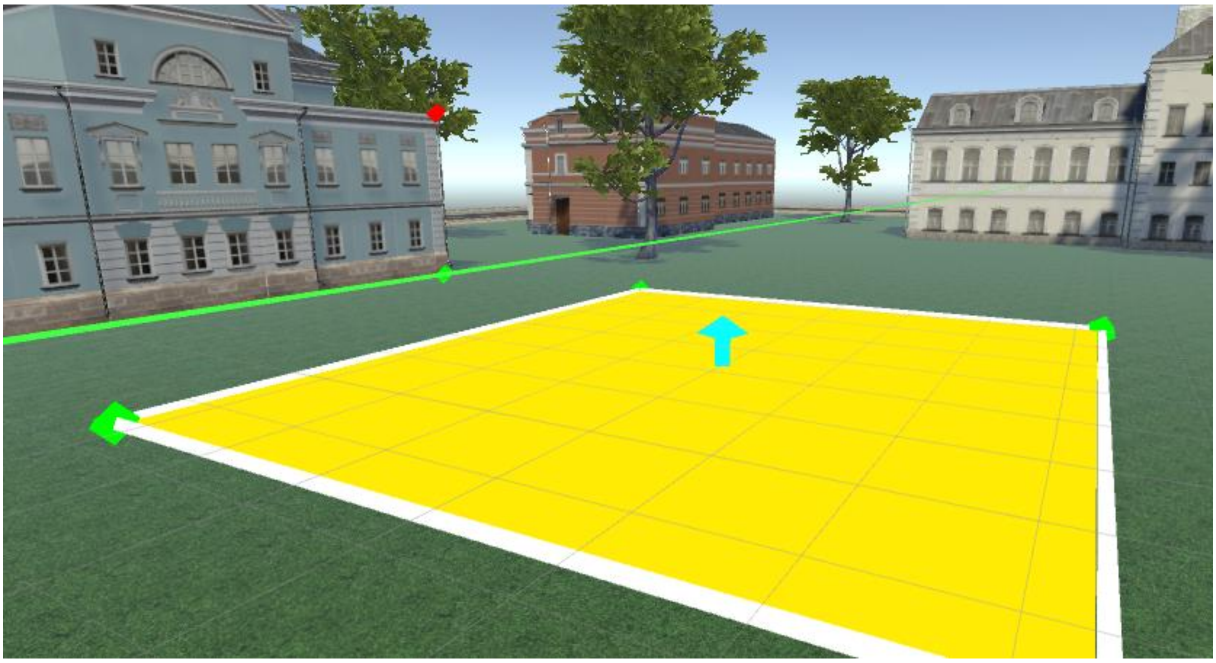

Figure 32 - Extrusion to point tool. After the user created a surface, they can define a point in the height that they want to extrude (red point) and select the surface (yellow). A little arrow shows the direction that the surface will be extruded.

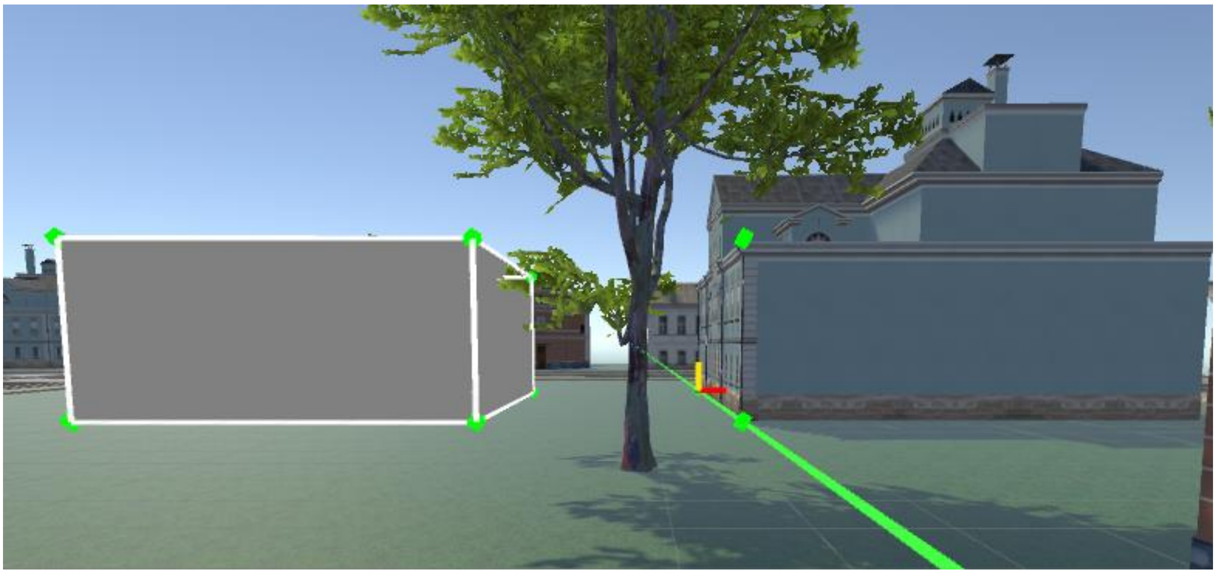

Figure 33 - Volume of the building created based on the extrude to point tool.

Finally, the user can use two tools for analyzing the content:

- the **measure tool**, which allows the user to measure the distance between two points (Figure 34), the angle between two adjacent line segments (Figure 35), and the area of a surface;
- and the **visualize tool**, which displays only faces and line segments, to allow the architect to visualize their creation.

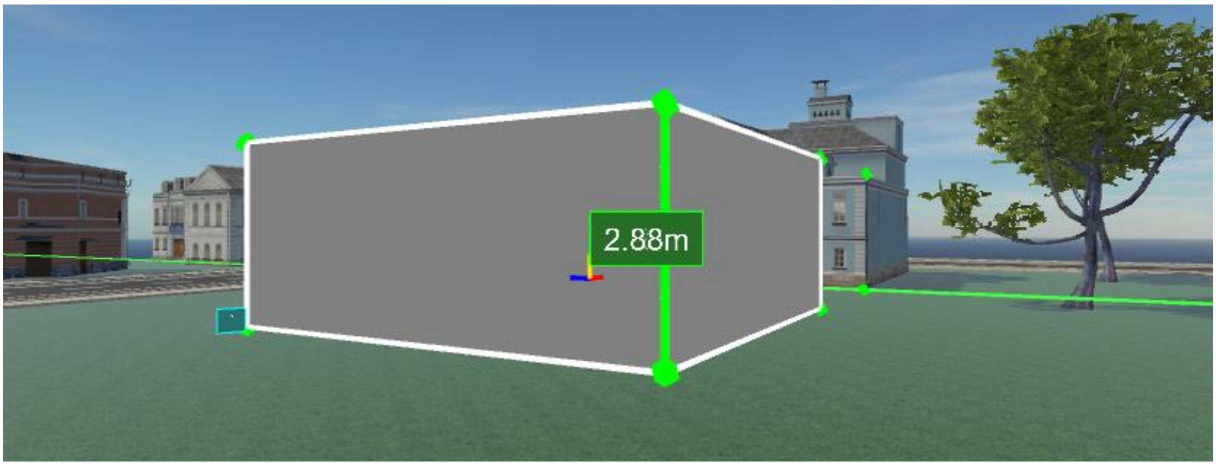

Figure 34 - User measured the distance between the bottom and top of the building.

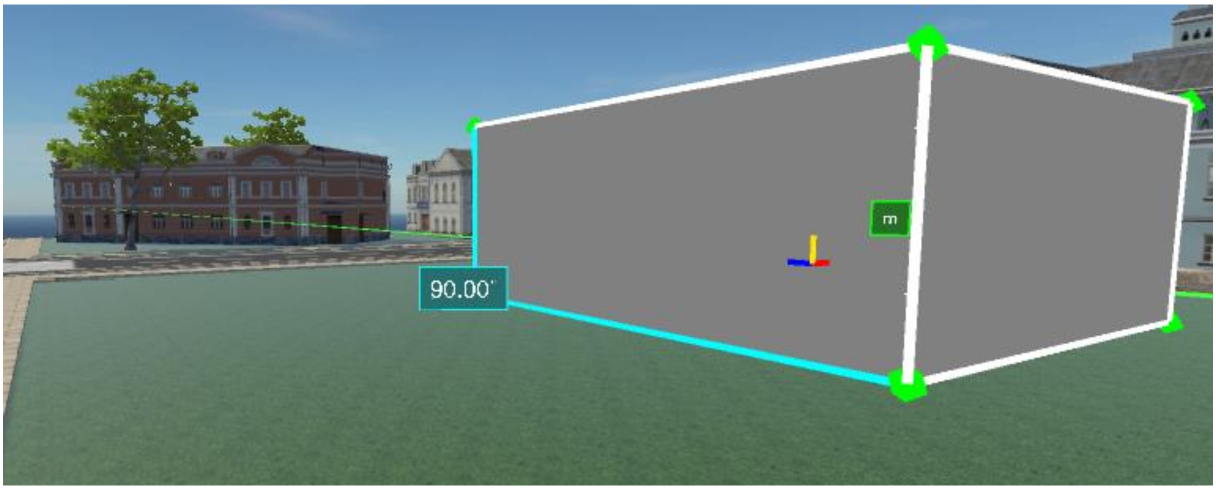

Figure 35 - User measures the angle between the base and the wall of the building.

The tools were organized under a radial menu, as can be seen in Figure 36. The user would keep one button of the controller pressed to see the menu, and then move the joystick in the direction of an item to select it. The center of the menu displayed the name of the currently active tool. This design was later improved, as described in Section 4.1.3.

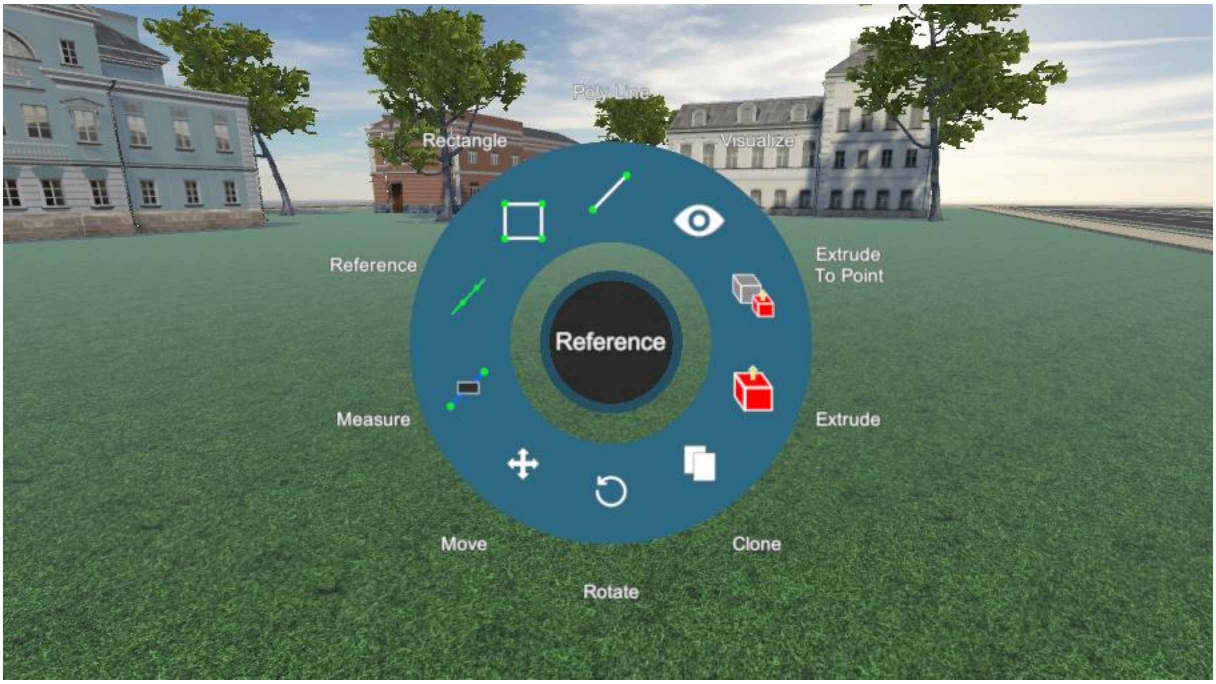

Figure 36 – Radial menu allows the user to switch tools quickly. To select an item, the user moves the joystick towards that direction.

After the interaction workflow and the techniques were implemented, we started working on the real augmented reality application. Our objective with the simulated augmented reality application was to prototype the interaction and the modeling tools quickly, while ignoring some aspects of the real application, like outdoor tracking and augmented reality head-worn display limitations. At this point, we achieved a system that was robust enough, and we would only need to make small adjustments that would be directly related to how the system performs under a real augmented reality setting and user studies.

3.2.3 Augmented Reality Application

The final MASS application was designed to be used on an augmented reality head-worn display (Microsoft HoloLens), which enables the user to see both virtual and real imagery overlaid. The controller was the same from the previous study (Microsoft Xbox One Wireless Controller). Figure 37 illustrates the equipment that the user needs to wear to use the application in-situ.

Figure 37 - User is wearing the Microsoft HoloLens and holding the Microsoft Xbox One Controller.

We decided on using an optical see-through head-worn display, in which the virtual content is displayed over a partially transparent screen, to reduce the distortion on the perception of the environment by the architect, and also to avoid losing the visual quality of the real world. For the same reason, we decided on displaying as little visual elements in the screen as possible, as can be seen in Figure 38. The device is also responsible for tracking the position of the user in the environment, by using visual odometry algorithms.

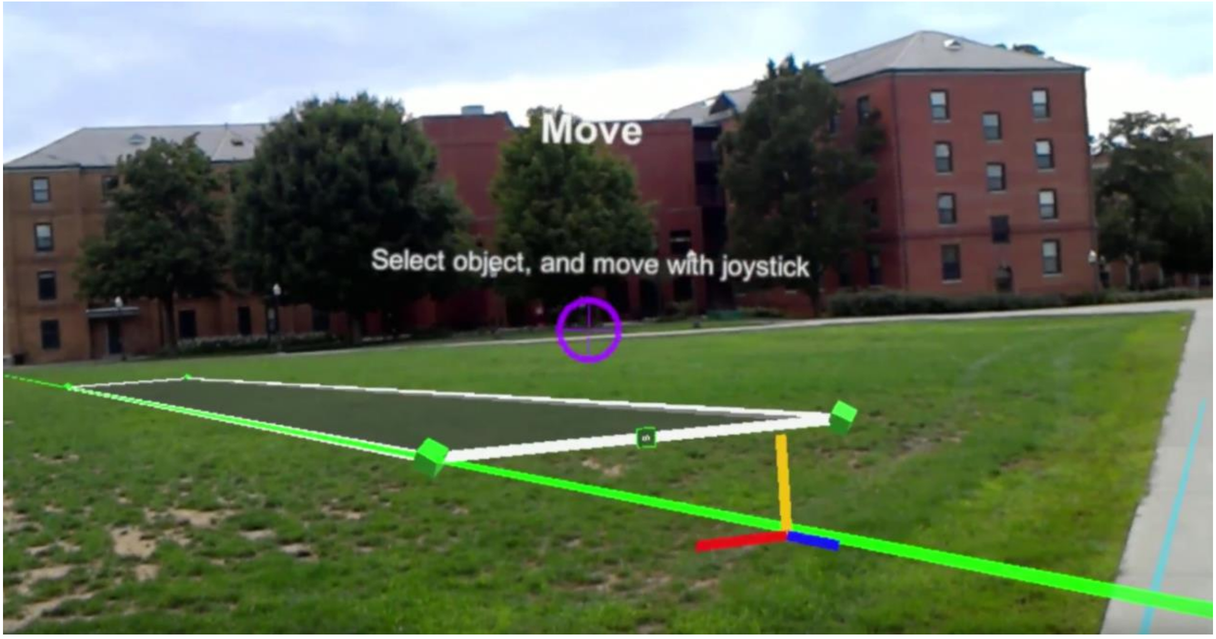

Figure 38 - User interface as displayed for the user. A purple cross-hair defines the point of interaction. If the cross-hair goes over a virtual object, it becomes a reticle and can be used to select the object.

Since we developed our application in Unity, we just changed a couple of configurations and were able to deploy the application to the HoloLens. We followed our concept workflow and were able to design a simple building while following some constraints on size, location, and alignment. We started the process by defining a couple of reference lines and making a rectangle from them, as can be seen in Figure 38. An extrusion as performed to a certain height and the result of this early model of a building can be seen in Figure 39.

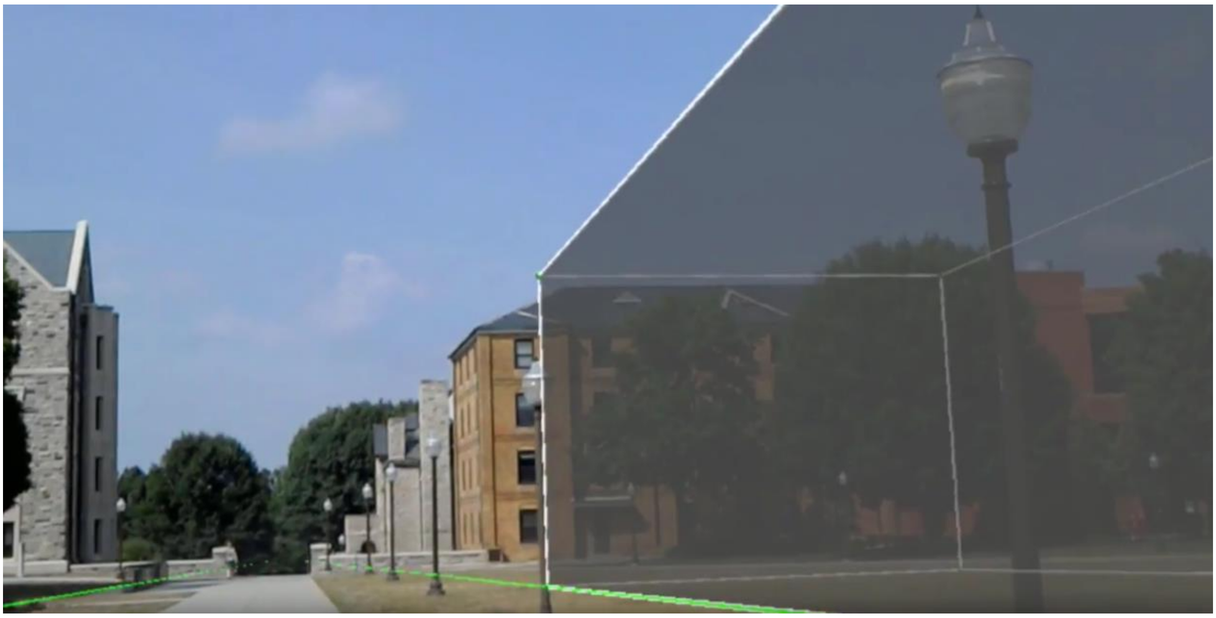

Figure 39 – Early model of a building designed using the system. The green line in the bottom represents a reference line used to align the model. The height of the model is the same as the building in the back.

4. PRELIMINARY USER STUDIES

We performed two preliminary studies, aimed at understanding some aspects of modeling in-situ. First, we performed a formative user study, which is an observational, empirical evaluation method that is applied during evolving stages of design [24], with the objective of understanding problems with the interaction and improving the usability of the application based on the participants' feedback. Second, we performed a summative user study, which is a comparative study between different configurations of the user interface [24], with the objective of understanding the importance of using real-world features while modeling in-situ. The consent forms and questionnaires used in the studies presented in this thesis can be seen in Appendix B - Informed Consent Forms, and Appendix C – Questionnaires.

4.1. Study 1: Evaluating User Interaction

We performed a formative user study aimed at understanding and fixing problems with the interaction before we started a summative study. Amid the questions that we aimed at answering were: How do participants feel about how the application performs? Which modifications are needed to improve the interaction? What are the best qualities of the application?

Three participants (ages 19 to 30) with a background in architecture or 3D modeling took part in the experiment in individual sessions of around 1h30m. 2 were male, and 1 was female. 2 were undergraduate students, and 1 was a graduate student. All participants consider themselves as not tired at all or a little tired. All had at least an intermediate expertise with computers and used a computer daily to work. All had at least intermediate experience with 3D modeling, while 1 had an advanced experience with specifically 3D modeling new buildings, while the other 2 were amateurs. All had little or intermediate experience with video-games, but no or little experience with virtual reality and augmented reality.

4.1.1 Procedure and Task

Upon arrival, each participant was given an explanation about the study and signed a consent form, which briefly explained the study and guaranteed their rights during the experiment. These rights included the anonymity of the generated data and the possibility of stopping the test at any time and for any reason. The consent form also authorized the data to be collected and published. After that, they answered a background questionnaire, with questions regarding the characterization of participants (e.g., age, gender, education), and we introduced them to the equipment. The participants used a Microsoft HoloLens head-worn display and a Microsoft Xbox One Wireless controller.

We divided the study into two parts: a training session, and an experimental task. We decided upon this design given the complexity of learning how to use the modeling tools. Although most of the concepts are known and commercially used by architects, the interaction using the head's position and orientation is not straightforward, especially regarding the techniques for marking points in the environment. We always conducted the training session before the experimental task and in an indoor location. We chose upon that because it guarantees a more controlled environment, being quieter and thus improving the focus of the user, and private, and thus reducing any effect on embarrassment.

During the training session, they had a couple of steps to perform (APPENDIX D – Training protocol), and could only move forward after completing them. In the experimental task, they were free to solve the task as they prefer. During both sessions, the participants used a think-aloud protocol [45]. This protocol requires participants to describe what they are trying to do verbally, along with any thoughts they have, and any possible frustrations or excitement that they experience. We recorded the audio to maximize the amount of data gathered for analysis.

Upon completion of the training session, we walked with the participant to an outdoors area where the main task took place. We briefly explained the task to the participant, including how to detect if there was any significant problem with the tracking of the system that would require a new calibration. We gave them a map and a few requirements of the building they needed to design.

The main task was to design the general geometry of a new building over a grass field area of the Virginia Tech Blacksburg Campus. This building had a predefined position and geometry. By defining those beforehand, we could isolate the creative part of the design process and evaluate the interaction itself. The map from Figure 40, which has a visualization of the building, was given to the participants. They were instructed to keep the map all the time for consults. They were told to follow some requirements for the building:

- The building should be parallel to building A;
- The building should have the same length of building A;

- The walls should be aligned to buildings A and B;
- The building should have the width equals to half the length of building B;
- The building should have two different heights:
    - Half of it will have the same height as building A;
    - Half of it will have twice the height of building A.

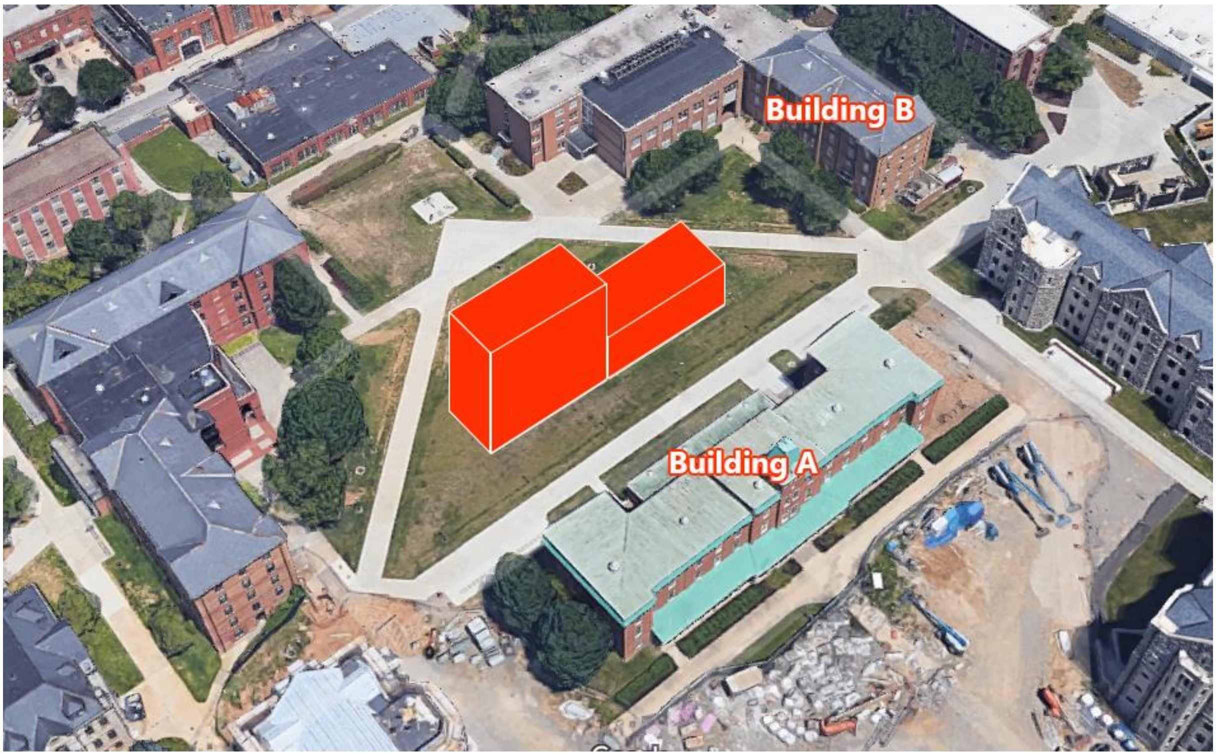

Figure 40 - Map given to the participants. The orange building defines the geometry that they had to model, at the center of a grass field.

Finally, the participant would answer a post-experiment questionnaire (Appendix C – Questionnaires), which included a few questions about the interaction, including a final question about their thoughts on the application. The participant could opt to answer this last question verbally, at his discretion.

4.1.2 Pilots and Adaptations

Before we started the study, we performed in-situ experimentations and pilots following the same procedure and task. During those, we learned that the tracking gets considerably unreliable in this kind of environment, due to the lack of geometric features, variations in illumination, and the size of the area. The Microsoft HoloLens uses a videodometry algorithm to map the space and for estimating the user position in the environment, which is prone to those problems.

We mitigated the problem by placing small columns in the virtual environment which were manually aligned to fixed features in the environment at the beginning of the experiment, as can be seen in Figure 41. The distance between those virtual columns was known, therefore, by calibrating the position of two columns using the position of the participant, we could ensure that the entire system was aligned (the HoloLens aligns the Y-axis automatically by using gravity).

Figure 41 – Two virtual columns added to a known feature (junction in the concrete ground), and a virtual line that shows the border of the pathway.

The participant could only interact with the system while over one of the columns. At each time the participant moved to a new stack, the investigator would hit a button in an auxiliary tablet and re-positioned the environment based on that known point. Of course, this is not an ideal approach for an end-user system, but we believe that tracking technologies are evolving fast and they may mitigate this problem in a couple of years. A map showing the placement of these columns for this study can be seen in Figure 42.

Figure 42 - Points where columns were placed (red). The participant can only interact with the system while over one of these points.

Another problem we had was related to the equipment and temperature. We used the Microsoft HoloLens, which does not have an active cooling system, as our head-worn display. The device conducts heat dissipation passively, and if the inside temperature surpasses a threshold, it starts to decrease processing power and to turn off features. Once the temperature reaches an upper limit, the system promptly shuts down. Furthermore, the device is painted using a dark-toned color, which is known to be much more absorbent of solar energy than lighter tones. We solved this problem by performing the study at the beginning of the day (7AM) or the start of the evening (6PM).

4.1.3 Lessons Learned

In the formative study, participants were asked to rate some aspects of the application on the post-experiment questionnaire. The rating was from 1 to 5, where 1 is the less, and 5 is the most. Regarding accuracy, their response averaged a 3; regarding ease of use, their response averaged a 3.67; regarding how fast they could complete the task, their response averaged 2; regarding how much natural the interaction felt, their response averaged 3.33; regarding how much fun they were having, their response averaged 4; finally, regarding comfort, their response averaged 3. Answering our questions about how the application performs, we can see that most of their responses were around the middle of the scale, with speed to complete the task a little worse, mostly due to interaction problems that will be explored further, and the fun they were having a little better.

Answering our research question about which modifications were needed, the users expressed some problems during the task or at the questionnaire at the end. All participants complained about the difficulty of selecting points in the distance. Since the selection is performed based on the user's head orientation, there are involuntary tremors that make it hard to change small angles. We solved this problem by changing the size of the collider based on the distance to the user. While the mesh was kept at the correct size to give cues on depth, the collider has a dynamic size that keeps the difficulty of selecting constant. Visual feedback was designed, where a bounding box of the collider is drawn on the screen once the ray-casting hits the object, and before the user confirms the selection.

All participants also complained about the menu. Initially, our menu design had only one level, and it presented all the tools at once on the screen, as depicted in Figure 36. Moving the joystick towards such small angles led the participants to select the wrong tools many times. We solved this problem by implementing a two-level menu. We divided the tools into four groups. The first set of tools can create new primitives, including marking new points, and therefore was named Add. Then, the Edit tool-set followed, where the user could make modifications to the existing primitives. The Extrude tool-set allowed to apply different types of extrusions to a surface to obtain a volume. Finally, the Analyze tool-set focused on helping the user understand the model. The first level of the new menu can be seen in Figure 43. To select a level or a tool, the user would need to move the joystick towards the item. Therefore, any tool was always two movements of distance from being selected. A diagram of the organization of this new menu is shown in Figure 44.

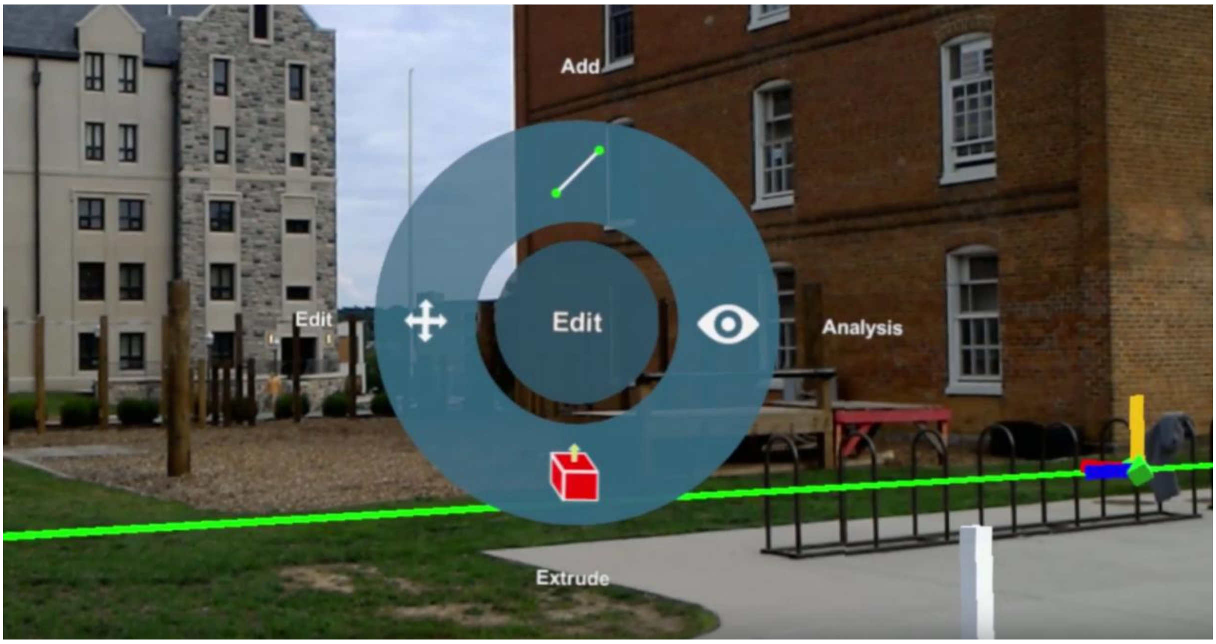

Figure 43 - Menu allows the user to switch tools quickly. To select an item, the user moves the joystick towards that direction. Each of the four options on the menu opens a sub-menu with the tools.

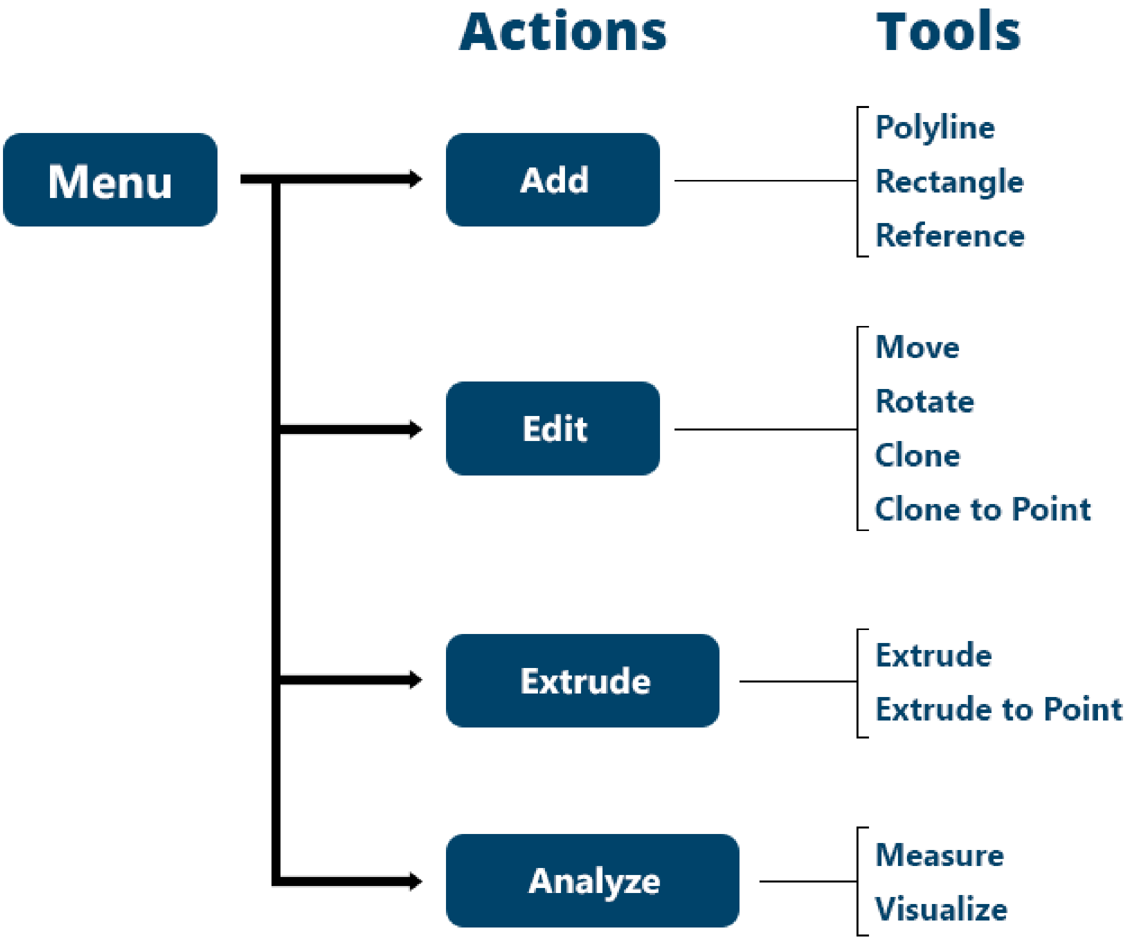

Figure 44 - Diagram of the new menu. Tools were grouped into sub-menus by type of action.

Two participants also complained about the difficulty of undoing actions, due to the lack of an undo button. This problem was solved by implementing undo and redo stacks, each with a fixed button on the controller. At every action, the system stores the state of the system. Once the undo or redo button was pressed, the system would restore the whole model. The system stored and could recover up to 5 following states on each stack.

Participants also described the best quality of the application as allowing you to see the real world and virtual content at the same time. One participant stated that it could really be used to help designers. Another participant considered the simple visuals and clear colors helpful in understanding the application.

4.2. Study 2: Evaluating the Usage of Real-World Features

We performed a summative user study with the objective of understanding the importance of using real-world features while modeling in-situ. In this study, we explored two versions of the MASS application with different levels of support for using those features. The question that we aimed at answering was: How supporting real-world features improve interaction for a tool to design preliminary buildings in-situ?

Naturally, one variation that we explored was the original system, with all the modeling tools that we presented previously (except for the clone to point tool, which was introduced in a later study). This version was able to allow the participant to use neighboring features that were not directly over the area that we want to construct, allowing the participant to modify the model indirectly. For instance, the reference tool can create points over the corners of an existing building and define an infinite line that can cross the terrain and be used by the model; extrude to point can discover the height of extrusion by marking a point on the top of an existing building.

The other variation removed the access to these specialized tools, namely the extrude to point and reference tools. By removing them, we restrain the interaction to the immediate area where the model will be created. The participant would not be able to align their building with the existing one explicitly but would instead be able to mark points and create segments over the empty terrain. We hypothesized that these extra levels of support would yield a better accuracy, ease of use and usefulness for such a tool.

Twelve participants (ages 18 to 53) with a background in architecture took part in the experiment in individual sessions of around 1h30m. 6 were male, and 6 were female. 7 were undergraduate students, 1 was a graduate student, and 4 were professionals. 4 participants consider themselves as not tired at all, 6 were a little tired, and the remaining 2 were considerable tired. 9 had at least an intermediate expertise with computers, and 10 used a computer daily to work. 9 had at least intermediate experience with 3D modeling, while 8 had at least intermediate experience with 3D modeling specifically of new buildings. 6 had none or little experience with video-games. 8 had none or little experience with virtual reality, while 9 had none or little experience with augmented reality.

4.2.1 Procedure and Task

We used a similar design as of the prior study, also following the same procedure. We divided the study into two parts: a training session, which was the same as in the prior study and was conducted on the room shown in Figure 45; and an experimental task, which was like the previous study, although at a different location shown in Figure 46. We no longer used the think-aloud protocol, but an interview at the end aimed at getting detailed feedback from the participants.

Figure 45 - Location where the training session took place. Colored tapes were used to simulate features of the real world.

Figure 46 - Location where the main task took place. The participant would walk on the right and create their building in the left.

A between-subjects approach was used to evaluate the system, with the independent variable being the version of the system. One group of participants used the complete version of the system, while the other used the more restricted version. Initially, we aimed to analyze the following dependent variables: time to complete the task, accuracy of the edification compared to the ground truth, and the number of times the participant had to undo actions.

The main task was to design the general geometry of a new building over an empty parking lot at the PUCRS Campus. This building had a predefined position and geometry. The map from Figure 47, which has a visualization of the building, was given to the participants. They were instructed to keep the map all the time for consults. They were told to follow some requirements for the building:

- The building should be parallel to building A;
- The building should have the same length of building A;
- The walls should be aligned with building A and sidewalk B;
- The building should have the width equals to 15m;
- The building should have two different heights:
  - Half of it will have the same height as building A;
  - Half of it will have half the height of building A.

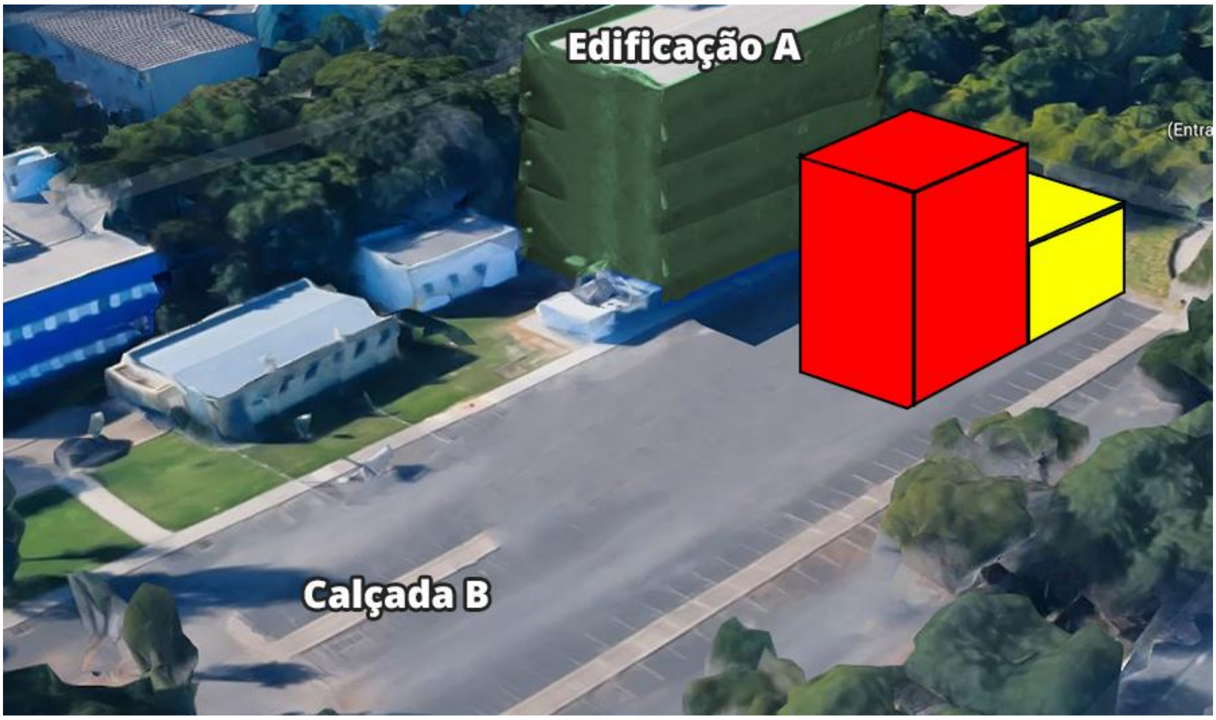

Figure 47 – Map given to the participants. The red and yellow building defines the geometry that they had to model, at the center of the empty parking lot. "Edificação A" means "Building A"; and "Calçada B" means "Sidewalk B".

After finishing the main task, the participants answered a post-experiment questionnaire, which included a few questions about the interaction, and a final questionnaire which contained the following questions:

- What is your opinion about the use of augmented reality for architectural planning, including massing studies?
- What would be the benefits and potential negative points?
- How important do you think it is to design new buildings using the real-world context?
- Do you think it is useful to define the footprint of the building by using real-world features?
- Which other tools do you think could be added to the application you have just tested?

4.2.2 Lessons Learned

We initially aimed for this study to be an explicit comparison between both systems to understand the impacts of having those extra tools that use real-world features in the final design, but a couple of problems prevented us from reaching this result. However, we did obtain some valid knowledge on the problem we are trying to solve, and we will be discussing it in this section.

The first problem we had was related to the location. Since we were doing the study outdoors, we were exposed to weather conditions. We canceled sessions in case of rain, which led to a high canceling rate due to geographic characteristics of our city. Sensitivity to weather is a problem that is not related to the equipment or our implementation, but rather the whole concept. Unless under particular environments where the user could stay in a protected environment and work from a distance, which is supported by our approach, the weather will always play an essential role in modeling in-situ. The user could use an umbrella if someone else were to hold it, but that is not a very practical solution. On the other side, our experience also supports the idea that the environment will influence the characteristics of the building, and the weather is an essential factor.

The overheating problem that was detected in the previous study was still a factor. During some sessions, the device just turned off, and the participant could not finish the model, while during other sessions, the system would turn off some essential feature, like Bluetooth or wi-fi connectivity, making the experiment unmanageable. We tried to minimize this problem by using an umbrella, which reduced the temperature of the device considerably, although as mentioned before, that is not a practical solution.

Due to the problems of overheating, and the difficulty of visualization the digital information on bright environments, as detected in the previous study, we had to schedule the sessions at the beginning or end of the day (8 AM, 6 PM), when there was some light (needed for tracking), but when it was not warm or bright enough to make the session unlikely to succeed. These constraints led to a low turnout of participants, and a minimal number of days where we could conduct the study.

All those previous explained problems rendered the study undoable in large scale. We tried to conduct the study for eight weeks before we concluded that we would not be able to finish it until we have found a more permanent solution to the problems. Only 6 participants completed the full session, while the other 6 completed it partially. Therefore, performing quantitative data analysis is not possible. We can, however, discuss what we learned from the final interview and the general behavior of the participants.

All participants agreed that augmented reality could be used in the architecture domain. In fact, since some participants were professors of the architecture department, the study triggered a discussion in the department about how the use of augmented reality technologies could be taught in the courses of their bachelor’s degree program.

Participants highlighted the need in architecture for designing a building that fits the environment. Otherwise, it could look like out of place, sometimes referred to as a “spaceship.” By being at the location, the user has a first-person viewpoint of the building in the actual environment, and this helps in this process. Also, by modeling at the location, the process can take less time and be more iterative. Sometimes pictures and maps can be outdated and make the process more difficult. At the location, they would look at things like the height of surrounding buildings, the presence of vegetation, the flow of people, the presence of nearby streets or highways. One participant also commented on the importance of showing early results for the client in real-time, to discuss the ideas for the project.

They pointed out some negative aspects. Mostly, they complained about the brightness of the display, because it was difficult to visualize the virtual content, and the ergonomics of the device, which is too heavy and not very comfortable. They suggested adding other tools, such as shortcuts to create circles, curves and other geometric forms; an expansion of the extrusion tool to also allow extrusions inside volumes, to remove parts was also suggested. They commented that the application is not as fast to make modifications as a volumetric mock-up, while also not being as precise as a traditional modeling tool, such as Trimble Sketchup or a CAD tool.

Some participants discussed the accuracy of the model. Although they agreed that the model they created was not very accurate, they also argued that for this phase of the design process this would not be an issue. They did, however, express that if in the future they use this kind of system in later phases of the process such as the modeling of a detailed version of the project, or an executive project, then some problems would arise. The accuracy of the marked points would play a significant role, and the system would need to support interoperability with commercial tools, importing and exporting the geolocalized models.

From our qualitative observations, we can also add that participants from both groups ended up using features from neighboring structures. While they did not have the specialized tools, we did not constrain the area where they could use the other tools, which they naturally combined to be able to use those features. One participant from the group with the restricted version verbally complained about not having guidelines, while they were solving the task. The participant explained that by using line segments and move operations they were able to get the points that a guideline or reference tool would provide.

At this study, our initial aim was to understand how the level of support for using real-world features would improve the process of design. From the qualitative data we gathered, we can conclude that there would make no sense to design the building without using such neighboring features, which were naturally used by participants from both groups. Tools like references and extrude to point could potentially improve the process, but we cannot prove our hypothesis with the data we were able to gather. This hints that our design for this study may not have been well defined. Instead of evaluating the support for neighboring real-world features, we should instead be evaluating (a) the influence of the accuracy of the marking technique in the final model, and (b) the use of real-world features based on marking versus their use based on perception.

5. SUMMATIVE STUDY: EVALUATING THE IMPACT OF POINT MARKING PRECISION ON MODELING PERFORMANCE

Following the leads that we obtained on the preliminary studies, we performed a summative user study with the objective of understanding the impact of the precision of the point marking technique on the process of modeling in-situ. Initially, the question that we aimed to answer was: How are the accuracy, ease of use, and usefulness of 3D modeling techniques affected by the precision in which points based on real-world content were defined? Later, we also included a secondary question: How are the accuracy, ease of use, and usefulness of 3D modeling techniques affected by the use of perception for aligning lines with real-world content?

5.1. Experimental Design

We made some changes to the experimental design and procedure from the preliminary studies. We decided on conducting this study in a single session. Instead of teaching the participants how to use the entire system and giving them a task, we simplified the training session to a small tutorial on how to use the point marking technique and some basic commands (selection, release, and deletion). After the tutorial, we guided them through the main task that was described using a step-by-step approach.

We evaluated the effects of point marking technique in the modeling process within-subjects, having the marking technique as the independent variable. We know from Lages et al. study [22] that the Geometric technique has lower precision than the Vector Cloud technique when marking points, which led us to decide on using these same techniques in our study. The ordering of the techniques was counterbalanced to minimize any learning or boredom effects.

The following dependent variables were analyzed: accuracy of the position of points that defined the new building compared to the ground truth, the orientation of line segments compared against the ground truth, and the angle between the intersecting line segments that define the new building. From the questionnaire, we also tried to obtain information on the visualization and perception aspects, by asking the participants some questions about how they perceived the final building and its relation to the environment.

5.2. Experimental Design Modification

After we completed the first round of participants, we noticed that the most significant accuracy errors in their solutions were not related to the marking techniques, which we were aiming to evaluate, but rather a step of the task where they had to align reference lines to real-world features using the clone and move tools, which were visual. Therefore, we decided to automate this process with a new tool and compare how this changed the results, resulting in a new research question and hypotheses.

This comparison was done between-subjects. Group A participants, which consisted of our original group, cloned and moved the references visually, using the joystick and receiving visual feedback with the position of the reference in the environment. Group B participants, which consisted of our new group, created a point at the place where they wanted the reference to cross and used a new tool, called Clone to Point, to clone a new reference passing through this position, while maintaining the same orientation as the base reference.

5.3. Research Questions and Hypotheses

We worked with two research questions, the primary one being about the effects of precision of the point marking technique, and a secondary question about the use of perception to align lines.

RQ3 - How are the accuracy, ease of use, and usefulness of 3D modeling techniques affected by the precision in which points based on real-world content were defined?

From this we have drawn our hypotheses:

H1. *If techniques for defining points based on real-world content are <u>imprecise</u>, then the overall **accuracy** of the model <u>will be lower, on a much larger scale.</u>*

We believe imprecise point marking will have a cascading effect on the accuracy of the model deriving from the marked points. For instance, if there is an error of 20 cm in the positioning of a point, and this point was used to make a reference line, this could turn into a 2m error when creating another pointer over the reference line. The reasoning behind this is that the error would influence the orientation of the said reference line, making the error cumulative. The further away the point is created over the reference line, the bigger the error will be.

H2. *If techniques for defining points based on real-world content are imprecise, then the **ease of use** of the modeling tools will be compromised because it becomes harder to understand the geometry being created.*

Based on the assumption that **H1** is right, we believe that the lower accuracy of the marked points will lead to difficulty in understanding the model. Not only the accuracy is lower, but since the technique is imprecise, the range of how inaccurate the points are will be broader. We believe that considering this and the lack of occlusion and visual cues like shades, the user could get confused when trying to understand the model.

H3. *If techniques for defining points based on real-world content are imprecise, then the **usefulness** of the modeling tools will be compromised. This happens because the error becomes too big to justify the usage of said references.*

The argument for using reference lines, and clones or extrusions based on point positions is because they are well defined, making it is easier to mark these points. If the propagation of error that we verify in **H1** is indeed big enough, it might be useless to use these tools. For instance, marking the point directly in the final position could have the same 2m error as creating a reference line with the 20cm error.

We also investigate how aligning lines based on perception performs while modeling in augmented reality.

RQ4 - How are the accuracy, ease of use, and usefulness of 3D modeling techniques affected by the use of perception for aligning lines with real-world content?

From these, we draw the hypotheses:

H4. *If the technique for aligning lines is based on perception, then the overall **accuracy** of the model will be lower.*

Although the point marking techniques can be imprecise, both techniques we are using are still based on triangulation. We believe that, when modeling, the error of the final model will always level with the lowest precision operation. Here, we believe that even if we have precise marking techniques, the model would still be imprecise, because the alignment based on perception introduces much error. For instance, we could have less than 10 cm error in point, while a 3m error is introduced in the alignment.

H5. *If the technique for aligning lines is based on perception, then the* ***ease of use*** *of the modeling tools will be compromised because it* *becomes harder to understand the geometry* *being created.*

Based on the assumption that **H4** is right, we believe that the introduction of error would make users confused. In this case specifically, we believe users would get confused with the task of aligning an infinite line without occlusion to a real-world feature. They may not understand when the line is crossing said reference.

H6. *If the technique for aligning lines is based on perception, then the* ***usefulness*** *of the approach will be compromised, because the* *error in the alignment is much bigger* *than the error in the marked points.*

Here we argue that using a precise point marking technique becomes useless, since the error in alignment is much bigger, as we hypothesized in **H4**.

5.4. Procedure

The participant would arrive in the area where the study would take place, the conventions center of the PUCRS university, and the investigator would greet them. They would sign a consent form, which explained their rights and explained the study, as in the previous studies. Upon completion, the investigator would show them a video of the application being used in the outdoors, namely the solving of the task from study two from the user's viewpoint. Some aspects of the modeling process would be briefly outlined in the video, to guarantee that the participant understood what the tools look like and the cases where architects could use it.

They would also answer a background questionnaire (Appendix C – Questionnaires), with questions regarding the characterization of participants (e.g., age, gender, education), and would be presented the equipment to them. The participant would use the same equipment from the previous studies, a Microsoft HoloLens head-worn display and a Microsoft Xbox One Wireless controller. Before starting, the HoloLens calibration app would measure and calibrate the interpupillary distance (IPD) of the participant, and our application would screen participants for color blindness, by showing numbers and colors on the screen and asking the participant what they were seeing.

This study comprised a within-subjects design where the participant would test both marking techniques. For each technique, a training session to understand the usage of the technique was done right before the main task. During each of these training sessions, they marked two points using the current technique, and in the end, were asked if they understood it and were ready to proceed. After the first training session, the participant would also receive two extra steps of instructions, where they learned how to select and release existing objects, and how to undo or redo operations.

The main task comprised recreating the geometry of a building. Unlike in the previous studies, the participant did not have the freedom to determine how to solve the task but would instead follow a sequence of steps to achieve the building. Each of those steps was a well-defined small task, like creating a reference line. The participant could, however, undo actions if they believed that, at the end of each of those steps, something was wrong (e.g., the alignment, the position of the points). These were done at the participant's discretion and would strongly rely on their perception of the modeling. Once they passed to the next step, however, they could not undo something from the previous step, unless there was some system failure in a past operation unrelated to marking that would render the rest of the task undoable.

After the main task, the participant would answer a couple of questions about their perception from a pre-defined point of view. This step would help us to determine their understanding of what they built, and how the marking techniques could influence that. This part included the following questions:

- How many people do you think would be able to walk side by side in the space between the real wall and the new building?
- How do you feel about the height of the building related to the ceiling where you marked the point before? Is it the same, lower or higher?
- Do you think that the building is leveled with the ground, or is there a slope?
- Do you think that the building is correctly aligned with the columns where the reference lines were created?

Upon verbally answering those questions, participants would fill a questionnaire (Appendix C – Questionnaires) on how they rate the system using the current marking technique, regarding some aspects like comfort, fun, and precision.

Then they would redo the training and main task for the second marking technique. Since our design counterbalanced the ordering, half of the participants started with Geometric, and half started with Vector Cloud. After finishing the questionnaire for the second marking technique, the participant would fill a final questionnaire (Appendix C – Questionnaires) with questions that compared both techniques, including questions like which one they preferred and why.

The procedure was the same for both groups in the between-subjects approach. The only difference between them consisted of two steps regarding the alignment of references in the main task, which we discuss in Section 5.5.

5.5. Environment and Task

As mentioned before, the study took place in the convention center of PUCRS University. It consists of a vast room, of around 6 meters in height, that allowed us to try to replicate the distances and sizes of the use case of designing a new building located in the outside. We decided on this approach to remove most of the technical issues we had in the previous studies that we conducted outdoors. The temperature was lower than outdoors, and the brightness of the environment was well controlled, allowing us to focus on the evaluation of the technique rather than equipment limitations. We still used the artifice of aligning virtual columns to positions in the real world, to minimize any tracking errors. Figure 48 is a picture of the room, covering the area where the study took place.

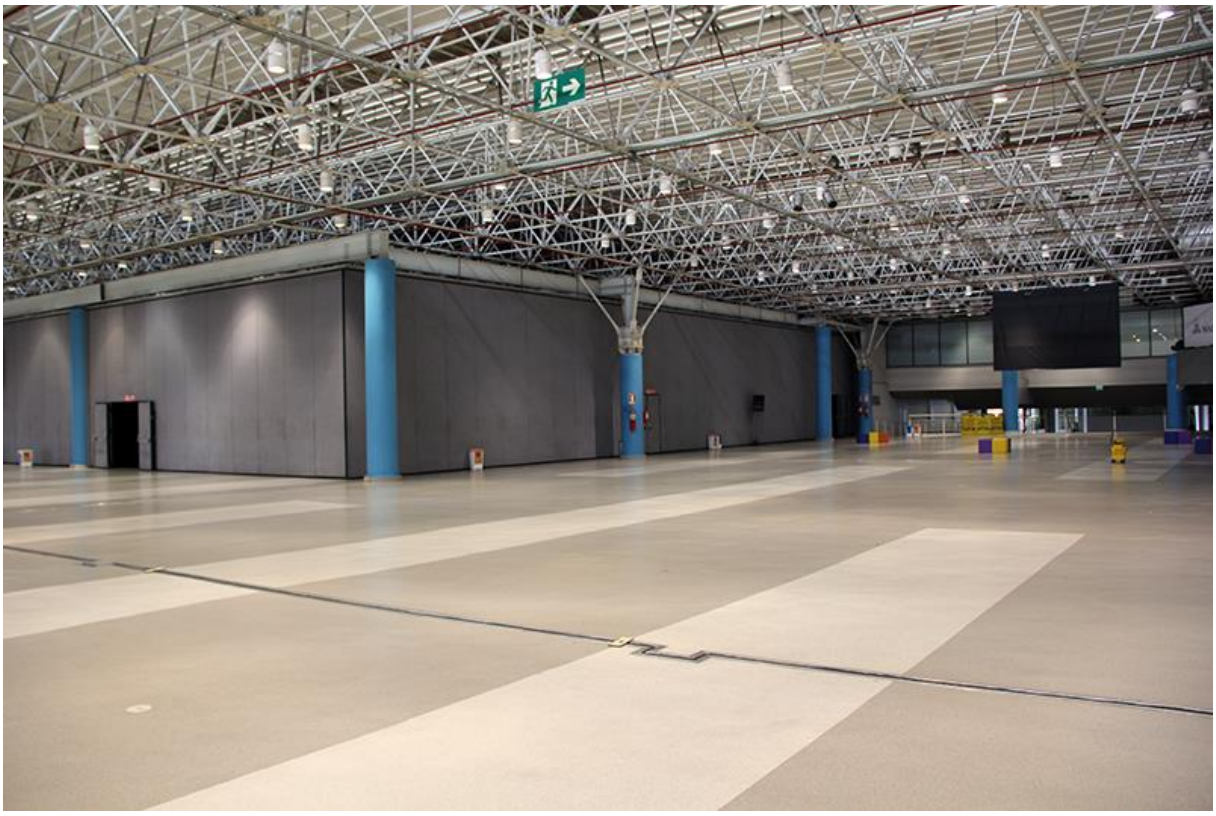

Figure 48 - Events center room where the experiment took place

The main task consisted of nine steps that were described gradually by the investigator. Each step comprised a well-defined task that together would result in the new building. Unlike in the previous studies, the participant was not free to choose how to solve the task, but instead, followed the instructions provided.

The task starts with the participant creating points in existing features. A wooden marker was placed for the participant to know the exact point that they should mark, for example, the column which had Point 1 had a marker with a number 1 on it, as depicted in Figure 49. The participant was always asked to perform the marking at the center of the wooden marker horizontally, but at the bottom vertically, where it touches the ground.

Figure 49 - Location of points A, B and C in the real environment (top), and wooden marker for point A (bottom). The marker had a number 1. Participants were asked to mark the columns at the center of the plate, in the bottom part, where it touches the ground.

The first step consisted of marking points A and B on the respective columns while using the reference tool. This step would result in our reference line, which was parallel to the line that the user walked along. Figure 50 (left) is a drawing of the first step from a top view, which the participant location in black/light-blue, the points in blue, and the reference line in green. The second step consisted of the same operation, but now the participant had to create a reference connecting point A, which he had already marked and only had to select, and point C, which they had to mark. The result is a second reference line, which should be perpendicular to the original reference if no error is present. Figure 50 (right) shows the result after the participant finished the second step.

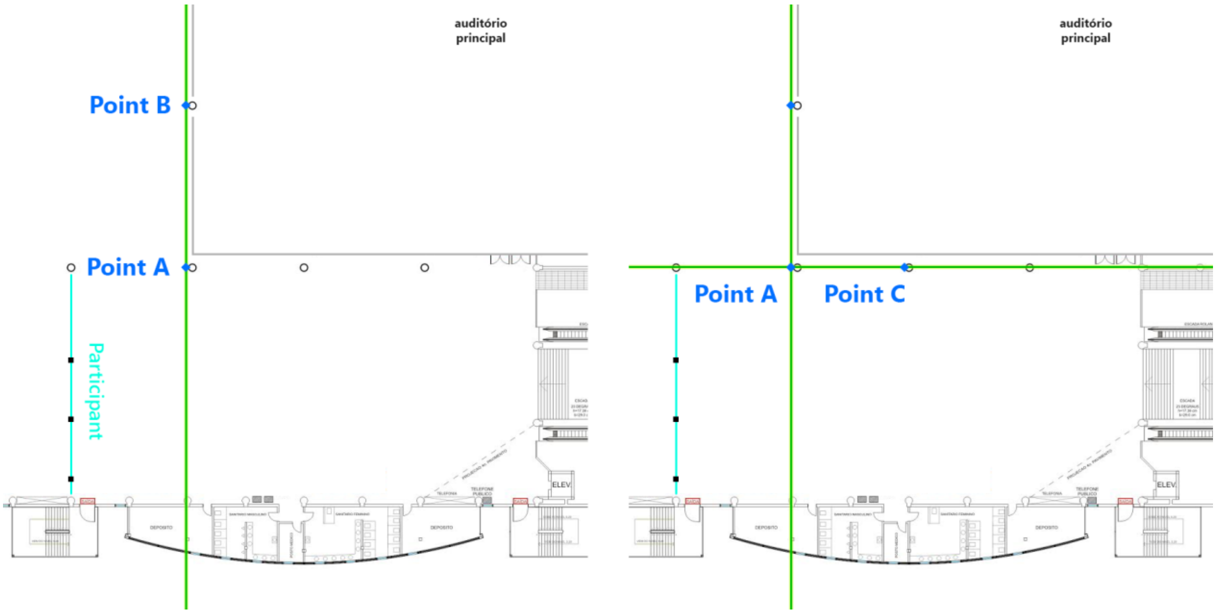

Figure 50 - Step 1(left) and Step 2(right). In both steps, the participant had to create a reference line using one of the points described.

Steps 3 and 4 were different depending on which group of participants was. The problem to be solved was to align the second reference to point D, and to create a clone of it aligned to point E. The location of the points is shown in Figure 51.

Figure 51 - Location of points D and E in the real environment.

Participants from group A solved this problem based on perception. In step 3, they used the move tool to translate the reference line perpendicular to its direction, until they thought that the line was passing through point D. In step 4, they used the clone tool to perform to create a copy and translate the reference to align it with point E. Figure 52 draws what should be obtained at the end of each of those steps.

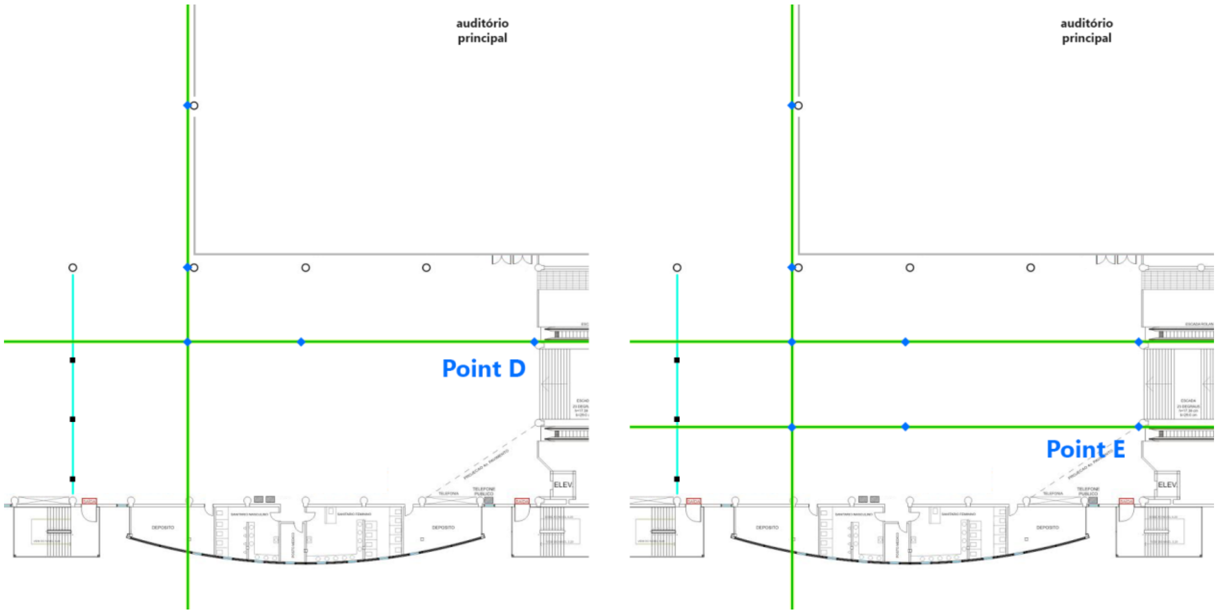

Figure 52 Step 3 (left) and step 4 (right) for group A. In step 3 the participant had to use the move tool to align the reference to the far columns visually. In step 4 he did the same, but with the clone tool. Points D and E were not marked.

Participants from group B did not rely on perception for solving these steps. Instead, they marked points D and E using the free-model marking technique. They used a new tool, called clone to point, that was created especially for these steps. After marking the point using this tool, they select the reference that they want to clone. A copy of the reference will be created and dislocated to match the position of the point automatically. In step 3, they also deleted the old reference, since it was no longer needed. Both steps are presented in Figure 53.

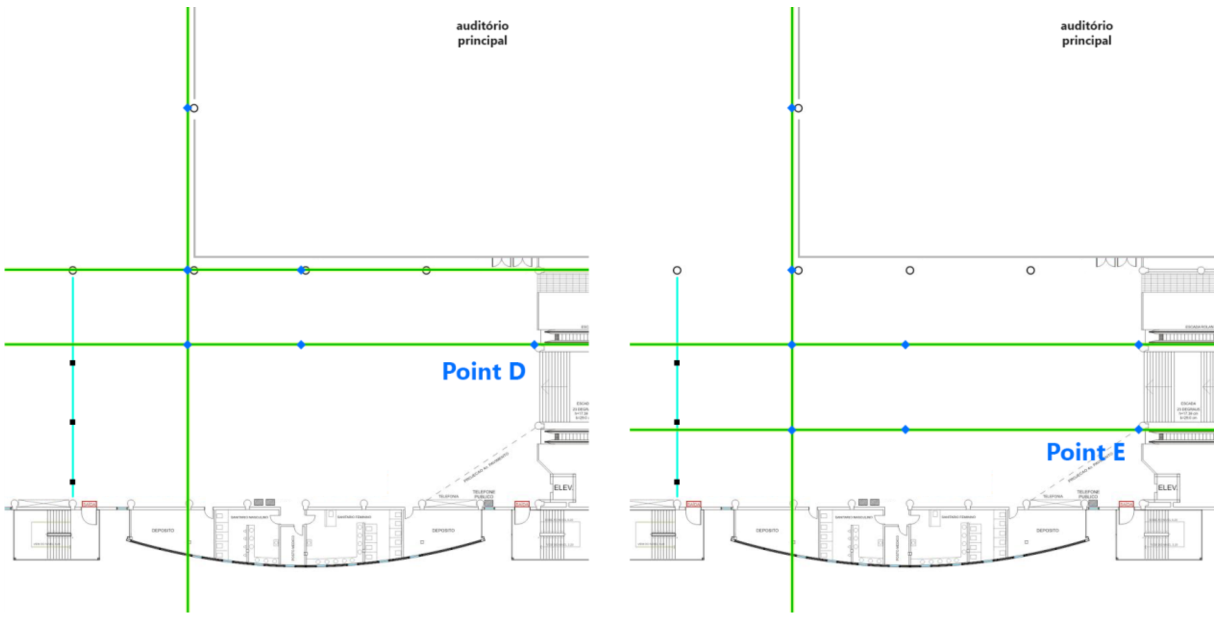

Figure 53 - Step 3 (left) and step 4 (right) for group B. In both steps, the participant had to mark a point in the far columns and clone the reference line to that point. The original reference line created in step 2 was no longer needed and was deleted.

In steps 5 and 6, the participant had to deal with the footprint of the building. In step 5 they would have to select three points over the references (points H, F and G) to define the base surface with the rectangle tool. In step 6, they divided this surface in two using the polyline tool. The division is performed by creating a line segment that splits the surface. Figure 54 defines the steps.

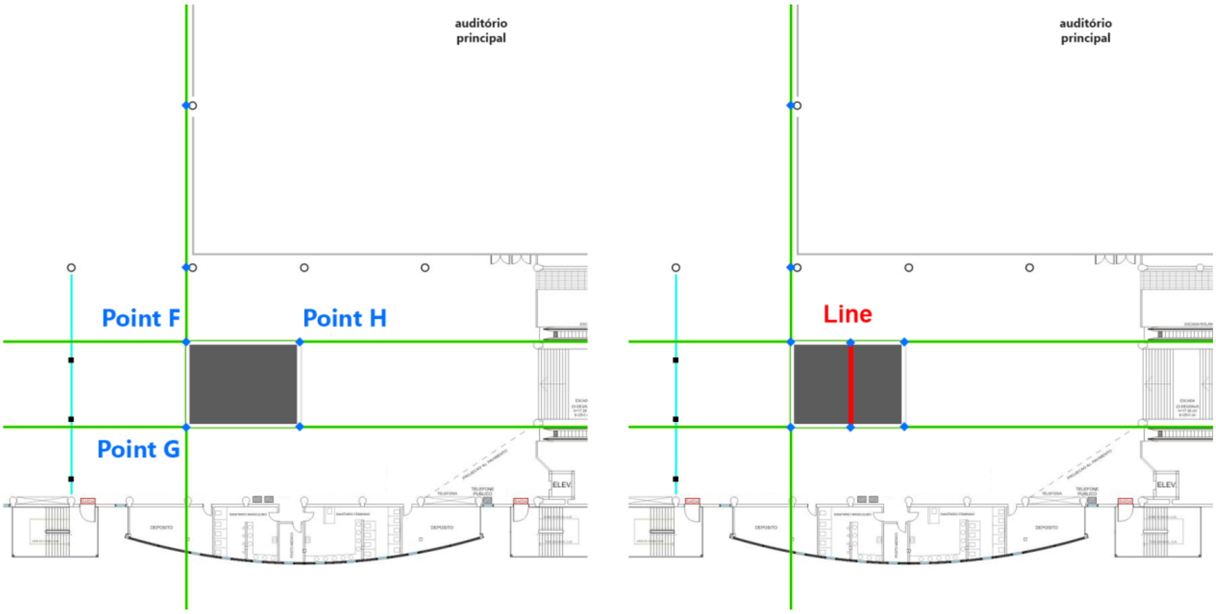

Figure 54 - Step 5 (right) and step 6 (left). In step 5 the participant created a footprint by selecting 3 existing points using the rectangle tool. In step 6 the participant divided the footprint in two with a line segment.

Steps 7 and 8 consisted of extrusions. In step 7, the participant had to mark point I in the ceiling of the room, which we can see in Figure 55. By using the extrude to point tool, they would perform an extrusion on Face A up to Point I, as shown in Figure 56 (left). In step 8, the participant would perform a manual extrusion on Face B up to half of the height of Face A, as shown in Figure 56 (right).

Figure 55 - Location of the point I in the real environment

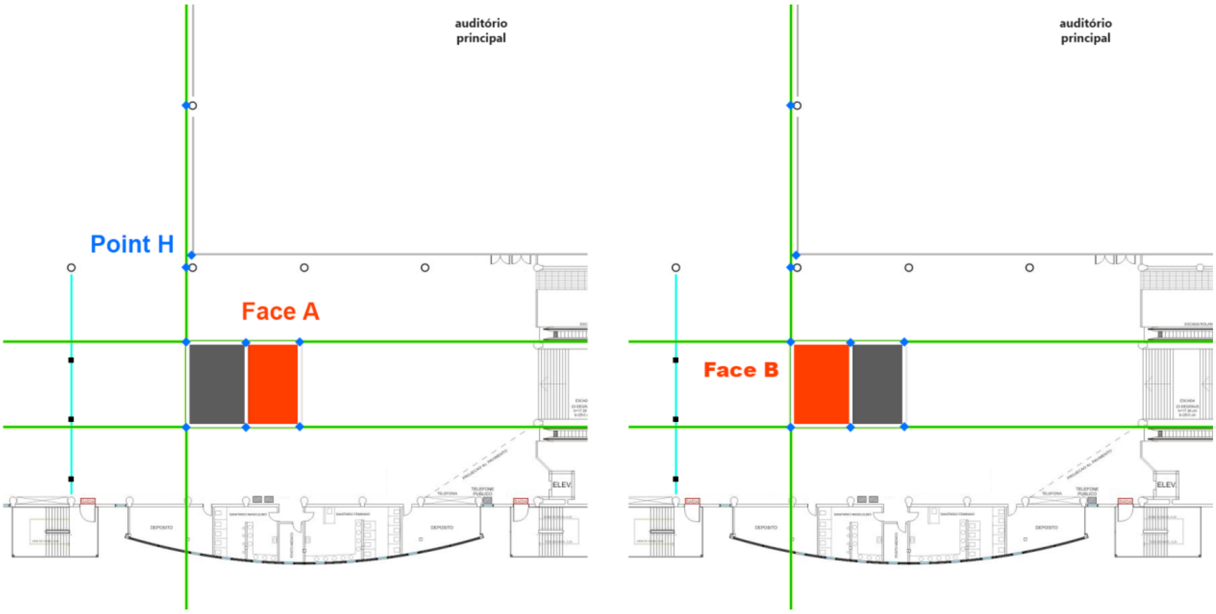

Figure 56 - Step 7 (left) and step 8 (right). In both steps, the participant performed an extrusion. In step 7, they marked point H in the ceiling of the room, and extruded Face A automatically. In step 8 they manually extruded Face B up to half of the height of Face A.

Finally, on step 9 the participant would visualize the resulting building from another perspective and answer a couple of questions. The location where the participant stood is presented in Figure 57.

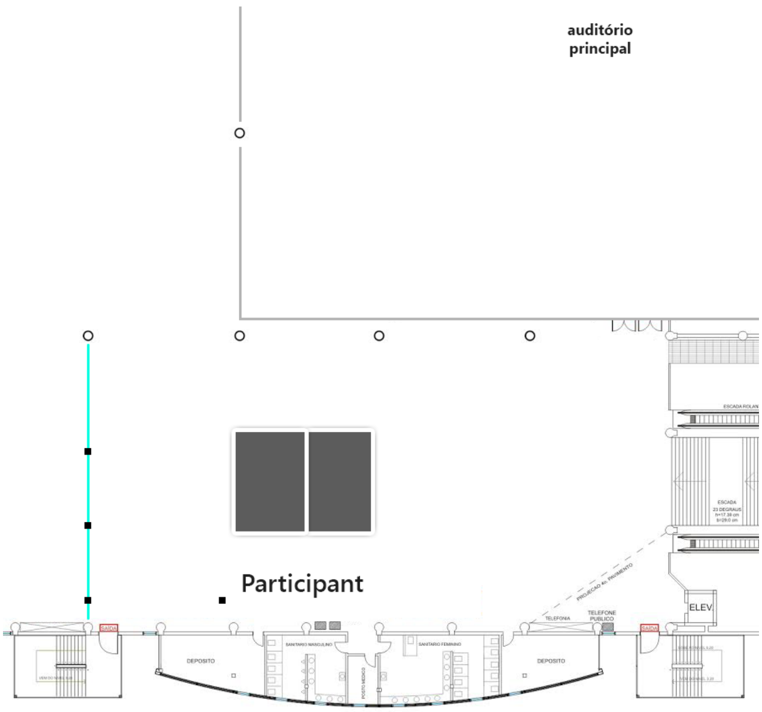

Figure 57 - Step 9. Participant moved to a position close to the building, from a different perspective than they used during the modeling process and were asked a couple of questions about what they could see.

5.6. Participants

Thirty-four participants (aged 19 to 39) from the general population of our campus (no architecture background required) took part in one of our two groups in individual sessions of around 50 minutes.

Twelve participants (aged 19 to 39) took part in the group A of the experiment. All 12 participants were male. 6 were graduate students, 4 were undergraduate students, and 2 were professionals. 6 participants consider themselves as not tired at all, while the remaining 6 were a little tired. 8 had advanced expertise with computers, and all 12 used a computer daily for work. 7 had at least some experience with 3D modeling, and also 7 had an advanced experience with video-games. 9 had none or little experience with virtual reality, while 10 had none or little experience with augmented reality.

Twenty-two participants (aged 19 to 38) took part in the group B of the experiment. 19 participants were male, and 3 were female. 12 were graduate students, 9 were undergraduate students, and 1 was a professional. 9 participants consider themselves as not tired at all, while the remaining 13 were a little tired. 17 had advanced expertise with computers, and all 22 used a computer daily for work. 13 had at least some experience with 3D modeling, and 9 had an advanced experience with video-games. 19 had none or little experience with virtual reality, while 21 had none or little experience with augmented reality.

5.7. Results

We developed an auxiliary application to understand better the data gathered during the sessions. The application allows a 3D visualization of the aggregate of the points and line segments of the final model achieved by each of the participants, organized by technique (Geometric or Vector Cloud), or by the order that they were performed (First or Second). Along with the gathered data, the application also displays a ground truth of the model, making clear how the perfect model would look like. Moreover, the application could also replay each of the sessions individually, allowing the visualization of the task being solved frame-by-frame from any 3D perspective. This application could also perform statistical analysis of our dependent variables automatically, performing a student t-test, calculating average, deviation, variation, and locating outliers by calculating the low and high quartiles of the distribution. All calculations were performed using double precision, 15-16 digits (64 bit). The application can be seen in Figure 58.

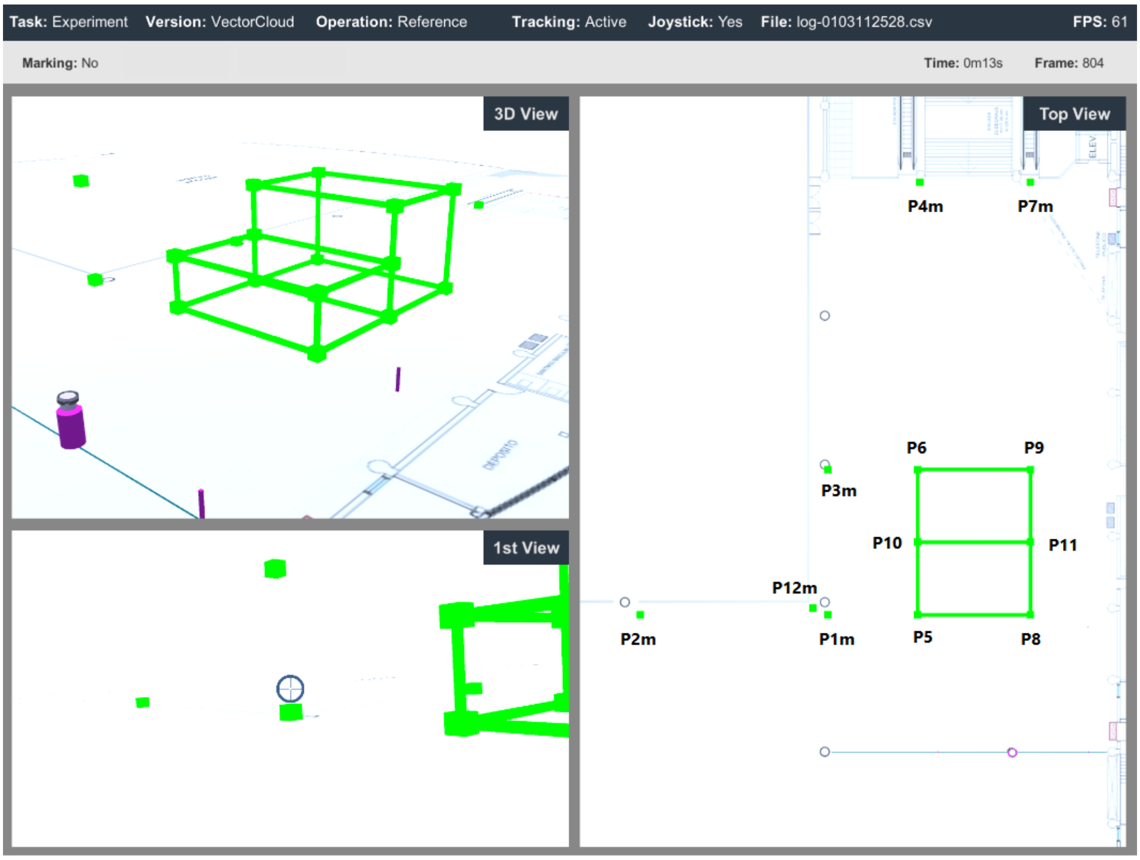

Figure 58 -Auxiliary application to visualize the data of the experiment. Labels enumerate the points that were created by the user. The 'm' means the point was marked using the point marking technique.

We performed visual inspections on both groups, but we did not perform a statistical analysis on group A, or between group A and group B. We chose not to do this because we also corrected a bug on the Vector Cloud technique before starting group B (the frequency of the samples was smaller than what it was supposed to be). Therefore, any quantitative analysis might not represent the real difference between them accurately. What we did instead, was to select a participant with good markings from each group, and describe, step by step, how their solutions differed.

5.7.1 Visual Inspection of Aggregate Sessions

The first analysis we did was a visual inspection of the aggregate of solutions. Dividing the models between the techniques, we were able to visualize the aggregate model for each technique. This aggregate comprised the points and line segments that contributed to the final model of each participant. The distance was calculated between each point and their corresponding ground truth. Points with an absolute error of 2 meters or higher were painted red, while points with an absolute error between 0 and 2 meters were painted on a scale from green to red.

We performed this analysis on group A: Figure 59 and Figure 60 display the aggregate viewed from three different viewpoints with the visual results from using the Geometric and Vector Cloud techniques, respectively.

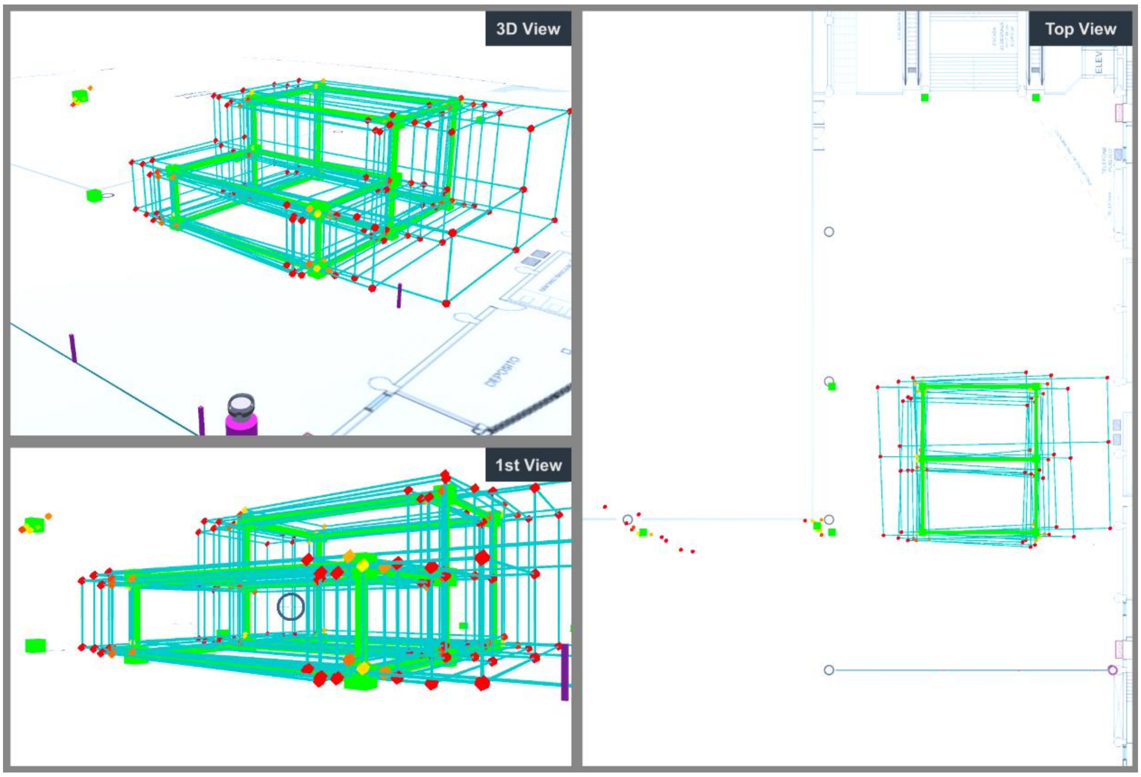

Figure 59 - Superposition of models by participants while using the Geometric Technique.

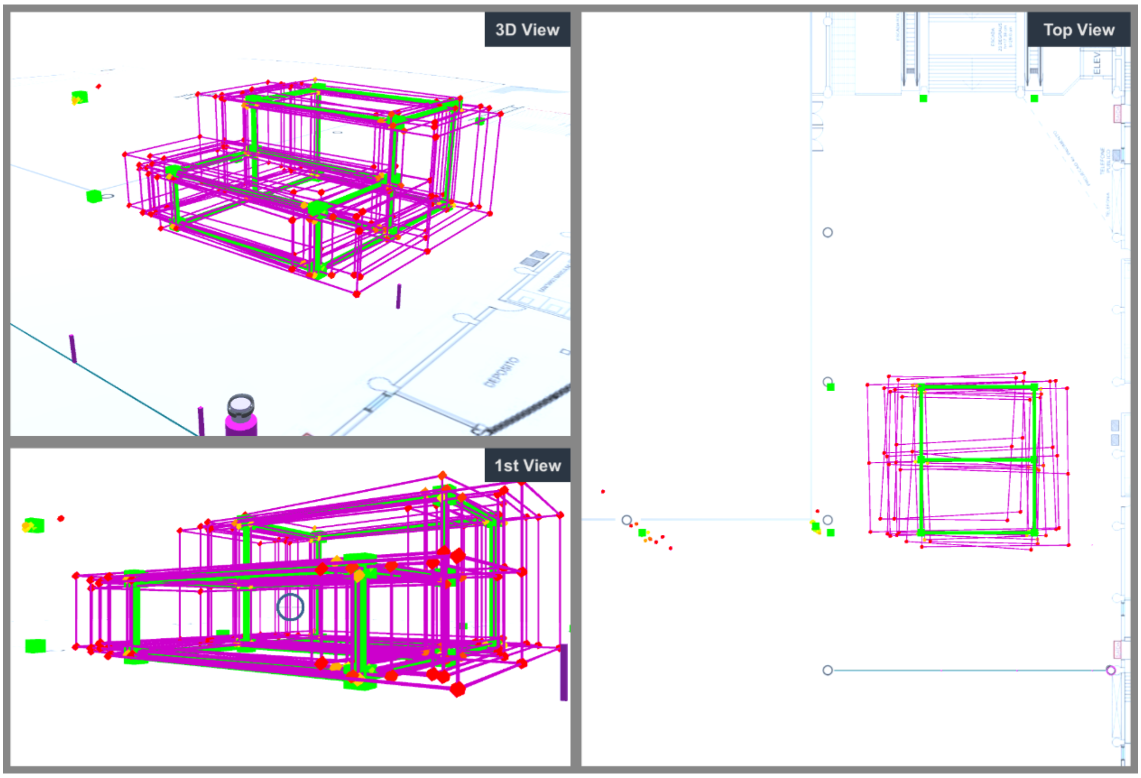

Figure 60 - Superposition of models by participants while using the Vector Cloud Technique.

We also performed the same analysis on group B: Figure 61 and Figure 62 display the aggregate viewed from three different viewpoints with the visual results from using the Geometric and Vector Cloud techniques, respectively.

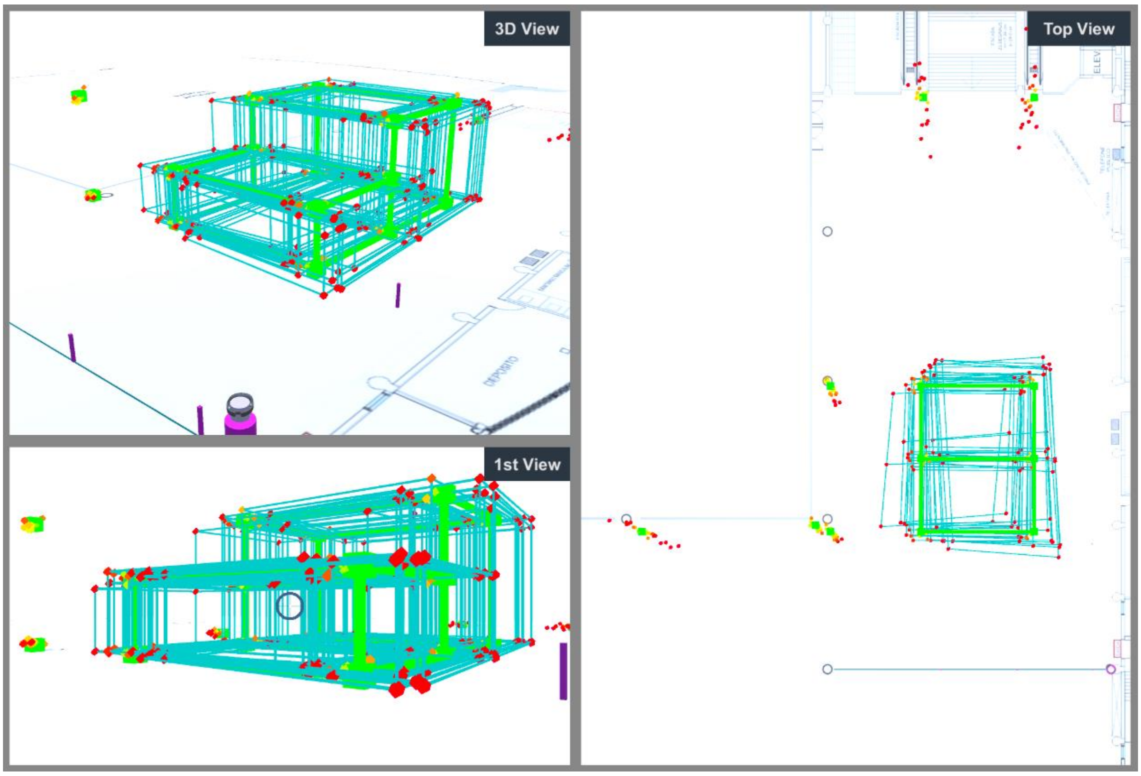

Figure 61 - Superposition of models by participants while using the Geometric Technique.

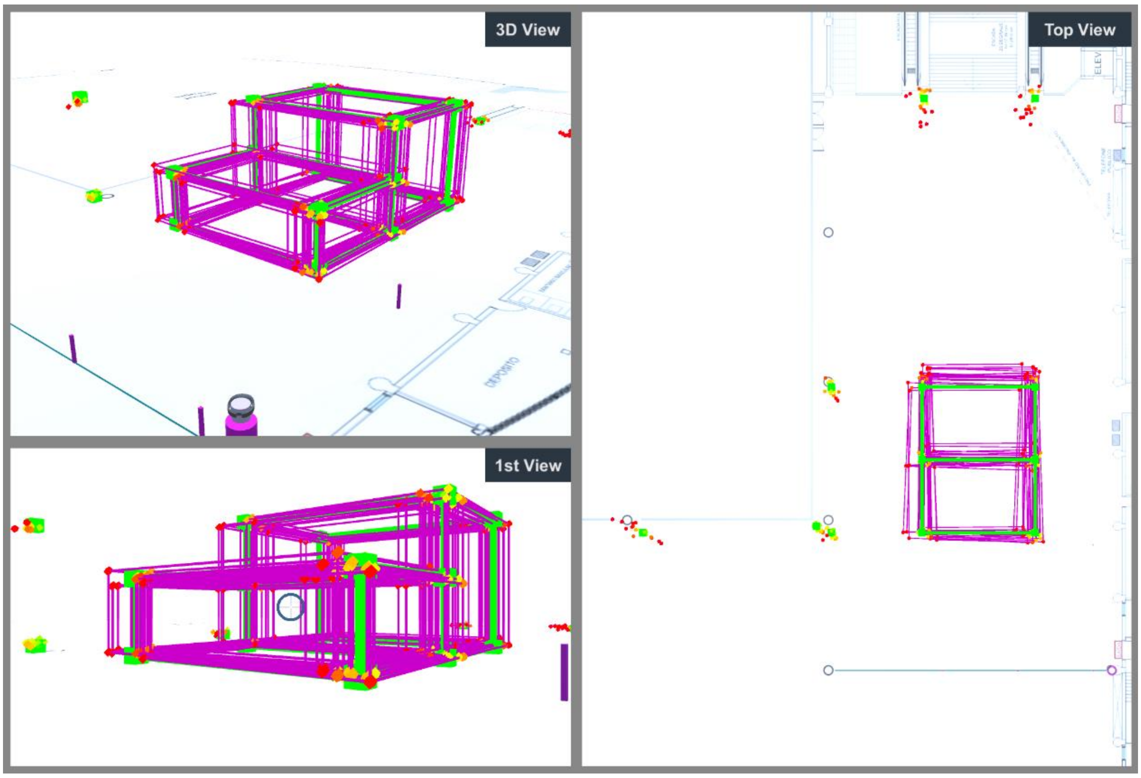

Figure 62 - Superposition of models by participants while using the Vector Cloud Technique.

5.7.2 Visual Inspection of Individual Sessions

We conducted an individual analysis on a sample from each group where the participant had a reasonable accuracy on the marking points. Although starting with the same good markings, their solutions to the task were different, when they were required to perform the alignment of reference lines relative to the real-world features.

For group A, we selected a sample that had a reasonable marking. The first reference has almost no angular error, and the second has a small error. Figure 63 shows the reconstruction of the session, with the ground truth outlines in blue. Later in Figure 64, the participant tried to visually align a clone of the second reference to the columns in the back of the room. We can see that after the operation, these references were considerably in the wrong place. Finally, in Figure 65 the participant completes the task, and we can see the massive error in the area of the building.

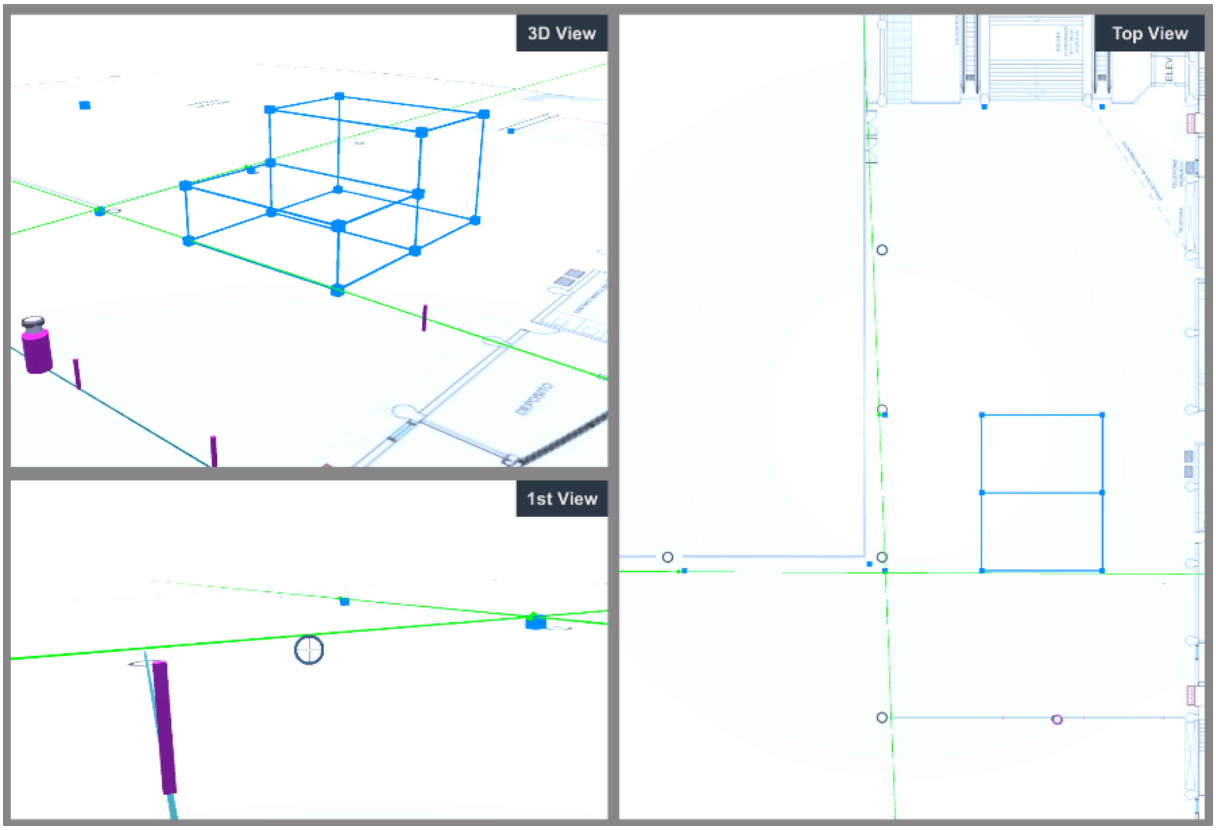

Figure 63 - Participant created three points with reasonable accuracy, generating two reference lines with small to no orientation errors.

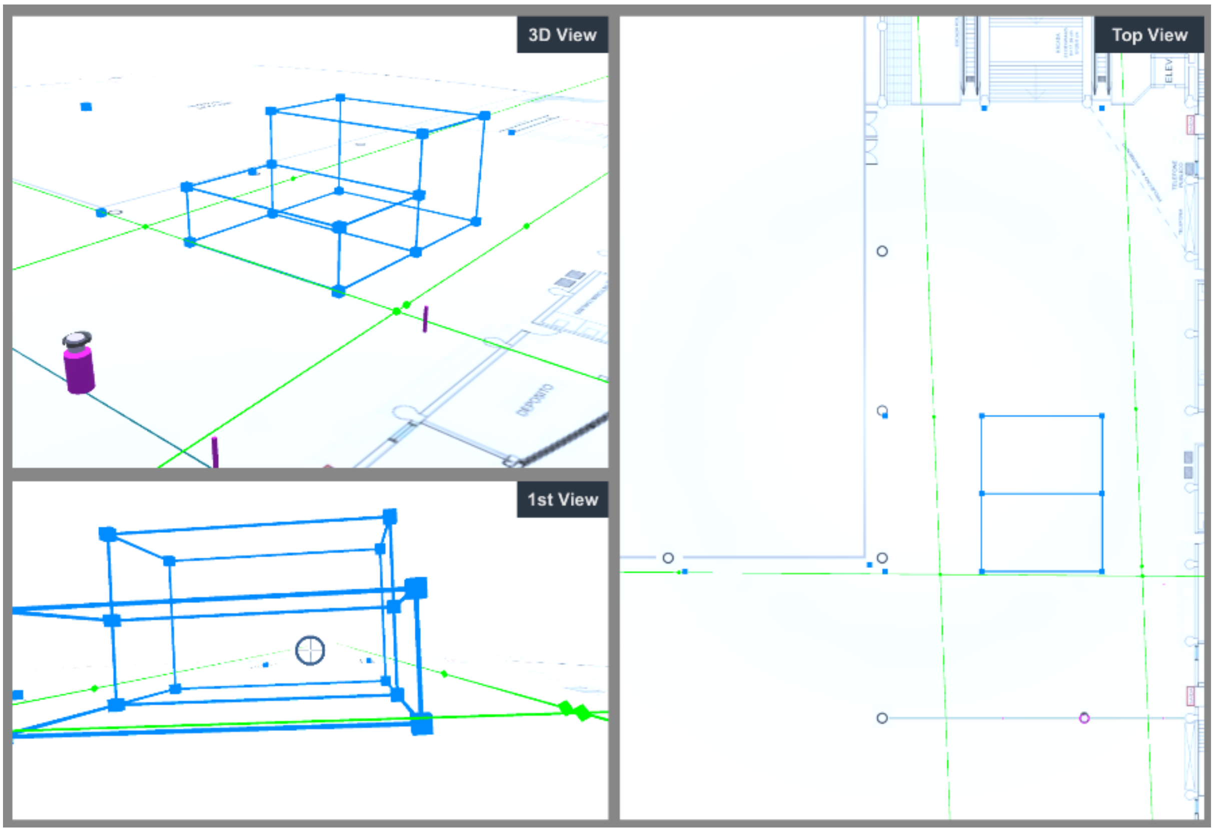

Figure 64 - Participant aligned the references using the cloning tool, with the columns in the back. We can see the lines are not aligned at all with the ground truth points, in blue.

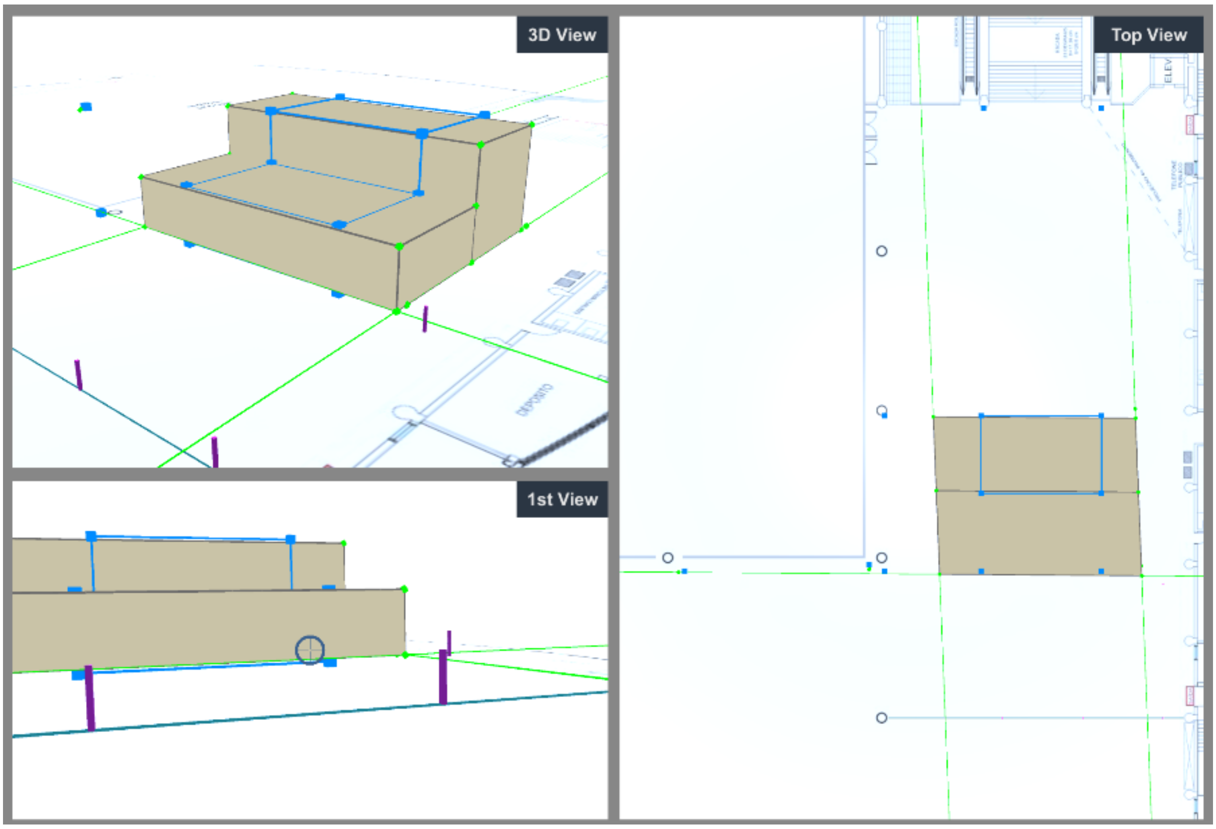

Figure 65 - Participant completed the task. We can see significant errors in the lines that were visually aligned, while the lines on the other axis present a reasonable result.

For group B, we selected a sample that also had a reasonable marking. Both references have almost no angular error. Figure 66 shows the reconstruction of the session, with the ground truth outlines in blue. Later in Figure 67, the participant used the point marking technique to define points over the columns in the back of the room and then cloned the references to cross those points. We can see that after the operation, these references seemed to be reasonably aligned with the ground truth. Finally, in Figure 68 the participant completes the task, and we can see, although the result is not perfect, there is only a small error in the area of the building.

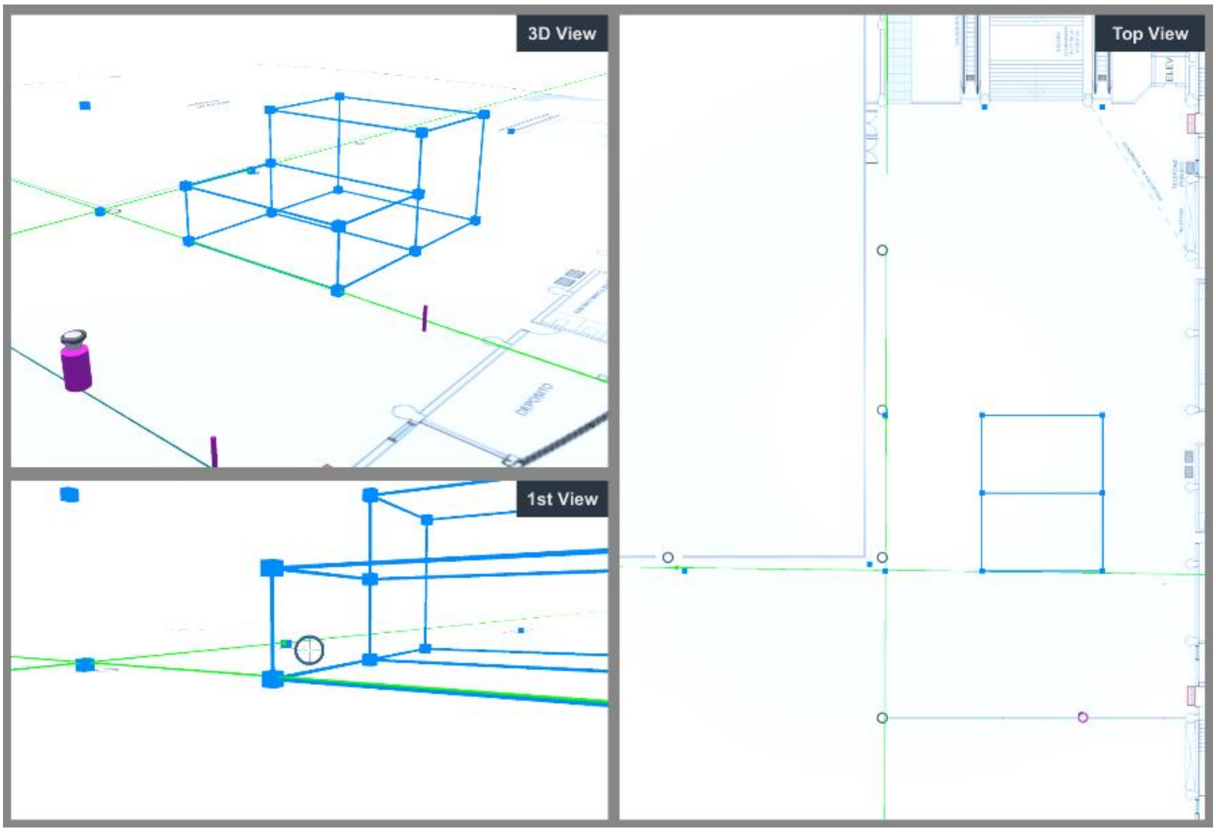

Figure 66 - Participant created three points with reasonable accuracy, generating two reference lines with small to no orientation errors.

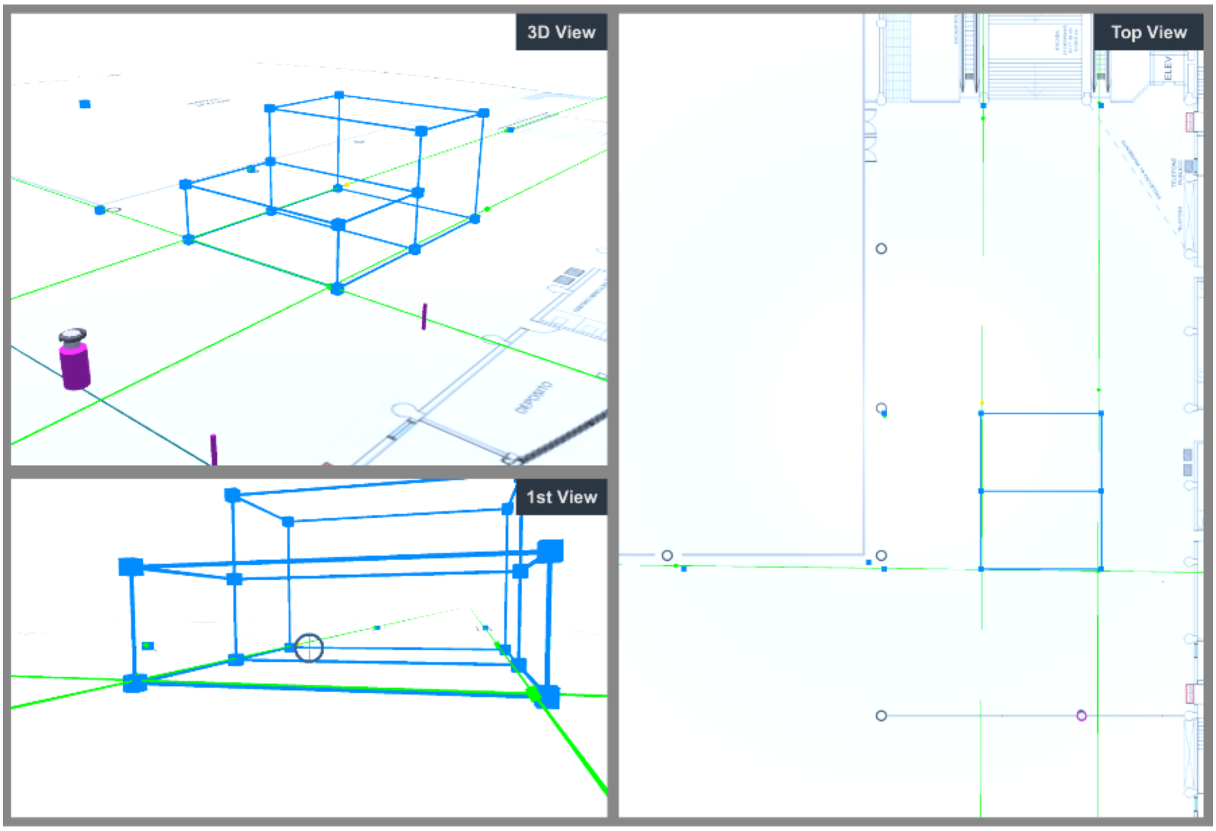

Figure 67 – Participant marked points in the columns in the back and aligned the references using the clone to point tool. We can see the lines are close to the ground truth points, in blue.

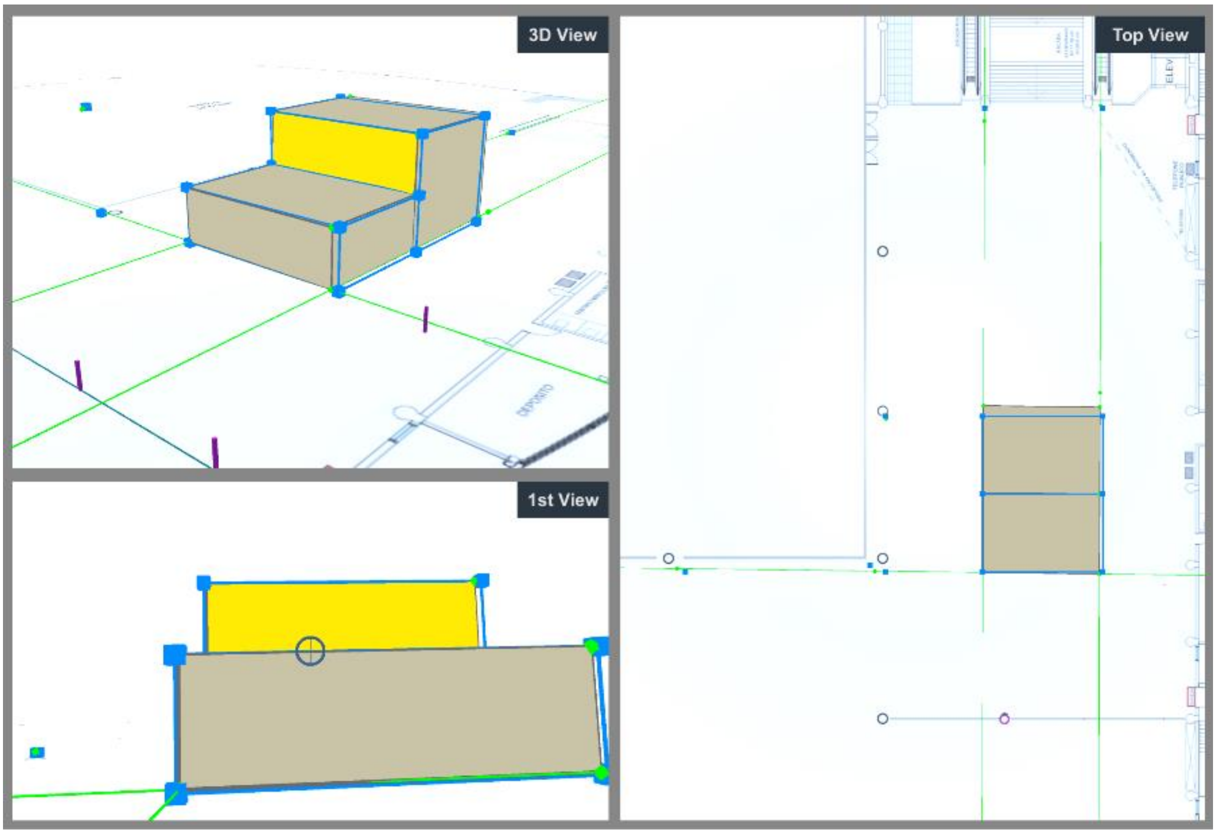

Figure 68 - Participant completed the task. We cannot see errors as significant as in the previous case.

5.7.3 Absolute Positional Error of Points

We used a quantitative analysis for analyzing the within-subject variable of group B. We performed an independent-samples t-test to compare the effects of the Geometric and Vector Cloud techniques. We obtained the average and standard deviation for each point based on the absolute error values calculated for each technique's visualization. Results are expressed in Table 1, while Figure 69 provides a visualization of the results. The points were numbered based on the order that they were created, and the "m" suffix represents points that were marked using the technique directly (instead of created by another tool), as shown in Figure 58.

Table 1 - T-test results for absolute position error in each point, while comparing Geometric and Vector Cloud techniques.

	Geometric		Vector Cloud		t-test		
Point	Average	Deviation	Average	Deviation	p-value	t	df
P1m	0.469701	0.278216	0.310737	0.165779	0.027527	2.302229	34.24287
P2m	1.165948	0.835113	0.84979	0.647872	0.168416	1.403005	39.5562
P3m	0.664673	0.399777	0.481717	0.281973	0.087526	1.754121	37.74909
P4m	1.424649	1.180802	0.91621	0.578887	0.079602	1.813435	30.5432
P5	1.254918	0.805121	0.685941	0.400813	0.005764	2.967331	30.80668
P6	1.200243	0.657168	1.051543	0.340106	0.353074	0.942572	31.4963
P7m	1.555538	1.304443	1.000467	0.554472	0.076741	1.836829	28.34864
P8	1.553915	0.788774	0.722955	0.393059	0.000113	4.42258	30.82363
P9	1.323834	0.572794	1.015141	0.405918	0.046082	2.062409	37.8443
P10	1.113098	0.657732	0.721389	0.403044	0.022829	2.381751	34.82199
P11	1.350494	0.699393	0.752949	0.379806	0.001299	3.521614	32.39499
P12m	0.374445	0.201234	0.438648	0.314166	0.424913	-0.80716	35.74917
P13	1.11562	0.657822	0.723697	0.401466	0.022652	2.385361	34.73756
P14	1.201139	0.660018	1.05316	0.338128	0.356467	0.93594	31.31266
P15	1.327721	0.568595	1.018346	0.400208	0.043706	2.086959	37.70684
P16	1.350259	0.704146	0.75463	0.379239	0.001409	3.493157	32.23734
P17	1.253399	0.809622	0.687207	0.403279	0.006235	2.936062	30.8164
P18	1.116684	0.653844	0.723189	0.404383	0.02181	2.400731	35.01471
P19	1.347751	0.707235	0.752323	0.386062	0.001506	3.466113	32.49452
P20	1.551299	0.79621	0.719889	0.403652	0.000129	4.368466	31.12576

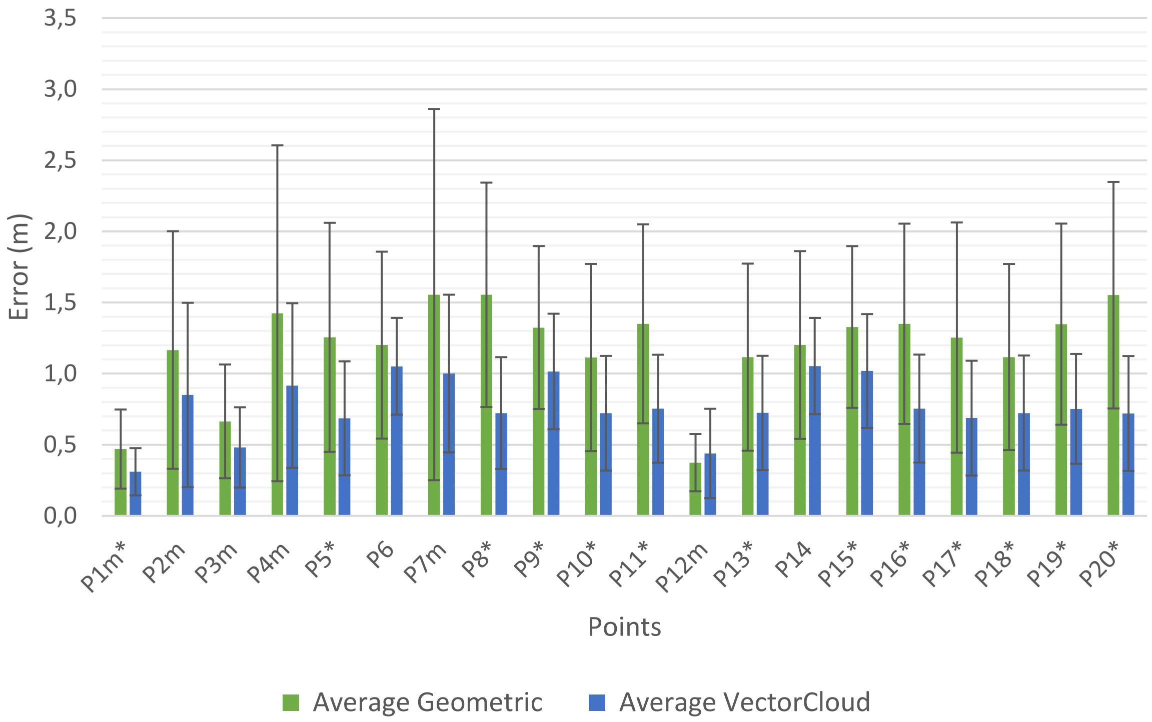

Figure 69 - Average error for each point depending on the marking technique. Points with "m" were directly marked. Points with "" were statistically different. Error bar indicates standard deviation.*

We also conducted an independent-samples t-test to compare the variance of the points using each technique, since a higher variance implies in a higher imprecision of the tool that created the point. There was a significant difference ($t(21)=4.20$, $p=0.0004$) in the variance between Geometric ($M=0.54$, $SD=0.39$) and Vector Cloud ($M=0.16$, $SD=0.08$) techniques. We also created a visualization with the variance of the data for each point, which can be seen in Figure 70.

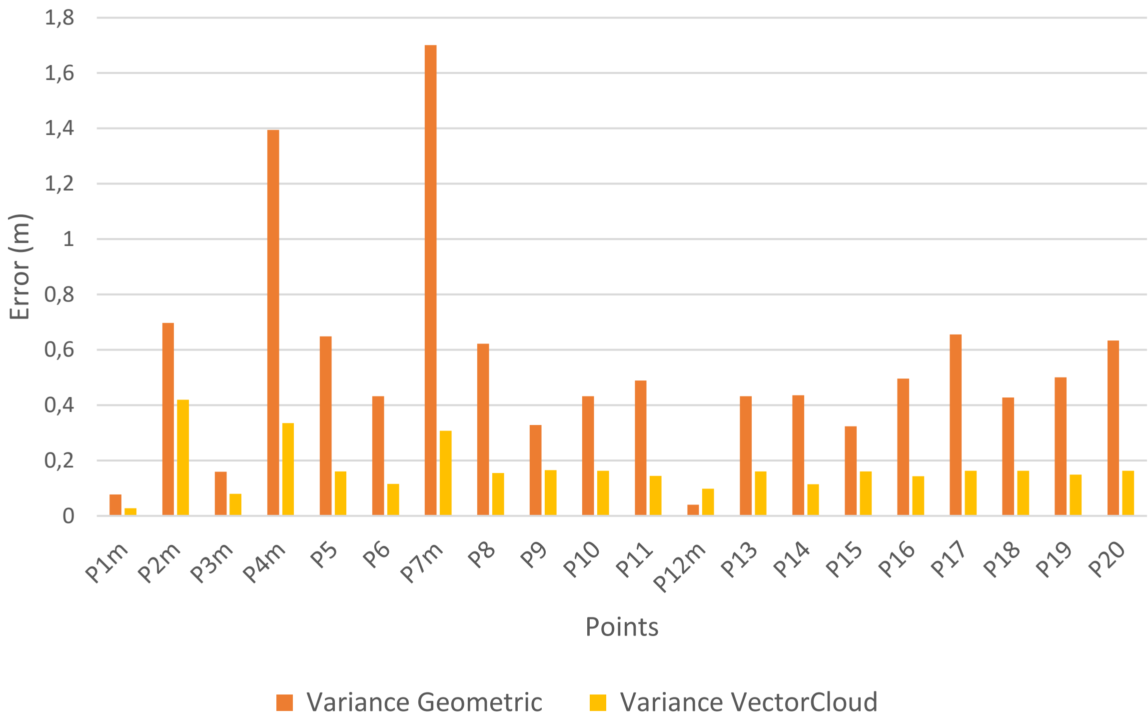

Figure 70 - Variance of average error for each point.

5.7.4 Absolute Orientation Error of Line Segments

We analyzed the angle between each line segment and the ground truth for that line segment. In other words, the error in the orientation of the line segments individually. Results are expressed in Table 2, while Figure 71 provides a visualization of the results.

Table 2 - T-test results for absolute orientation error in degrees in each segment, while comparing Geometric and Vector Cloud techniques.

	Geometric		Vector Cloud		t-test		
Segment	Average	Deviation	Average	Deviation	p-value	t	df
S1	1.800739	1.485112	1.135122	0.792717	0.072876	1.854552	32.06803
S2	1.774953	1.474339	1.136331	0.792387	0.082929	1.7896	32.19762
S3	1.963825	1.31592	1.058958	0.818294	0.009617	2.738908	35.12831
S4	1.962536	1.315978	1.060406	0.821124	0.009877	2.727903	35.19958
S5	1.963365	1.31508	1.060404	0.819543	0.009749	2.733232	35.17355
S6	1.962901	1.314846	1.05904	0.818743	0.009658	2.737054	35.15685
S7	1.801039	1.485583	1.207801	0.78602	0.107614	1.65557	31.90322

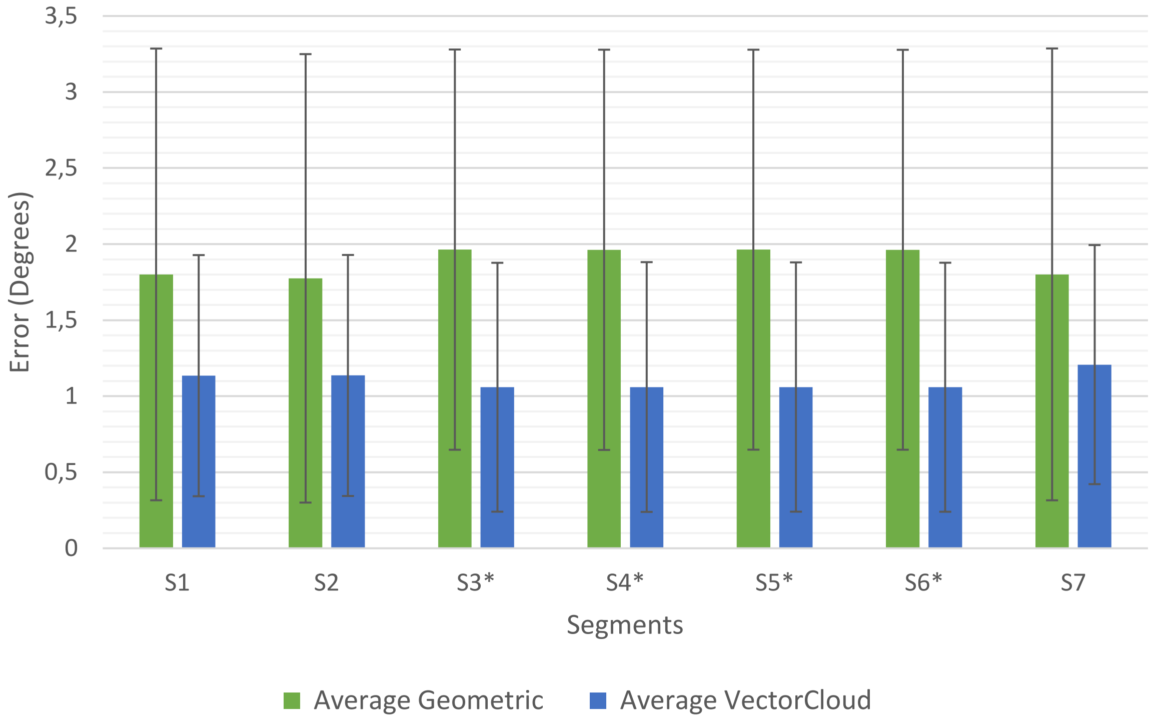

Figure 71 - Average orientation error in degrees of segments of the footprint. Segments with "" were statistically different. Error bars indicate standard deviation.*

As in the previous analysis, we also conducted an independent-samples t-test to compare the variance of the orientation using each technique. There was a significant difference ($t(6)=13.52$, $p < 0.0001$) in the variance between Geometric ($M=1.92$, $SD=0.24$) and Vector Cloud ($M=0.65$, $SD=0.02$) techniques. We also created a visualization with the variance of each technique on the angle of each line segment, which can be seen in Figure 72.

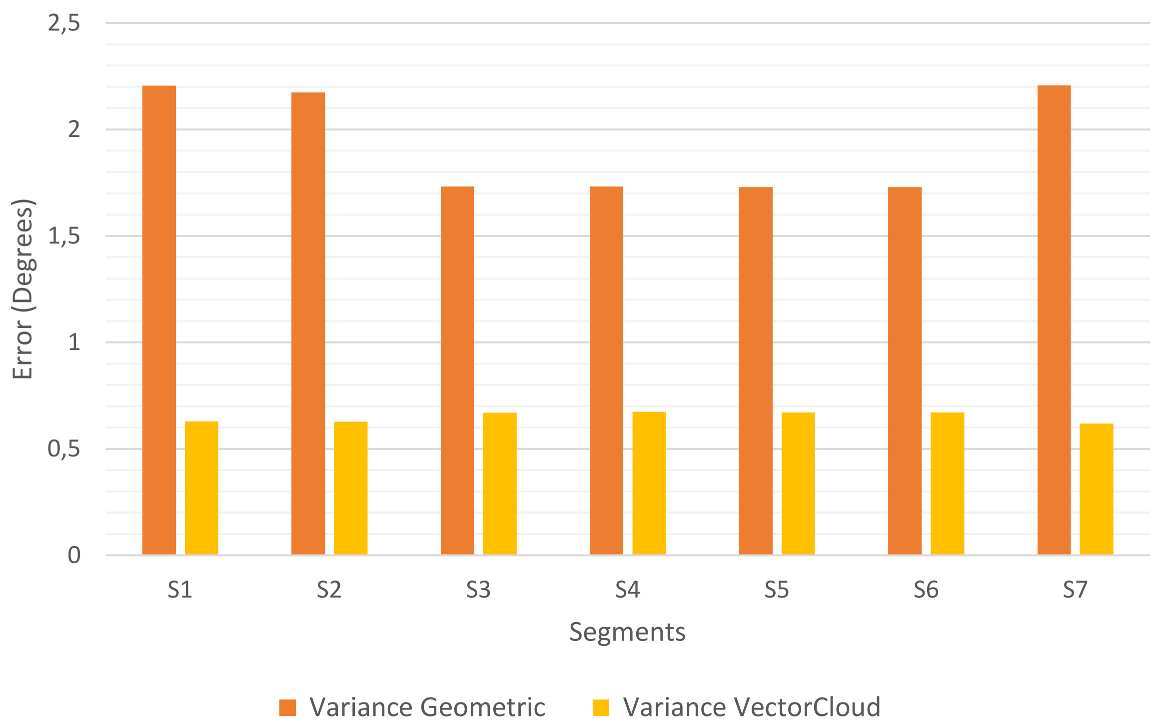

Figure 72 - Variance of average error for each point.

5.7.5 Absolute Angular Error Between Line Segments

We wanted to understand if the footprint of the building was skewed. We analyzed the angles between each pair of adjacent line segments that compose the footprint compared to the ideal value for that angle (i.e., 90 degrees). Results are expressed in Table 3 and Figure 73.

Table 3 - T-test results for absolute angle error between line segments, while comparing Geometric and Vector Cloud techniques.

	Geometric		Vector Cloud		t-test		
Point	Average	Deviation	Average	Deviation	p-value	t	df
P5	2.935036	2.564652	1.514218	1.169445	0.024883	2.364295	29.37087
P6	2.910026	2.516945	1.511205	1.167227	0.02479	2.364833	29.63329
P8	2.934928	2.563973	1.512891	1.16936	0.024738	2.366871	29.37383
P9	2.909031	2.516855	1.512845	1.167977	0.025049	2.36018	29.64397

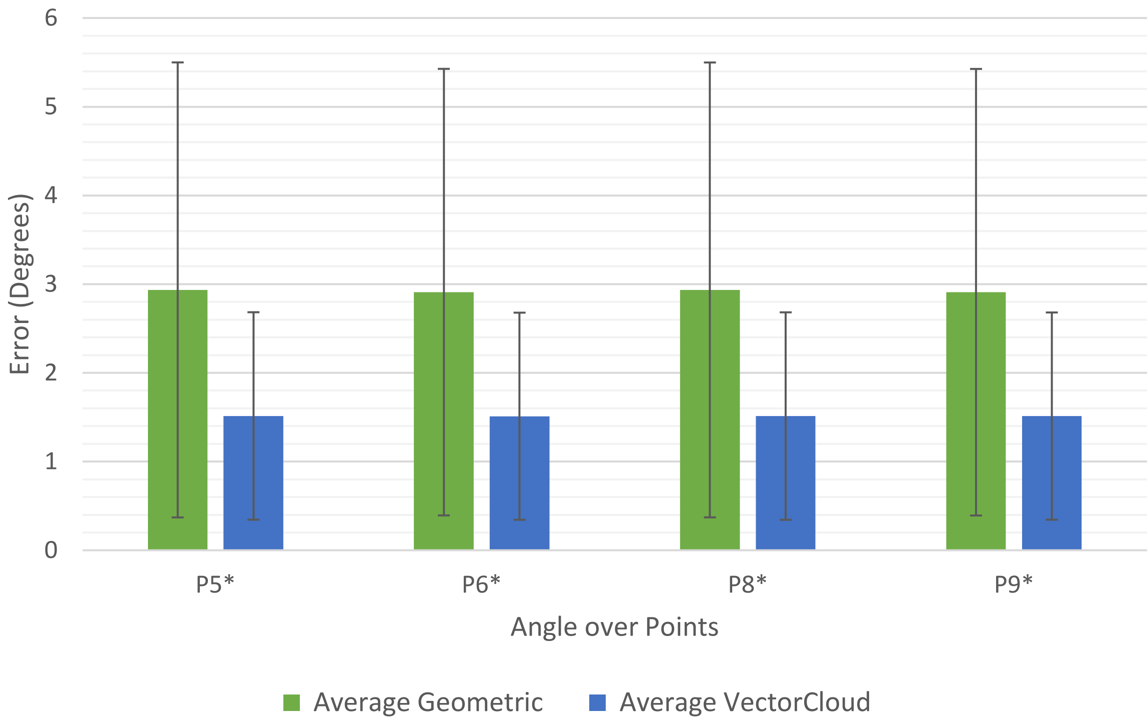

Figure 73 - Average angle error between segments of footprint that intersect over points. Angles with "" were statistically different. Error bars indicate standard deviation.*

As in the previous analysis, we also conducted an independent-samples t-test to compare the variance of the angle between pairs of line segments using each technique. There was a significant difference ($t(3)=73.17$, $p < 0.0001$) in the variance between Geometric ($M=6.45$, $SD=0.13$) and Vector Cloud ($M=1.36$, $SD=0.002$) techniques. We also created a visualization with the variance of each technique on the angle of each point, which can be seen in Figure 74.

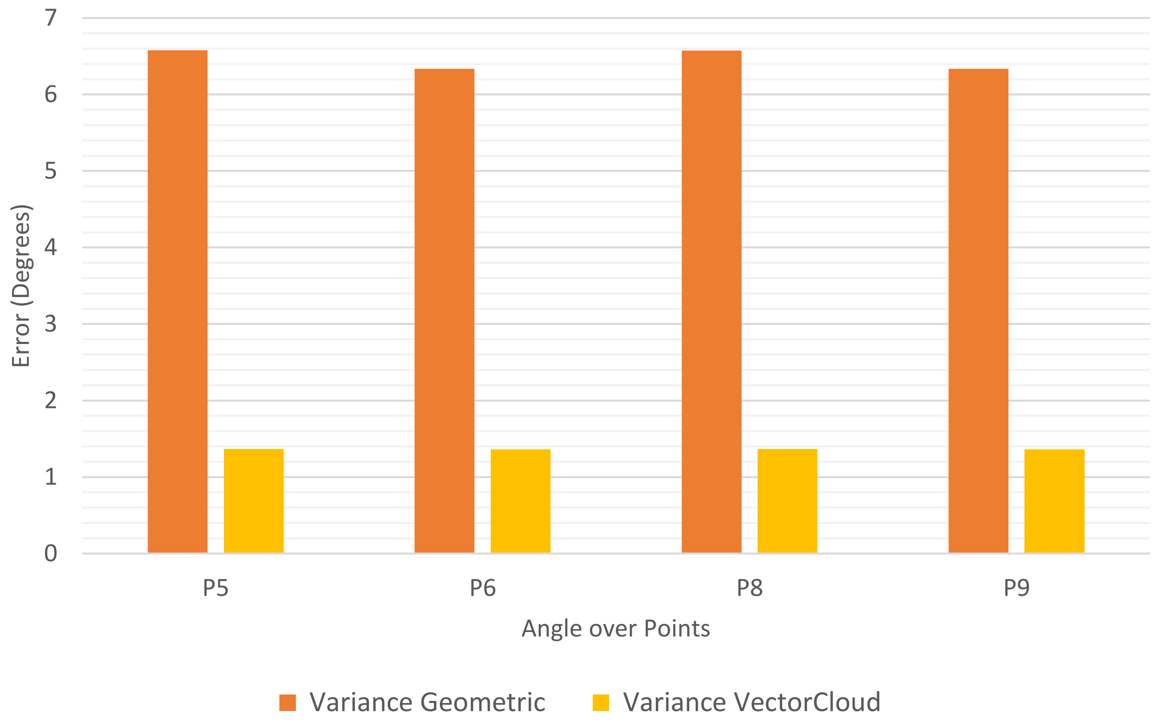

Figure 74 - Variance of average error for each point.

5.7.6 Visualization Questions Analysis

At the end of each main task, we asked the participants some questions about how they understand the model in the environment. Here we report the results of the 22 participants of group B.

In question 1, participants were asked how many people could walk between the new building and the existing wall of the room. They both performed similarly, Geometric (M=11.77, SD=4.12) and Vector Cloud (M=12.04, SD=4.76). However, we noticed on calculating the differences between the ordering of use, participants reported in aggregate 28 additional people on the second run, independent of which technique it was. We did an independent-sample t-test to look for statistically significant differences for ordering effect. No difference was found ($t(39)=-0.99$, $p = 0.32$) between first technique (M=11.28, SD=4.06) and second technique (M=12.66, SD=4.9).

In question 2, participants were asked about the height of the building relative to the ceiling of the building, both techniques performed similarly, with 16 participants saying they were the same for Geometric, and 17 for Vector Cloud; 3 for each said the height of the building was higher; 1 said it was lower for Geometric, and 2 for Vector Cloud.

In question 3, participants were asked whether the structure was leveled (there was a slope) relative to the ground. Both techniques performed the same, with 17 people saying it was leveled, and 5 saying it was not. 7 users who reported that they were levels also said that the building was floating in the air, and not touching the ground, 3 of which using Geometric and 4 using Vector Cloud.

In question 4, participants were asked whether the structure was aligned with the columns where the reference lines have been created. 15 participants using Geometric said they were correctly aligned, while 16 from Vector Cloud, from the 22 participants.

5.7.7 Questionnaire Analysis

We also questioned the participants on how they perceived the interaction technique. The answers were ranged between 1 (lesser) and 5 (higher) for each technique. The following answers were found between participants of the 22 participants of group B.

The first question was about how precise they think the technique was. Vector Cloud scored slightly higher (M=4.22, SD=0.75) than Geometric (M=3.81, SD=1.00), but not statistically significant (t(39)=-1.52, p=0.13).

The second question was about how easy it was to use the application. Both techniques scored similarly, Vector Cloud (M=4.5, SD=0.67) and Geometric (M=4.54, SD=0.59), and no statistically difference was found (t(41)=0.23, p=0.81).

The third question was about how fast they think it was to complete the model. Again, both performed similarly, Vector Cloud (M=4.40, SD=0.79) and Geometric (M=4.54, SD=0.59), and no statistically difference was found (t(39)=0.26, p=0.52).

The fourth question was about how natural the interaction felt like. One more time, their average was similar, Vector Cloud (M=4.27, SD=0.76) and Geometric (M=4.31, SD=0.83), and not statistically difference was found (t(42)=0.18, p=0.85).

The fifth question was about how much fun they had using the application. Geometric scored slightly higher (M=4.68, SD=0.47) than Vector Cloud (M=4.40, SD=0.85), but not statistically significant (t(33)=1.30, p=0.19).

Finally, the last questions asked how comfortable it was to use the application. Geometric score slightly higher (M=3.77, SD=0.81) than Vector Cloud (M=3.68, SD=0.99), but not statistically significant (t(40)=0.33, p=0.74).

5.8. Discussion

In this section, we will explain how the data we gathered and presented in the previous section are evidence to support our hypotheses. We will present the evidence going through each of the hypothesis, from **H1** to **H6**.

5.8.1 Point marking effects on model accuracy

Our **H1** stated that an imprecise point marking technique would make the overall accuracy of the model lower. Looking at the visual inspection of group B, we can visually see a distinction between the aggregate of both techniques. The Geometric technique models (Figure 61) are more spread than the Vector Cloud ones (Figure 62), and this can be specially noticed if we look at the colors of the points defining the model; most of the Geometric points are red, while Vector Cloud ones are more leaning towards a yellow tone. They also presented some line segments with more significant orientation errors, especially on the right edge.

These readings are corroborated by the data analysis. In most of the points, the Vector Cloud technique presented a higher accuracy than the Geometric with statistical significance (p-value < 0.05 - Table 1), while also having significantly smaller errors in the orientation of the line segments (Table 2) and being significantly less skewed (angles between segments - Table 3). A variance analysis also shows that the Geometric technique variance was significantly higher, implying in some participants being able to create reasonable models, but also other participants creating models with considerable amounts of error.

More than that, if we look at where the most differences appear, we see that the cascading effect that we hypothesized indeed happens. While the accuracy difference for some of the first points was not statistically different, the ones that were got amplified and accumulated with other markings, especially as the region of interest moved further away from the real-world feature that created the reference. This means that the accuracy of the model relies strongly on the accuracy of the marked points because it transforms a simple positional error into a cumulative error. Knowing that Vector Cloud is more precise than Geometric [22], these pieces of evidence support **H1**, that the precision of the point marking technique indeed influences the errors on a much larger scale.

5.8.2 Point marking effects on ease of use

Our **H2** stated that an imprecise point marking technique would compromise the ease of use of the application. If we look at the results from the visualization questions, we can see that users had many difficulties answering some of the questions.

In the first question, regarding how many people could walk between the building and the real wall, participants were indeed able to give a fair estimate, possibly due to their advantaged point of view. In the second question, however, that was about the height of the building, we can see that answers were purely perceptions that did not reflect reality. In the third question, which asked about a slope in the base of the building, this becomes even more evident. We know that there was no slope because we constrained reference lines to the same height in the Y-axis for this study. Therefore, some participants who answered that there was a slope were probably confused due to the lack of visual cues. Finally, on the last question, which was about the alignment of the walls of the virtual building with the columns where the points were marked, we can also see confused participants. Some participants that had previously answered that the building had a slope, in these questions answered that the walls were directly aligned, when in fact, what happened was the opposite. There is an apparent confusion between the existence of angular errors in the Y-axis instead of X or Z axes. An example of a model where this happens can be seen in Figure 75.

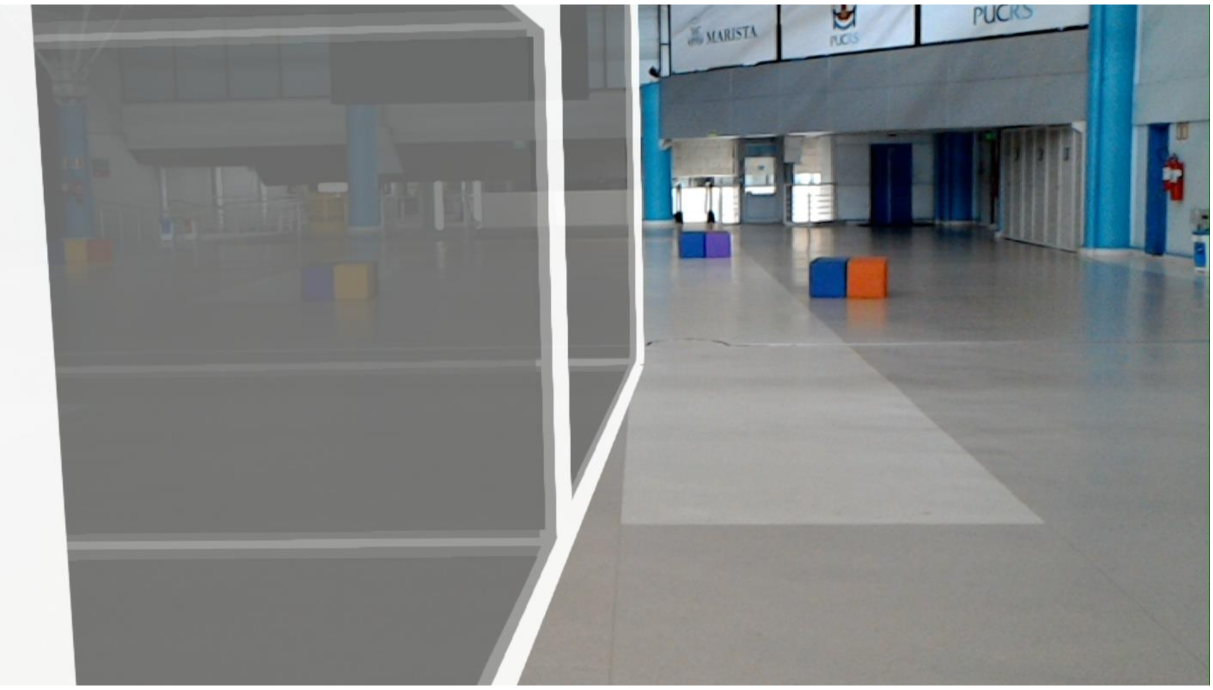

Figure 75 - Example of a final building with an angular error in the reference line. The line should have been parallel to the color in the ground. This confused participants.

Also, if observe the behavior of the participants during the steps of the task, we will notice that many of them could not notice some considerable errors in the alignment of references during steps 1 and 2, that later led to most of the angular errors of the model. Some did notice the problems in later steps, like when they were creating the footprint, but, since we constrained that in our study, they could not go back to fix it. In a real-world application, upon notice, the participant would have to go back many steps, and this would lead to losing time. All this evidence suggests that **H2** may be partially correct, reducing the usability of the application. While the part about understanding the problems in the geometry does seem to be supported by our data, this problem seems to affect both Vector Cloud and Geometric, with the difference being that the higher accuracy of the points when using Vector Cloud did not require this judgment as frequently. Therefore, using Vector Cloud does make the modeling process easier.

5.8.3 Point marking effects on usefulness

Our **H3** stated that an imprecise point marking technique would compromise the usefulness of the application. When observing the overall accuracy errors and mixing them with the results from the visualization questionnaire, discussed in the analysis of the two previous hypotheses, it is clear that using a less precise technique will reduce the usefulness of the application. As we have shown, a less precise technique can sometimes lead to considerable accuracy errors, and these errors may not be detected by the user, which may lead to a final building that is not faithful to the concept or even provides a wrong understanding of the model. For our use case of designing a massing model, although extreme accuracy is not required, the understanding of the building must be correct, because the design decisions are based on that. Therefore, using a lower precision point marking technique may not achieve their objectives, supporting **H3**.

5.8.4 Perception alignment effects on model accuracy

Our **H4** stated that performing an alignment operation based on would make the overall accuracy of the model lower. At first glance we can see at the visual inspection of group A that the aggregate results for each technique do not appear to be much different; both are somewhat representing the general idea of the task model, although somewhat spread. Even having a higher precision marking technique resulted in a bad overall result, if we compare to the result from group B. However, as explained before, there is also another difference between group A and B apart from the use of perception to align reference lines.

A small adjustment on the sampling rate of the Vector Cloud technique was performed, and therefore doing an aggregate or statistical analysis is not conclusive and may lead to wrong understanding.

Instead, we performed an individual evaluation, showing one session from each group where the participants had somewhat precise markings at the beginning, and how the visual alignment was responsible for errors in a larger magnitude. In the session from group A (Figure 65), we can see that the error in the area of the footprint of the building is almost 50% of the area of the ground truth, a significant error. In the session from group B (Figure 68), we can see just a small error, smaller than 10% of the area of the footprint. We have therefore presented some evidence supporting **H4**, but future studies are needed to validate this finding.

5.8.5 Perception alignment effects on ease of use

Our **H5** stated that performing an alignment operation based on would compromise the ease of use of the application. The visual inspection demonstrates there is difficulty in aligning reference lines to features due to the lack of occlusion. Many participants got confused trying to understand when the reference crossed a column, with one participant even missing the target for 6 meters (which can be seen in Figure 59). Some participants verbally reported that the line was “bending” at a distance, which corroborates the idea that the lack of occlusion introduced confusion in the task. This evidence supports **H5** and state as a guideline that using perception for performing alignment of lines increases the difficulty of using the application and the difficulty of achieving satisfactory results.

5.8.6 Perception alignment effects on usefulness

Finally, our **H6** stated that performing an alignment operation based on would compromise the usefulness of the application. The data shows that the usefulness indeed becomes much worse, because the accuracy errors generated by the alignment and the difficulty of use generated by the lack of occlusion, discussed in the analysis of the two previous hypotheses, create models that may look entirely different than the intention of the user.

6. CONCLUSION AND FUTURE WORK

In this work, we proposed a novel approach for modeling large structures in-situ. It uses features already present on the real-world as the basis upon to build. These features can be any element that is distinguishable by the user, and that is important for the modeling that they are aiming to perform. For instance, while designing a new building, corners of surrounding buildings of pathways may be used; while designing streets or bridges, edges of existing traffic elements may be used; and while planning on the placement of elements that must respect the environment, anything from pathways to vegetation can be used. We believe this approach is flexible and simple enough to be applied in many areas.

We validated our approach by developing an application for the use case of modeling in the early phases of designing new buildings. We conducted interviews with stakeholders and were able to define their needs, and how they usually approach the problem. A workflow was drawn based on this information, and we explored augmented reality solutions for the problem, by developing several modeling tools. Some of these tools were specially created based on our premises, allowing us to take advantage of the real-world features surrounding the construction area, instead of just the ones directly over it.

The application was improved through a formative used study, where the interaction was evaluated and improved. Problems like selecting objects that are distant and improving the usability of the menu were attenuated. In a summative study, we tried to evaluate the advantage of using the real-world features but concluded that our question was misplaced, that there would make no sense to design a building without using such neighboring features. We did, however, gain some practical knowledge on issues faced by the concept of modeling in-situ, and some constraints that would be required to make a more definitive study.

Later, we performed another summative study with the objective of evaluating the impact of point marking precision on the performance of the model. By using techniques with different levels of precision, we were able to understand how their error propagate throughout the modeling process. We performed this study in a more constrained environment, to avoid lurking variables that contributed to render the previous study undoable. We defined some hypotheses for two research questions and provided evidence to support them through visual and statistical analysis.

Our results indicated that the precision of the point marking technique is essential to the accuracy on the model, while also determining the ease of use and usefulness of our approach. The two marking techniques that were used, Geometric and Vector Cloud, showed statistically significant results when comparing the accuracy of the position of points, the orientation of the line segments, and angles between the walls of a building. Using Vector Cloud, which was more precise to mark points individually, resulted in an improvement in the performance of the technique. The results also indicate that using a tool based on visual perception to align lines to real-world features has an adverse effect on the accuracy of the model, and ease of use and usefulness of the system.

We believe that although exciting research has been done in the topic of modeling in augmented reality, our knowledge about it is still in its early days and that there are many directions in which this can be further explored in future studies. Following suit of this work, future work could include a more focused study on the effects of using perception-based techniques on the modeling task. We could not generate a statistical analysis of the issue, although our individual analysis suggests there may be adverse effects in accuracy, ease of use and usefulness. Also, these questions could be expanded to other types of operations using perception techniques like moving points, rotating lines, or even performing an extrusion on surfaces. Data is required as evidence to support that these operations perform worse using perception.

There are also open questions regarding the point marking techniques. While our data demonstrate a better performance when the precision of the technique is higher, it also pointed to some possible usability issues in the individual techniques. Participants complained about Vector Cloud technique taking too long and being difficult to keep their heads still, while also tensing up their muscles. More robust techniques are required to improve this approach even further. A technique that preserves a high precision, but that has a smaller weight on the user should be explored. Some ideas include using a drone for marking the second perspective, which would reduce how much the user needs to walk even further or using computer vision to aid the user in marking the point in the second perspective, possibly doing it automatically.

Taking a different path, there are also questions regarding the relationship with other approaches. We don’t really know how this approach compares in performance to the previously proposed augmented reality working planes techniques. Moreover, we believe some of the ideas explored in our concept could be combined with ideas from the working planes technique and others. For instance, the point marking at-a-distance strategy could be used to align the working planes to real-world features, and the opposite also holds, the landmarks alignment strategy could be used to align our reference lines. Understanding which performs better in determined situations would be essential to advance the field.

And finally, we also believe that there are many other specialized modeling techniques that can be designed to take more advantage of the real-world features. For instance, a line segment could be rotated automatically based on an angle measured in a neighboring building, allowing more detailed shapes; dealing with slopes in a terrain could also receive a special tool, that could help with the understanding the angle of the slope, by measuring the slope and the leveled surrounding buildings, possibly; some sort of tool that can understand and replicate curves on the features, such as curved building, and able to measure things like the radius of curve. There are many possibilities, but we believe that the focus of them should be precisely on maximizing how much information we can obtain from the real world and the quality if this information.

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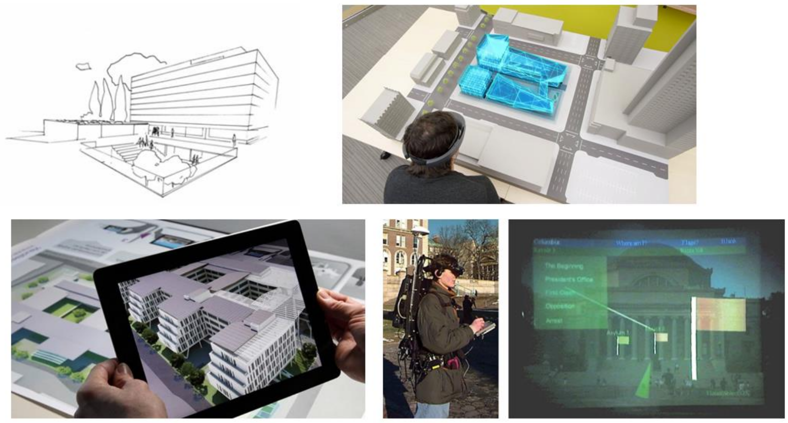
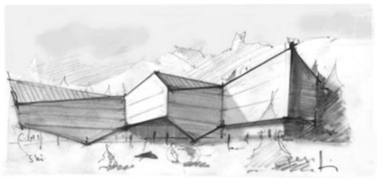
APPENDIX A – PRESENTATION TO STAKEHOLDERS

ABOUT THIS WORK



ABOUT THIS WORK

- Design of buildings in-situ using AR
- Very early design phases, such as “massing studies”



ABOUT THIS WORK

- **Features already present on the real-world**
  - Other buildings and objects
    - **Position, orientation, scale** and **texture**
- **Interview**
  - Few questions
  - Understand the area, including limitations and requirements

APPENDIX B - INFORMED CONSENT FORMS

Study 1

Informed Consent for Participant of Investigative Project
Virginia Polytechnic Institute and State University

Title of Project: Modelling New Buildings in Augmented Reality

Investigators: Dr. Doug A. Bowman, Leonardo Pavanatto Soares.

I. THE PURPOSE OF THIS RESEARCH/PROJECT

Study massing is one of the early stages in the process of designing a new building. During this stage, architects develop models or concepts of the new buildings in order to see how the general geometry of the project looks like, and to try to understand some of the consequences of their design choices. This research investigates the use of Augmented Reality (AR) to support the design outdoor large-scale buildings by using an Augmented Reality (AR) system.

II. CONDITIONS

To participate in this study, you must be architecture student, faculty or professional and be **at least 18 years of age**. You should have normal vision (corrected or uncorrected) and normal range of movement with hands and fingers. Furthermore, you should have no motor disabilities that keep you from walking or standing normally.

III. PROCEDURE

This study examines interaction techniques for modelling in Augmented Reality (AR). You will be asked to design a building using these techniques, all based on head orientation and joystick input.

1. Upon arrival, you will be asked to read and sign this consent form. A digital copy of this consent form was emailed to when you sign up for this research study, for your appreciation. This is expected to take around 5 minutes.
2. You will then be asked to complete a background questionnaire. This is expected to take around 5 minutes.
3. You will be introduced to the equipment that you will use throughout the experiment, including an AR Head-Worn Display (HWD), and a hand-held control device (joystick). The used HWD is the Microsoft HoloLens, and the joystick is the Microsoft Xbox One Controller. This is expected to take 5 minutes.
4. You will be asked to put on the HWD and get familiar with the application through a training session. You will be asked to try all of the interaction modes, such as create, move, and clone some primitives. Primitives here are defined as point, line, surface and solid objects. During this part, think-aloud protocol will be used, and the audio will be recorded. Think-aloud protocol means that you will be asked to say out loud what are you doing or thinking during the interaction. This is expected to take 15 minutes.
5. After the training session, you will be presented with the actual tasks that are similar to what you did in the training session, namely designing a building using the available primitives and interaction modes. You will perform the same task two times, with different variants of the applications. This part will be performed outdoors (in the grass field of the Upper Quad) and

will only take place if the weather is permitting. In case of rain, storms, or lightning the entire session will be canceled or rescheduled. During this part, think-aloud protocol will also be used, and the audio will be recorded. This step is expected to last around 25 minutes.

6. After all interaction tasks are completed, you will be asked to answer a final survey expressing your perception and thoughts about the application. This is expected to take 5 minutes.

Please note that, if you need to take a break at any time during the experiment, please complete the current task, and then inform the experimenter.

Also, note that this experiment is evaluating the two variants of the application and not your individual performance.

IV. RISKS

There are minimal risks involved in the study. The risk of injury resulting from falling is minimal, although existent, since you will be required to walk while wearing an HWD. Some users also experience discomfort from using the HWD. If you experience eye strain, headaches, nausea, or other discomfort during the session, please tell the experimenter before taking a break. Since some parts of this study will be conducted in a public setting (in the grass field in the Upper Quad), you should be aware that there is also a risk of embarrassment. You may terminate your participation at any time.

Neither VT nor the research team has funds set aside for research-related injuries; therefore, you would be responsible for any costs associated with injury or sickness.

V. BENEFITS OF THIS PROJECT

Your participation will help us to understand and improve modelling in AR environments. The problem has implications for performance of real, production-grade AR environments used for the design of new buildings. You will, through this study, help us explore effective interaction techniques and provide useful insight into research of interaction design in 3D user interfaces.

VI. EXTENT OF ANONYMITY AND CONFIDENTIALITY

Your participation in this study will be kept confidential. Your written consent is required for the researchers to release any data that identifies you as an individual to anyone other than personnel working on the project. The information you provide will not contain your name. The data will use a unique number, unlinked to your name, during analyses and any written reports of the research. Some data might have metadata, such as the date the study was conducted. This information will not be disclosed.

VII. COMPENSATION

Your participation is <u>voluntary</u> and <u>unpaid</u>.

VIII. FREEDOM TO WITHDRAW

You are free to withdraw from this study <u>at any time</u> for <u>any reason</u>.

IX. APPROVAL OF RESEARCH

This research has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University.

X. QUESTIONS OR CONCERNS

Should you have any questions about this research or its conduct, you may contact:

Investigators: Dr. Doug A. Bowman Phone (540) 231-2058
Professor, Computer Science Department (231-6931)
Email: dbowman@vt.edu

Leonardo Pavanatto Soares
Visiting Graduate Student, Computer Science Department
Email: lpavanat@vt.edu

Should you have any questions or concerns about the study's conduct or your rights as a research subject, or need to report a research-related injury or event, you may contact the Virginia Tech Institutional Review Board at irb@vt.edu or (540) 231-3732.

XI. SUBJECT'S RESPONSIBILITIES AND PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

____ ______________
Signature Date

____
Name (please print)

Study 2

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO (TCLE)
Pontifícia Universidade Católica do Rio Grande do Sul

Título do projeto: **Modelando Novas Edificações em Realidade Aumentada**

Investigadores: Dr. Márcio Sarroglia Pinho, Dr. Doug A. Bowman, Leonardo Pavanatto Soares.

I. PROPÓSITO DA PESQUISA/PROJETO

O estudo de massa é um dos primeiros estágios no processo de projeto de uma nova construção. Durante este estágio, arquitetos desenvolvem modelos ou concepções da nova construção para visualizar a geometria geral do projeto, e tentar entender algumas consequências das suas escolhas. Esta pesquisa investiga o uso de Realidade Aumentada (RA) para o design de grandes edificações em ambientes externos.

II. CONDIÇÕES

Para participar neste estudo, você deve ser um estudante, professor, ou profissional com formação em arquitetura ou semelhante, e deve possuir **ao menos 18 anos de idade**. Você deve possuir visão normal (corrigida ou não corrigida) e movimentação normal das mãos e dedos. Além disso, você não deve possuir nenhuma deficiência motora que o impeça de caminhar ou ficar em pé normalmente.

III. PROCEDIMENTO

Este estudo investiga técnicas de interação para modelagem em Realidade Aumentada (RA). Você será solicitado a projetar uma nova construção utilizando estas técnicas.

1. Ao chegar no local no estudo, você será solicitado a ler este formulário de consentimento. Se você concordar em participar deste estudo, você rubricará todas as páginas e assinará e datará duas vias originais deste termo de consentimento. Para a sua apreciação, uma cópia digital deste formulário foi enviada por e-mail quando você se inscreveu para participar neste estudo. *Esta etapa deve durar cerca de 10 minutos.*
2. Você será solicitado a completar um questionário com informações de caracterização, como idade, gênero, experiência com computadores, modelagem, etc. *Esta etapa deve durar cerca de 5 minutos.*
3. Você será introduzido ao equipamento que você irá utilizar durante o experimento, incluindo um Head-Worn Display (HWD) de RA, e um controle de mão (joystick). O HWD utilizado é o Microsoft HoloLens, e o joystick é o controle do Microsoft Xbox One. *Esta etapa deve durar cerca de 5 minutos.*
4. Você será solicitado a colocar o HWD e se familiarizar com a aplicação através de uma sessão de treinamento. Você será solicitado a testar os modos de interação da aplicação, como criar, mover, e clonar algumas primitivas. Primitivas aqui são definidas como pontos, linhas, superfícies e sólidos. *Esta etapa deve durar cerca de 25 minutos.*
5. Após a sessão de treinamento, você será introduzido a tarefa do estudo, que é similar ao que você fez na sessão de treinamento, nominalmente projetar uma construção utilizando as primitivas e modos de interação disponíveis. Esta parte será conduzida em um ambiente externo e somente acontecerá se as condições climáticas permitirem. Em caso de chuva, tempestade, ou raios, a sessão será cancelada ou remarcada. *Esta etapa deve durar cerca de 30 minutos.*

Rúbrica do Participante	Rúbrica do Investigador Principal	Rúbrica do Profissional que obteve consentimento

6. Após as tarefas serem concluídas, você será solicitado a responder um questionário final para expressar a sua percepção e pensamentos a respeito da aplicação, além de responder a uma pequena entrevista, que terá o seu áudio gravado. *Esta etapa deve durar cerca de 10 minutos.*

Nota 1: o objetivo do experimento é avaliar as técnicas de modelagem, e não a sua performance.
Nota 2: se você precisar interromper o experimento para descansar por um tempo, informe o investigador.

IV. RISCOS E DESCONFORTOS

Existem riscos mínimos envolvidos neste estudo. O risco de lesão resultante de quedas é mínimo, porém existente, pois você deverá caminhar enquanto utiliza um HWD. Alguns usuários sentem desconforto ao utilizar o HWD. Se você sentir cansaço nos olhos, dores de cabeça, náusea, ou outro desconforto durante a sessão, informe o investigador para que um intervalo seja feito. Como algumas partes do estudo vão ser conduzidas em público, você deve estar ciente do risco de ser reconhecido ou se sentir envergonhado. Você pode encerrar a sua participação a qualquer momento.

V. BENEFÍCIOS DO PROJETO

Sua participação vai nos ajudar a entender e melhorar o processo de modelagem em ambientes de RA. O problema afeta diretamente a performance em ambientes de RA utilizados para projeto e modelagem de novas edificações. Você irá, através deste estudo, nos ajudar a explorar técnicas de interação efetivas e prover informações úteis para a pesquisa de interfaces de usuário 3D.

VI. ANONIMIDADE E CONFIDENCIALIDADE

As informações desta pesquisa serão confidencias, e serão divulgadas apenas em eventos ou publicações científicas, não havendo identificação dos participantes, a não ser entre os responsáveis pelo estudo, sendo assegurado o sigilo sobre sua participação. Todos os dados coletados são anônimos e os formulários não possuem qualquer informação que possa identificar o participante.

Este projeto é realizado em parceria com a Virginia Polytechnic Institute and State University (Virginia Tech), dos Estados Unidos da América. Os investigadores de ambas universidades que trabalham diretamente neste projeto possuem acesso aos dados fornecidos por você. Na Virginia Tech, este estudo foi aprovado sob matricula **IRB #18-520**.

VII. COMPENSAÇÃO

A sua participação é voluntária e não remunerada.

VIII. DIREITO DE DESISTÊNCIA

Você pode encerrar a sua participação no estudo a qualquer momento e por qualquer motivo, bastando informar o investigador, sem nenhum tipo de prejuízo ou retaliação, pela sua decisão.

IX. ACESSO AOS RESULTADOS

Você tem direito a receber acesso aos resultados desta pesquisa após ela ter sido publicada. Entre em contato com um dos investigadores para requisitar acesso a informação.

Rúbrica do Participante	Rúbrica do Investigador Principal	Rúbrica do Profissional que obteve consentimento

X. APROVAÇÃO DA PESQUISA

Esta pesquisa foi aprovada, conforme requerido, pelo Comitê de Ética para projetos envolvendo participantes humanos da Pontifícia Universidade Católica do Rio Grande do Sul.

XI. RESPONSABILIDADE E PERMISSÃO DO PARTICIPANTE

Eu concordo voluntariamente em participar deste estudo, e eu não estou ciente de nenhum motivo que me impeça de fazê-lo. Eu li e entendi este formulário de consentimento livre e esclarecido. Eu tive todas as minhas perguntas respondidas. Eu reconheço tudo que foi escrito neste documento e dou o meu consentimento voluntário para a participação neste estudo, sem remuneração. Se eu participar, eu posso desistir a qualquer momento sem qualquer penalidade. Eu concordo em seguir as regras deste estudo.

XII. QUESTÕES

Se eu tiver qualquer dúvida ou precisar de qualquer outro esclarecimento a respeito deste projeto, eu posso entrar em contato com qualquer um dos investigadores a qualquer hora:

Investigadores:

Dr. Márcio Sarroglia Pinho — Telefone (51) 3320-3611
Professor, Escola Politécnica - PUCRS
E-mail: marcio.pinho@pucrs.br

Dr. Doug A. Bowman
Professor, Computer Science Department - Virginia Tech
E-mail: dbowman@vt.edu

Leonardo Pavanatto Soares
Estudante Pós-graduação, Escola Politécnica - PUCRS
E-mail: leonardo.pavanatto@acad.pucrs.br

Caso você tenha qualquer dúvida quanto aos seus direitos como participante de pesquisa, entre em contato com Comitê de Ética em Pesquisa da Pontifícia Universidade Católica do Rio Grande do Sul (CEP-PUCRS) em (51) 33203345, Av. Ipiranga, 6681/prédio 50 sala 703, CEP: 90619-900, Bairro Partenon, Porto Alegre – RS, e-mail: cep@pucrs.br, de segunda a sexta-feira das 8h às 12h e das 13h30 às 17h. O Comitê de Ética é um órgão independente constituído de profissionais das diferentes áreas do conhecimento e membros da comunidade. Sua responsabilidade é garantir a proteção dos direitos, a segurança e o bem-estar dos participantes por meio da revisão e da aprovação do estudo, entre outras ações.

Rúbrica do Participante	Rúbrica do Investigador Principal	Rúbrica do Profissional que obteve consentimento

Ao assinar este termo de consentimento, você não abre mão de nenhum direito legal que teria de outra forma. Não assine este termo de consentimento a menos que tenha tido a oportunidade de fazer perguntas e tenha recebido respostas satisfatórias para todas as suas dúvidas.

____ ________________
Assinatura do participante Data

____
Nome do participante (letras de forma)

XIII. DECLARAÇÃO DO PROFISSIONAL QUE OBTEVE O CONSENTIMENTO

Expliquei integralmente este estudo de pesquisa ao participante. Na minha opinião e na opinião do participante, houve acesso suficiente às informações, incluindo riscos e benefícios, para que uma decisão consciente seja tomada.

____
Assinatura do Profissional que obteve consentimento

LEONARDO PAVANATTO SOARES
Nome do Profissional que obteve consentimento

____
Assinatura do Investigador Principal

MÁRCIO SARROGLIA PINHO
Nome do Investigador Principal

Rúbrica do Participante | Rúbrica do Investigador Principal | Rúbrica do Profissional que obteve consentimento

Study 3

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO (TCLE)

Pontifícia Universidade Católica do Rio Grande do Sul

Título do projeto: **Modelando Novas Edificações em Realidade Aumentada**

Investigadores: Dr. Márcio Sarroglia Pinho, Dr. Doug A. Bowman, Leonardo Pavanatto Soares.

I. PROPÓSITO DA PESQUISA/PROJETO

O estudo de massa é um dos primeiros estágios no processo de projeto de uma nova edificação. Durante este estágio, arquitetos desenvolvem modelos ou concepções da nova edificação para visualizar a volumetria do projeto, e tentar entender algumas consequências das suas escolhas. Esta pesquisa investiga o uso de Realidade Aumentada (RA) para o projeto de grandes edificações em ambientes externos.

II. CONDIÇÕES

Para participar neste estudo, você deve possuir **ao menos 18 anos de idade**. Você deve possuir visão normal (corrigida ou não corrigida) e movimentação normal das mãos e dedos. Além disso, você não deve possuir nenhuma deficiência motora que o impeça de caminhar ou ficar em pé normalmente.

III. PROCEDIMENTO

Este estudo investiga técnicas de interação para modelagem em Realidade Aumentada (RA). Você será solicitado a projetar uma nova edificação utilizando estas técnicas.

1. Ao chegar no local no estudo, você será solicitado a ler este formulário de consentimento. Se você concordar em participar deste estudo, você rubricará todas as páginas e assinará e datará duas vias originais deste termo de consentimento. Para a sua apreciação, uma cópia digital deste formulário foi enviada por e-mail quando você se inscreveu para participar neste estudo. *Esta etapa deve durar cerca de 5 minutos.*
2. Você será solicitado a completar um questionário com informações de caracterização, como idade, gênero, experiência com computadores, modelagem, etc. *Esta etapa deve durar cerca de 5 minutos.*
3. Você receberá uma introdução ao equipamento que será utilizado utilizar durante o experimento, incluindo um Head-Worn Display (HWD) de RA, e um controle de mão (joystick). O HWD utilizado é o Microsoft HoloLens, e o joystick é o controle do Microsoft Xbox One. *Esta etapa deve durar cerca de 5 minutos.*
4. Você será solicitado a colocar o HWD e se familiarizar com a aplicação através de uma sessão de treinamento para uma técnica de interação 3D. *Esta etapa deve durar cerca de 5 minutos.*
5. Após a sessão de treinamento, você irá recriar uma edificação utilizando as ferramentas disponíveis. Você receberá instruções passo a passo para realizar esta tarefa. Ao final você responderá algumas perguntas sobre a interação. *Esta etapa deve durar cerca de 15 minutos.*
6. Você será solicitado a colocar o HWD e se familiarizar com a aplicação através de uma sessão de treinamento para uma segunda técnica de interação 3D. *Esta etapa deve durar cerca de 5 minutos.*

Rúbrica do Participante	Rúbrica do Investigador Principal	Rúbrica do Profissional que obteve consentimento

7. Após a sessão de treinamento, você irá recriar uma edificação utilizando as ferramentas disponíveis. Você receberá instruções passo a passo para realizar esta tarefa. Ao final você responderá algumas perguntas sobre a interação. *Esta etapa deve durar cerca de 15 minutos.*
8. Após as tarefas serem concluídas, você será solicitado a responder um questionário final para expressar a sua percepção e pensamentos a respeito da aplicação. *Esta etapa deve durar cerca de 5 minutos.*

Nota 1: o objetivo do experimento é avaliar as técnicas de modelagem, e não a sua performance.
Nota 2: se você precisar interromper o experimento para descansar por um tempo, informe o investigador.

IV. RISCOS E DESCONFORTOS

Existem riscos mínimos envolvidos neste estudo. O risco de lesão resultante de quedas é mínimo, porém existente, pois você deverá caminhar enquanto utiliza um HWD. Alguns usuários sentem desconforto ao utilizar o HWD. Se você sentir cansaço nos olhos, dores de cabeça, náusea, ou outro desconforto durante a sessão, informe o investigador para que um intervalo seja feito. Como o estudo vai ser conduzidas em área aberta ao público, você deve estar ciente do risco de ser reconhecido ou se sentir envergonhado. Você pode encerrar a sua participação a qualquer momento.

V. BENEFÍCIOS DO PROJETO

Sua participação vai nos ajudar a entender e melhorar o processo de modelagem em ambientes de RA. O problema afeta diretamente a performance em ambientes de RA utilizados para projeto e modelagem de novas edificações. Você irá, através deste estudo, nos ajudar a explorar técnicas de interação efetivas e prover informações úteis para a pesquisa de interfaces de usuário 3D.

VI. ANONIMIDADE E CONFIDENCIALIDADE

As informações desta pesquisa serão confidencias, e serão divulgadas apenas em eventos ou publicações científicas, não havendo identificação dos participantes, a não ser entre os responsáveis pelo estudo, sendo assegurado o sigilo sobre sua participação. Todos os dados coletados são anônimos e os formulários não possuem qualquer informação que possa identificar o participante.

Este projeto é realizado em parceria com a Virginia Polytechnic Institute and State University (Virginia Tech), dos Estados Unidos da América. Os investigadores de ambas universidades que trabalham diretamente neste projeto possuem acesso aos dados fornecidos por você. Na Virginia Tech, este estudo foi aprovado sob matricula **IRB #18-520**.

VII. COMPENSAÇÃO

A sua participação é voluntária e não remunerada.

VIII. DIREITO DE DESISTÊNCIA

Você pode encerrar a sua participação no estudo a qualquer momento e por qualquer motivo, bastando informar o investigador, sem nenhum tipo de prejuízo ou retaliação, pela sua decisão.

Rúbrica do Participante	Rúbrica do Investigador Principal	Rúbrica do Profissional que obteve consentimento

IX. ACESSO AOS RESULTADOS

Você tem direito a receber acesso aos resultados desta pesquisa após ela ter sido publicada. Entre em contato com um dos investigadores para requisitar acesso a informação.

X. APROVAÇÃO DA PESQUISA

Esta pesquisa foi aprovada, conforme requerido, pelo Comitê de Ética para projetos envolvendo participantes humanos da Pontifícia Universidade Católica do Rio Grande do Sul.

XI. RESPONSABILIDADE E PERMISSÃO DO PARTICIPANTE

Eu concordo voluntariamente em participar deste estudo, e eu não estou ciente de nenhum motivo que me impeça de fazê-lo. Eu li e entendi este formulário de consentimento livre e esclarecido. Eu tive todas as minhas perguntas respondidas. Eu reconheço tudo que foi escrito neste documento e dou o meu consentimento voluntário para a participação neste estudo, sem remuneração. Se eu participar, eu posso desistir a qualquer momento sem qualquer penalidade. Eu concordo em seguir as regras deste estudo.

XII. QUESTÕES

Se eu tiver qualquer dúvida ou precisar de qualquer outro esclarecimento a respeito deste projeto, eu posso entrar em contato com qualquer um dos investigadores a qualquer hora:

Investigadores:

Dr. Márcio Sarroglia Pinho — Telefone (51) 3320-3611
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Caso você tenha qualquer dúvida quanto aos seus direitos como participante de pesquisa, entre em contato com Comitê de Ética em Pesquisa da Pontifícia Universidade Católica do Rio Grande do Sul (CEP-PUCRS) em (51) 33203345, Av. Ipiranga, 6681/prédio 50 sala 703, CEP: 90619-900, Bairro Partenon, Porto Alegre – RS, e-mail: cep@pucrs.br, de segunda a sexta-feira das 8h às 12h e das 13h30 às 17h. O Comitê de Ética é um órgão independente constituído de profissionais das diferentes áreas do conhecimento e membros da comunidade. Sua responsabilidade é garantir a proteção dos direitos, a segurança e o bem-estar dos participantes por meio da revisão e da aprovação do estudo, entre outras ações.

Rúbrica do Participante	Rúbrica do Investigador Principal	Rúbrica do Profissional que obteve consentimento

Ao assinar este termo de consentimento, você não abre mão de nenhum direito legal que teria de outra forma. Não assine este termo de consentimento a menos que tenha tido a oportunidade de fazer perguntas e tenha recebido respostas satisfatórias para todas as suas dúvidas.

____ ______________

Assinatura do participante Data

____

Nome do participante (LETRA DE FORMA)

XIII. DECLARAÇÃO DO PROFISSIONAL QUE OBTEVE O CONSENTIMENTO

Expliquei integralmente este estudo de pesquisa ao participante. Na minha opinião e na opinião do participante, houve acesso suficiente às informações, incluindo riscos e benefícios, para que uma decisão consciente seja tomada.

____

Assinatura do Profissional que obteve consentimento

LEONARDO PAVANATTO SOARES

Nome do Profissional que obteve consentimento

____

Assinatura do Investigador Principal

MÁRCIO SARROGLIA PINHO

Nome do Investigador Principal

______________ ______________ ______________

Rúbrica do Participante

Rúbrica do Investigador Principal

Rúbrica do Profissional que obteve consentimento

APPENDIX C – QUESTIONNAIRES

Background Questionnaire

Please help us to categorize our user population by completing the following items.

Gender (circle one): Male Female

Age: ____________

Occupation (if student, indicate graduate or undergraduate): ________________________

Major / Area of specialization (if student): ______________________________

Rate how tired you are today: (circle one)

•---------------------------•---------------------------•---------------------------•

very tired | somewhat tired | a little tired | not tired at all

Rate your expertise with computers: (circle one)

•---------------------------•---------------------------•---------------------------•

beginner | amateur | intermediate | advanced

How often do you use computers...

...for work? (circle the best answer)

a. not at all
b. once a month
c. once a week
d. several times a week
e. daily

...for fun? (circle the best answer)

a. not at all
b. once a month
c. once a week
d. several times a week
e. daily

Rate your expertise with any type of 3D modelling: (circle one)

•---------------------------•---------------------------•---------------------------•

beginner | amateur | intermediate | advanced

Rate your expertise with 3D modelling buildings: (circle one)

•---------------------------•---------------------------•---------------------------•

beginner | amateur | intermediate | advanced

Rate your experience with video games: (circle one)

•---------------------------•---------------------------•---------------------------•

Never | Sometimes | Often | Everyday

Rate your experience with Virtual Reality (VR): (circle one)

•---------------------------•---------------------------•---------------------------•

Never | Sometimes | Often | Everyday

Rate your experience with Augmented Reality (AR): (circle one)

•---------------------------•---------------------------•---------------------------•

Never | Sometimes | Often | Everyday

Perception Questionnaire

Based on what you can see, please answer the following questions.

(1) How many people do you think would be able to walk side by side in the space between the real wall and the new building?

(2) How do you feel about the height of the building related to the ceiling where you marked the point before? Is it the same, lower or higher?

(3) Do you think that the building is leveled with the ground, or is there a slope?

(4) Do you think that the building is correctly aligned with the columns where the reference lines were created?

Post-Experiment Questionnaire

Please complete the following questions.

(1) **How accurate do you feel about the application you've just tried? Please rate the accuracy on a scale of 1 to 5.**
With 1 being not accurate at all and 5 being very accurate

1 2 3 4 5
•----------------------•----------------------•----------------------•----------------------•
Not accurate at all Very accurate

(2) **Was the application easy to use? Please rate the ease of use of on a scale of 1 to 5.**
With 1 being very hard to use and 5 being very easy to use

1 2 3 4 5
•----------------------•----------------------•----------------------•----------------------•
Very hard to use Very easy to use

(3) **How fast do you feel you can complete the task using this application? Please rate the speed on a scale of 1 to 5.**
With 1 being very slow and 5 being very fast

1 2 3 4 5
•----------------------•----------------------•----------------------•----------------------•
Very slow Very fast

(4) **How natural do you feel about the interaction you've just tried? Please rate the naturalness on a scale of 1 to 5**
With 1 being not natural and 5 being very natural

1 2 3 4 5
•----------------------•----------------------•----------------------•----------------------•
Not natural Very natural

(5) **Was the application fun to use? Please rate the comfort on a scale of 1 to 5**
With 1 being not fun at all and 5 being very fun

1 2 3 4 5
•----------------------•----------------------•----------------------•----------------------•
Not fun at all Very fun

(6) **Was the application comfortable to use? Please rate the comfort on a scale of 1 to 5**
With 1 being very uncomfortable and 5 being very comfortable

1 2 3 4 5
•----------------------•----------------------•----------------------•----------------------•
Very uncomfortable Very comfortable

Final Questionnaire

Please complete the following questions.

(1) Which point marking technique did you preferred?

- Geometric (one click to mark)
- VectorCloud (wait count until 50)
- None, they were both similar

(2) Can you describe why did you preferred to use this technique?
(pros, cons, what bothered you)

____

____

____

____

APPENDIX D – TRAINING PROTOCOL

Welcome

Welcome to the <location>. My name is Leo, and I will be conducting this experiment today. The first part of our experiment will take place in the <location> room. This experiment explores how early stages of architectural design, namely massing studies, can take place in an augmented reality setting. You will be asked to use an application to design a building and give feedback on the application.

1. Go to Sandbox

Before we start, I will ask you to read and sign this consent form. It is the same one that I send you through email. Take as long as you need. Also, remember that you can revoke consent and withdraw from the study at any time and for any reason.

2. Participants sign consent;

Now that you have consent to participate in the study, I will ask you to fill a background questionnaire in the computer.

3. Fill background questionnaire;

Any question?

Equipment

Our experiment will take part in two sessions. First, we will do a training session inside this room, where you will be able to understand how the equipment and the application work. Then, we will head outside, to the grass field in the Upper Quad, where the experiment itself will take place.

During both parts of the experiment I will ask you to use think-aloud protocol. By that I mean that I want to say out loud what are you thinking, what your though process is, what are you trying to accomplish and if any problem or frustration you are experiencing with the application. Don’t be worried about saying “something wrong”, this experiment is testing the application and not you. The audio will be recorded for this evaluation of the application.

Before we start with the training session, let me introduce you to the equipment we will be using. This is the Microsoft Xbox One controller. You might have used before, there is nothing special about it. During the experiment you will be using the joystick on the left, along with the left bumper and trigger, and the four buttons on the right.

4. Move joystick and press bumper and trigger, rotate the device so they can see you pressing the back buttons. Press four buttons.

The other device you will be using is the Microsoft HoloLens. This is an augmented reality head worn display, meaning that you will wear this on your head, and will be able to see both the real world and virtual content at the same time. I will ask you to put the HoloLens in a second. To do that, you can turn the knob in the back of the adjustable head strap to make it bigger or smaller, and you can also adjust the strap on the top.

5. Turn the nob to make it bigger, the smaller.

You can put the device over your head, and downwards (demonstrate). If you wear glasses, pull the visor forward and wear it over your glasses. After it is in place, make sure that it is not too loose. You can adjust the knob again to fix it.

Any question?

Hololens CALIBRATION

PUT ON HoloLens

Is it comfortable? The weight of the equipment should be place on your forehead and not on your nose.

6. Adjust if needed

If you look over here (point), you should be seeing a hologram. This hologram opens the application that calibrates the HoloLens specifically to be used by you. Notice that there is a white dot in the center of the screen. Think of it as computer cursor, but instead of moving your hand to move the cursor, you rotate your head. Go ahead and try positioning the dot over the hologram. (wait)

Now, place you index finger in front of your vision, and tap the Hologram, like this. (demonstrate)

7. Run calibration

I will ask you to open the “AR-Massing” application window, which is located on this wall (point). Use the same procedure as before, position the dot over the window, and tap with your finger.

Let me know if you can see the four corners of the screen, you should be seeing squares with numbers inside. Can you tell me those numbers?

8. Red 16, Blue 41, Green 35, Pink 00.
9. Load scene (hold menu and select buttons, release select first).

Great, now I will give you the Xbox controller. You should be seeing a crosshair, and you will used it to point to the object that you want to interact with and press the buttons on the joystick for actions.

PUT ON Xbox Controller

TRAINING – PART 1

Now we will start the training session. You will be presented with small tasks that will make you understand how to use the application, and that, together, will result in two small-scale buildings. During this training session, please, do not perform any action unless instructed by me. If you feel dizzy, or need to stop the experiment, please let me know.

Start recording AUDIO

Task 1: Using the menu

Before we start building, I will teach you how to use the menu and select which tool of the application you are using. **Hold the button “X”** (it is the one on the left), and you will see that a circular menu will appear with all the tools available to you: a polyline, a rectangle, a reference, a measure, move, rotate, clone, extrude, extrude to point, and visualize. To change the mode you are using, keep the "X" pressed, and **move the joystick** on your left towards the tool you want. Once the circle moves over it, you can release the "X" button to select the tool. Try changing tool sometimes, once you feel you understood it, select the polyline tool and **release the button**. (wait)

Task 2: Creating a point

The first task I will ask you to do is create a point at this corner of the box (point). To do that, you will need to know a few things. First, the HoloLens does not know the geometry of the real world in distant settings, therefore we will need to tell him where the point is. To do that, we will need to mark the same point two times, from two distinct positions. The crosshair you are seeing in the center of the screen works similarly to the dot you used before. Stay over this point (point) and position the crosshair over the corner of the box. (wait)

Great. Now, if you **hold the "A" button** on the controller (the one on the bottom), you will see that it starts to count. You need to keep the crosshair over the point and keep holding the button until this numbers reaches over 30, then you can **release it**. Go ahead and do that. (wait)

Now, you will need to **move to a new location**, like this point over here (point), and **perform the same operation again**. Notice that a purple ray will appear. This ray starts from the position you were before, and points in the direction that you marked before. Now, **place the crosshair** over the same point you marked before and **hold the "A" button** until it reaches 30. (wait)

So, as you can see, after you marked the same point for the second time, the HoloLens learned where the point is by triangulating both markings. Go ahead and walk around it, noticing if it is placed in the correct position. If the point is not exactly in the correct position, you can delete the point and perform the operation again.

Task 3: Deleting a point

To delete, you will need to point the crosshair over the point and **press the button "Y"** (it is the upper button) once. (wait) And then you can perform the **marking process again**. Go ahead and do it. (wait)

Task 4: Creating a line segment

Now that you have a point, let's make a line segment out of it using the polyline tool. To do so, you need to select the point, by **placing the crosshair over the point** and **pressing "A" once**. This means you selected that point as the start of your line. Once selected the point will become red. In this case the point was already red because it was the last point created. To complete the line, you need to **create a second point**, using the same process as before. (wait)

Notice that the last point you created will automatically be selected (red), this means that you can keep marking points to create the polyline. If you ever want to release the object, you can look to a place without any virtual object and **press the button "Y".** Go ahead and do it. (wait)

Task 5: Creating a line segment with multipoint

Another way of creating a line is marking multiple points at a time. Instead of doing the whole process for each point individually, you can mark multiple points from the first position, move to a new position, and mark the same points again, in the same order.

Notice this other blue tape over here (point). Then, from the first position, you can **mark the first extremity**, and then **mark the second extremity** of the tape (wait). After that, you **move to the second position**, and **mark the two points again**, in the same order. As you complete each point, they will be created. Once both have been created, a line will appear. (wait)

Task 6: Creating a reference line

Just like you create a line segment before, you can also create a line with infinite size that can be used as a reference. This line is especially useful if you want to align your model to other objects. For instance, let's say we want to make a model parallel to this box. (point)

To do that, you will just **select the reference tool from the menu**, and **mark two points**, the bottom corners of the box in the same way that we trained before. (wait)

After you created the reference line, notice that an object showing axes in different colors will appear aligned to that reference. This is the coordinate system of your model, which will be used by other operations later. The first reference you create in a model will always define how your coordinate system is positioned.

Task 7: Creating point over line

If line or reference already exists, you can create a point over then by just **pointing** (they will become yellow) and **pressing "A" once**. A point will appear exactly over the line. Create a point in the intersection of the reference and this line segment, here. (point)

If while you are modeling you decide that you want to divide a face in half, you could do exactly the same thing. Just create two points over the lines, at the location points that you want to divide, and connect them with a line.

Task 8: Creating a rectangle

If you want to create a rectangle, you can use a shortcut. **Select the rectangle tool** on the menu, and then you will need to mark 3 points. You can do that in clockwise or counterclockwise order, and the fourth point will be automatically generate by the system. **Select these two points** that already existed and **create a third point over the reference** here (point). Go ahead and try it. (wait)

Now you should have four points, four segments of lines, and a face. Notice it will not necessarily generate a rectangle, depending on how you marked the points you could have a parallelogram. (wait)

Now, let's take some time off. Please hand me the controller and take off the HoloLens.

REMOVE controller

REMOVE HoloLens

Are you feeling ok? Any dizziness or discomfort? Do you want to take some water?

10. Wait at least 2 minutes

 Any question before we proceed?

TRAINING – PART 2

Task 9: Creating measures

To make sure that we build this rectangle correctly, you can **select the measure tool** from the menu. There are three types of measurements we can do: distances, angles and areas.

- To measure the length of a line, you just **select the two points** that define it. Try it. (wait)
- To measure the angle between two lines, you can **select the two lines** you want to measure. (wait)
- To measure the area of the face you just created, **select the face**. (wait)

Notice that the values collapse to avoid clutter. To see the information, just position the crosshair over the label and the value will appear, while also highlighting the objects. You can also measure distances of real world objects. To do that, you could select two points, like if you were going to define a line.

Task 10: Moving

If you don't like the position of a point, or a line, or a face, you can move it. To do so, **select the move tool** on the menu. Then, you **point the crosshair to the object** you want to fix and **hold the "A" button**. While you are keeping the "A" button pressed, you can move the object by **using the joystick** on the left, and the **bumper and trigger** on the back. Notice that objects will move relative to the coordinate system that was define before. Try moving the that line (point) to here (point) now. (wait)

Task 11: Cloning

Just like you just moved objects, you can also clone them. To do that **select the clone tool** on the menu and do the exact same thing you did before when you were moving. Now, I want you to clone the reference line you created before. **Hold the "A" button** and **move with the joystick and the bumper and trigger**. Move the reference line to here. (point)

The only difference in this mode is that when you are cloning lines, you will not be allowed to move it along its own axis. (wait)

Task 12: RotatING

Now, let's learn how to rotate the objects. Go to the menu and **select the rotate tool**. Now **point the crosshair** over the new reference line you just created and **press "A" once**. (wait)

Notice that the line was rotated on its center by 45 degrees. You can rotate lines, references and faces as long as they are not connected to other objects. **Rotate it again**, so that we can achieve a 90 degrees rotation from the original position. And then, **use the move tool to align this new reference to the side of the box**, here (point)

Task 13: Coordinate based polyline

If you want to create a line along one of the same axes of your coordinate system, you can just select the first point, and as you move the crosshair around, you will see that a colored reference will appear a long with a point. If you just **position the point over this reference** and **press "A" once**, you can create a line easily.

Now, I want you to create a new face using this mode. **Select this point** over here (point) and **create the other points** that close the rectangle. (wait)

Task 14: Extrude

Now we have two faces. To create a solid from a face, we can use the extrusion tool. **Select the extrusion tool** on the menu and **position the crosshair** over one of the faces. (wait)

Now, while you are **holding the "A" button**, the extrusion will happen. Once you achieve the desired height, just **release the button**. (wait)

The face orientation will define the direction of the extrusion. In this case, both faces are horizontal, so the extrusion goes up.

Task 15: Extrude to point

If you want to extrude the face to a point that exists in the real world, you can do that using the extrude to point feature. You will need to **select the extrude to point tool** on the menu and **mark the point** that you want to extrude to. After the point is created, it will be red, and then you can select the face by **pointing to it** and **pressing "A"** once. The extrusion will stop automatically once it reaches the point. Do this to the other face that we did not extrude. Try extruding it to the height of a table (wait).

Task 16: Visualization

And finally, if you want to visualize the result of what you have built, you can **select the visualize tool** on the menu. (wait for it)

Notice how only segment lines and faces are kept, so you have a clear view of what you have built.

Stop recording AUDIO

Now that you learned how each of the interaction techniques work, we can move to our main experiment, where all of them can be used. This task is going to be performed outside. You can give me the controller and take the HoloLens off, and we can walk to the site.

REMOVE controller

REMOVE HoloLens

Are you feeling ok? Any dizziness or discomfort? Do you want to take some water?

Any question before we proceed?

APPENDIX E – ABSTRACT PUBLISHED AT THE WORKSHOP OF THESIS AND DISSERTATIONS OF THE 20TH SYMPOSIUM ON VIRTUAL AND AUGMENTED REALITY

Modeling New Buildings with an Augmented Reality Head-Worn Display

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***Abstract*—The initial phases of the design of new buildings require architects to define the general shape of the building, based on the client's requirements. In these so-called massing studies, the architect will try different approaches to the building, and try to analyze their relationship with the neighboring environment. We propose a new approach that uses Augmented Reality (AR) to perform this process by using features present in the real world, such as buildings and pathways. Our preliminary results include the definition of tools that use those features, and the implementation of a prototype, which was improved through a formative study. A summative study and analysis comparing this approach with a traditional approach are pending.**

***Index Terms*—3D Modeling, 3D Interaction, Augmented Reality**

I. Introduction

The process of designing a new building involves a number of consecutive stages, where each grows in scope and complexity. At the beginning of this process, based on the client's requirements, the architect must define the position of the building on the site and how the general shape is going to look like, through early sketches or models [4]. This step, sometimes called massing study, represents the stage where architects will try different design approaches for the building while trying to analyze their impact and how they fit the environment surrounding it.

This work proposes a novel approach for fast and preliminary design of new buildings using an AR system. AR is an approach that uses displays, tracking, and other technologies to enhance (augment) the user's view of a real-world environment with synthetic objects or information [3]. Most concepts and technologies used in AR are similar to the ones developed for Virtual Reality (VR), the main difference between both being manifested from the need of AR to combine both virtual and physical environments in a spatially and cognitive manner [7].

II. Motivation

Architects can use tools such as hand sketching, mock-ups, or 3D modeling tools to study the building's geometry. While those traditional tools are efficient for proposing a model design, their take on the relationship between the building and the environment surrounding it could be limited.

The understanding of the real-world must be done prior and separate to the modeling, which could lead to a more time-consuming process, and could raise the susceptibility of miscommunications. Therefore, the ability design and visualization of the model in-situ (where the building will be constructed) and in real-time could be a valuable tool to aid the process of architectural design.

III. Related Work

The first outdoor AR system was created by Feiner et al. [2], where a tool was implemented to provide tour guides over the campus of Columbia University. An optical see-through Head-Worn Display (HWD) showed information about the buildings as the user walked around the campus. Global Positioning System (GPS) and orientation tracking were used along with a handheld device for interaction.

Baillot et al. [1] expanded the Battlefield Augmented Reality System (B.A.R.S) to provide tools for authoring the environment. Methods for defining points and lines along with operations were used to create geometric models.

Piekarski and Thomas developed the TINMITH system [5]. It was a hand gesture and GPS based experimental platform, which was used for a wide range of applications, from the placement of objects in the real world to a first-person mobile AR game. Using this platform, they proposed multiple techniques for modeling large-scale objects on the outside [6].

These papers have mostly focused on modeling 3D versions of already existing buildings and did not explore further the problem of designing new buildings, and especially how real-world features could benefit this process.

IV. Proposed Solution

Our goal is the development of modeling techniques that allow the user to perform this kind of task in a practical and straightforward manner, by using features already present in the real world as references to support them (such as the geometry or texture of existing buildings or pathways).

The interaction is based on an optical see-through HWD, and relies on multimodal inputs, consisting of user's orientation, position, and a conventional joystick. This approach is aimed to design buildings from scratch, and therefore, no models (virtual or real) should be available to the user.

The main reasoning behind this approach is that new buildings are usually designed over open space areas, such as grass fields or parking lots, which do not provide much information about where the virtual content should be placed. The techniques proposed in this work aim to allow the user to take advantage of neighboring features to estimate or guide where the content should be placed along with its dimensions.

We hypothesize that using real-world features, such as other buildings' and objects' position, orientation, scale, and texture, is a compelling approach to improve easiness and usefulness of interfaces for designing buildings with AR.

V. Preliminary Results

Interviews with 7 stakeholders were performed to better understand the domain. From those interviews, we learned that the design process is flexible and depends on the architect and the characteristics of the new building itself.

The design process can usually be divided between: an **information gathering phase**, where the client will present a program with requirements for the building; an **ideation phase**, where the environment will be evaluated, such as height of surrounding buildings, shadow effects, etc; a **representation phase**, where an earlier model is created through as mass model; and an **iterative phase** creates a feedback loop, where the flow returns to the ideation phase.

The following modeling tools were designed: creation of polylines, rectangles, and references; translation, rotation, and cloning of primitives (vertices, edges or faces); extrusion of faces (manual and automatic up to a certain point); and analysis of the model with measures (distance, angle and area), and clear visualization. All those tools used at-a-distance marking, by doing a triangulation from two different positions. Therefore, points can be placed with a certain accuracy in locations where the features are well defined, such as corners of buildings.

Figure 1 shows one building created using the application. The green infinite line in the bottom represents a *reference*, which can be used to align the model to real-world features. By using the automatic extrusion, the height of the building could be easily aligned to the other building in the back.

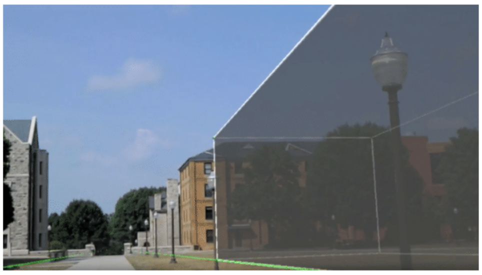

Fig. 1. General geometry of building designed using the system.

A formative study was performed with 3 participants with a background in architecture and modeling, in order to find problems in the interaction. The prototype consisted of a Microsoft HoloLens, and a Microsoft Xbox One Controller.

The procedure was as follows: participants signed a consent form and answered a background questionnaire; a training session was conducted, where they learned each of the tools available in the application; the main task was conducted, where participants had to design a new building; and finally, they answered a post-experiment questionnaire.

During the main task, participants used think-aloud protocol. Combining information from the think-aloud protocol and the questionnaires, we obtained enough information for improvements, such as: using larger bounding boxes on distant points, to make selection easier; a complete redesign of the menu; adding automatic measures during some operations.

VI. Conclusion

We proposed a new approach for modeling new buildings in AR, where the real world is the protagonist, and features present on it can be used to support the architect. During our informal interviews with stakeholders, we learned how the phases of the design process are defined. It is clear that our proposal would merge the ideation and representation phases into a single prototyping phase, at least for a first iteration. Of course, it does not replace other steps of analysis, that should be done using more detailed mock-ups and models.

A prototype implemented some tools designed to allow the modeling to take place, and improvements were performed through a formative user study, conducted with field-related participants. The next steps consist of performing a formal summative evaluation, to test our hypothesis and understand the pros and cons of this approach. We are going to compare the proposed system with a baseline version where the tools do not rely on neighboring world features.

VII. Acknowledgments

Our research is partially funded by (a) the National Institute of Science and Technology in Medicine Assisted by Scientific Computing (Grant CNPq 181813/2010-6) and (b) the Coordenação de Aperfeiçoamento de Pessoal de Nivel Superior – Brasil (CAPES) – Finance Code 001.

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ATTACHMENT A - VT IRB APPROVAL LETTER

VIRGINIA TECH

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE:	June 28, 2018
TO:	Douglas Andrew Bowman, Leonardo Pavanatto Soares
FROM:	Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)
PROTOCOL TITLE:	Modelling New Buildings in Augmented Reality
IRB NUMBER:	**18-520**

Effective June 28, 2018, the Virginia Tech Institution Review Board (IRB) approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 6,7**
Protocol Approval Date:	**June 28, 2018**
Protocol Expiration Date:	**June 27, 2019**
Continuing Review Due Date*:	**June 13, 2019**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

ATTACHMENT B - PUCRS CEP APPROVAL LETTER

PONTIFÍCIA UNIVERSIDADE CATÓLICA DO RIO GRANDE DO SUL - PUC/RS

PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: MODELANDO NOVAS EDIFICAÇÕES EM REALIDADE AUMENTADA
Pesquisador: Marcio Sarroglia Pinho
Área Temática:
Versão: 2
CAAE: 95675218.2.0000.5336
Instituição Proponente: UNIÃO BRASILEIRA DE EDUCAÇÃO E ASSISTENCIA
Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 2.892.395

Apresentação do Projeto:
O pesquisador principal Marcio Sarroglia Pinho, responsável pelo projeto com número de CAAE 95675218.2.0000.5336 e Título: MODELANDO NOVAS EDIFICAÇÕES EM REALIDADE AUMENTADA encaminhou ao CEP-PUCRS projeto contendo os seguintes documentos: carta de encaminhamento, folha de rosto da CONEP, carta de conhecimento e autorização do responsável pelo local onde a pesquisa será realizada, documento Unificado do SIPESQ, currículo Lattes dos pesquisadores brasileiros e documento com currículo do pesquisador dos Estados Unidos, orçamento financeiro, termo de consentimento livre e esclarecido, questionários (incluídos no documento unificado do SIPESQ), roteiro de entrevista e instrumento de coleta de dados (incluídos no documento unificado do SIPESQ) e documento de aprovação no comitê de ética do projeto nos Estados Unidos, na Universidade de Virginia Tech - Virginia Tech Institution Review Board (IRB).

Objetivo da Pesquisa:
O objetivo da pesquisa é o desenvolvimento de uma nova abordagem para o projeto de edificação de larga escala em ambientes externos de forma prática e fácil utilizando Realidade Aumentada (RA), para aproveitar características presentes no mundo real para ajuda-los (como edificações existentes ou calçadas). A interação é baseada em óculos de realidade aumentada e também utiliza entradas multimodais, incluindo a posição e orientação do usuário e um joystick.

Endereço: Av.Ipiranga, 6681, prédio 50, sala 703
Bairro: Partenon **CEP:** 90.619-900
UF: RS **Município:** PORTO ALEGRE
Telefone: (51)3320-3345 **Fax:** (51)3320-3345 **E-mail:** cep@pucrs.br

Avaliação dos Riscos e Benefícios:

Riscos: Existem riscos mínimos envolvidos neste estudo. O risco de lesão resultante de quedas é mínimo, porém existente, pois o participante deverá caminhar enquanto utiliza um HWD (Microsoft HoloLens). O participante pode sentir cansaço nos olhos, dores de cabeça, náusea, ou outro desconforto durante a sessão provenientes do uso do HWD. Como algumas partes do estudo vão ser conduzidas em público, existe o risco do participante ser reconhecido ou de se sentir envergonhado.

Minimização dos riscos: O participante vai ser informado dos riscos e será instruído a prestar atenção no ambiente ao seu redor. O investigador vai monitorar ativamente o ambiente e as ações do participante para reduzir qualquer risco de queda e vai trabalhar para que a área em questão esteja livre de obstáculos. O investigador vai alertar o participante para parar caso ele esteja prestes a entrar em uma área com riscos de tropeço ou demais obstáculos. A sessão incorporará paradas para descanso após cada tarefa, e o participante pode solicitar paradas extras caso sinta necessidade. O risco de ser reconhecido ou se sentir envergonhado será explicado ao participante antes do estudo. Ele também será lembrado que pode desistir a qualquer momento e por qualquer motivo.

Benefícios: O participante terá a chance de experimentar o estado da arte em tecnologia de Realidade Aumentada (RA), incluindo um HWD de RA, e uma forma inovadora de modelar edificações. A sociedade irá se beneficiar da avaliação formal desta aplicação, que poderá indicar formas mais eficientes de realizar modelagem em ambientes de RA.

Comentários e Considerações sobre a Pesquisa:

Foi incluído um espaço de rubrica e um espaço para assinatura do pesquisador principal no TCLE (Termo de Consentimento Livre e Esclarecido). Sendo assim, não existem mais pendências no projeto.

Considerações sobre os Termos de apresentação obrigatória:

Todos os termos foram apresentados.

Recomendações:

Não há recomendações.

Conclusões ou Pendências e Lista de Inadequações:

Não há pendências.

Considerações Finais a critério do CEP:

Diante do exposto, o CEP-PUCRS, de acordo com suas atribuições definidas nas Resoluções CNS n° 466 de 2012, n° 510 de 2016 e Norma Operacional n° 001 de 2013 do CNS, manifesta-se pela aprovação do projeto de pesquisa proposto.

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1191569.pdf	05/09/2018 17:24:43		Aceito
Outros	cartaRespostaPendencias050918.pdf	05/09/2018 17:22:39	Leonardo Pavanatto Soares	Aceito
Outros	cartaRespostaPendencias_050918.doc	05/09/2018 16:19:08	Leonardo Pavanatto Soares	Aceito
Outros	consentimento_050918.docx	05/09/2018 16:18:10	Leonardo Pavanatto Soares	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	consentimento_050918.pdf	05/09/2018 16:17:57	Leonardo Pavanatto Soares	Aceito
Folha de Rosto	folhaDeRosto2.pdf	10/08/2018 11:29:16	Leonardo Pavanatto Soares	Aceito
Projeto Detalhado / Brochura Investigador	DocumentoUnificado.pdf	10/08/2018 11:12:38	Leonardo Pavanatto Soares	Aceito
Outros	cv.pdf	10/08/2018 11:10:24	Leonardo Pavanatto Soares	Aceito
Declaração de Instituição e Infraestrutura	declaracao_instituicao.pdf	03/08/2018 15:55:22	Leonardo Pavanatto Soares	Aceito
Outros	VT_Approval_Letter.pdf	02/08/2018 16:07:33	Leonardo Pavanatto Soares	Aceito
Outros	lattes_marcio.pdf	02/08/2018 10:56:17	Leonardo Pavanatto Soares	Aceito
Outros	lattes_leonardo.pdf	02/08/2018 10:55:51	Leonardo Pavanatto Soares	Aceito
Outros	questionarios.pdf	02/08/2018 10:53:55	Leonardo Pavanatto Soares	Aceito
Orçamento	orcamento.pdf	02/08/2018 10:51:53	Leonardo Pavanatto Soares	Aceito

Declaração de Pesquisadores	carta_encaminhamento.pdf	02/08/2018 10:50:58	Leonardo Pavanatto Soares	Aceito

Situação do Parecer:
Aprovado

Necessita Apreciação da CONEP:
Não

PORTO ALEGRE, 13 de Setembro de 2018

Assinado por:
Paulo Vinicius Sporleder de Souza
(Coordenador)

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