Evaluating the Impact of Point Marking Precision on Situated Modeling Performance

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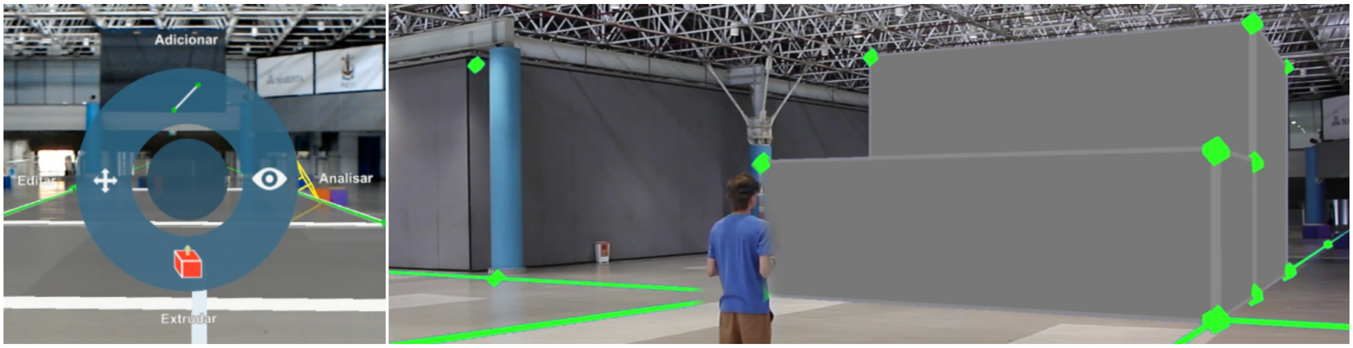

Figure 1: AR situated modeling application. Tools menu (left); completed building model from the experiment (right).

ABSTRACT

Three-dimensional modeling in augmented reality allows the user to create or modify the geometry of virtual content registered to the real world. One way of correctly placing the model is by creating points over real-world features and designing the model derived from those points. We investigate the impact of using point marking techniques with different levels of precision on the performance of situated modeling, considering accuracy, and ease of use. Results from a formal user study indicate that high-precision point marking techniques are needed to ensure the accuracy of the model, while ease of use is affected primarily by perceptual issues. In domains where correctness of the model is critical for user understanding and judgment, higher precision is needed to ensure the usefulness of the application.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Mixed / augmented reality**.

KEYWORDS

3d modeling; augmented reality; user studies

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1 INTRODUCTION

In recent years, researchers have proposed many mixed reality applications aimed at solving or simplifying problems in the architecture domain, such as visualization [5, 7, 20], sketching [6, 17] and geometric modeling [2, 4, 8, 9, 19]. Although designing 3D models digitally is not an unexplored topic, modifying existing methods to fit 3D user interfaces still provides challenges such as maintaining high accuracy while working with more degrees of freedom.

Domain characteristics must be considered when designing 3D tools. In architecture, even simple massing models require a definite shape [21]. Moreover, the technology determines what information can be used to aid modeling. For example, we can accurately place a new window on a wall in a virtual reality (VR) environment, because the location and the dimensions of the wall are known. However, we may need to estimate the position of the window in augmented reality (AR), because often a geometric model of the environment is inaccurate or unavailable, notably at large distances.

Considering the case of AR, the dimensions of the model influence the type of interaction. Designing a building mock-up over a table can take advantage of using direct mapping, which allows for fine precision and a natural interaction [11], and fiducial markers can provide computationally inexpensive tracking [18]. On the other hand, defining a full-scale building model outdoors may require at-a-distance interaction [15], because the user won't be able

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to navigate as easily. Model-free point marking techniques [10] can be used at a distance to obtain coordinates when an environment model is not available.

Situated modeling [18], the act of modeling directly at the site, preserves the relationship between real and virtual content, which is crucial in tasks where the former influences the latter. An important step in building design is to define the position of the new structure relative to real-world features [12]. Using a traditional modeling tool, modeling in VR, or even using AR tabletop modeling may force the architect to go back and forth between modeling and understanding the environment, resulting in inefficiency [18].

In this work we investigate the impacts of the precision of model-free point marking techniques on the situated modeling of large structures, in terms of accuracy and ease of use. We compared two existing point marking techniques in the context of an AR modeling application that derives shapes from initially obtained points. We contribute to the field by validating the findings of Lages et al. [10], by showing that these findings hold with a more ecologically valid task; and by demonstrating empirically how small errors in marked points can lead to larger errors in derived points.

2 RELATED WORK

Existing work presented techniques aimed at obtaining real-world coordinates and using them as the basis upon which the new model is defined [1, 3, 14, 16]. Applications usually support the creation of primitives such as lines, line segments, volumes [1, 3], AR working planes [13], and infinite planes [15]. These techniques were not evaluated with formal quantitative user studies, making it difficult to understand their limitations and optimal uses.

In particular, point marking techniques based on the intersection of two ray casts [1, 3] 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, creating points at the user position [14] requires the user to walk around the space, which for a large structure might be a big area, thus requiring highly accurate tracking.

Lages et al. [10] compared multiple geometric techniques for the creation of individual points in model-free AR, including one based on the intersection of single rays cast from two different locations, and another (VectorCloud) based on multiple ray samples from each location. Their results showed that VectorCloud had higher precision, especially at greater distances. However, the study only evaluated the creation of individual points, and did not consider any application. Our work explores the impact of point marking technique precision in a realistic AR modeling application, where new points and lines are usually derived from marked points, by asking how much extrapolation error is created in the model when using techniques with different levels of precision. We investigate how such errors impact the usability of the application.

3 SYSTEM DESIGN

We designed a system (Figure 1) called ***Modeling Architectural Structures in Situ (MASS)***, to be used on an AR head-worn display (Microsoft HoloLens). It uses an optical see-through display to maintain a high fidelity of the real world, while also tracking the position of the user in the environment. 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 on a handheld controller (Microsoft Xbox One Wireless Controller).

We implemented the Geometric and VectorCloud techniques from Lages et al. [10] to obtain the coordinates of features of the real-world environment. The **Geometric** technique allows users to obtain coordinates by pointing at the real-world target from two distinct perspectives. From each perspective, the user aims a crosshair located at the center of the head-worn display at the feature they aim to mark and presses a button, which will cast a single ray at the target. The closest point of intersection between the two rays returns the coordinates for the target. The **VectorCloud** technique follows a similar approach. However, from each perspective, the user holds a button, which will cast multiple rays at the target. The number of samples depends on how long users hold the button, with one ray cast per frame. Each ray from a perspective is paired with all rays from the other perspective, and their closest points are calculated. The average of these intersection points estimates the 3D position of the target point.

Since our system requires the user to mark a significant number of points, we designed an optimization which we called **Multipoint Marking**, where multiple points can be defined sequentially from the first perspective. A distance threshold informs the system when the perspective changes, and the user then marks the same points again, in the same order from the second perspective. In this way, the amount of walking required is reduced significantly.

Besides the direct creation of points, the application also supports the definition of reference lines, line segments and rectangles, by selecting points. New points can be created on existing virtual geometry using a simple ray cast. Translating, rotating, cloning, and extruding objects is also possible. Some tools also provide some shortcuts: an extrude-to-point tool allows for an extrusion to be made automatically to a certain height, defined by a point; a clone-to-point tool allows for a reference to be cloned and translated to intersect another point. Tools are selected through a circular menu accessed with the handheld controller, as shown in Figure 1. More details on system design can be seen in the supplementary video.

4 USER STUDY

We performed a summative user study with the objective of understanding the effects of the precision of the point marking technique on the process of situated modeling. The question that we aimed to answer was: How are the accuracy and ease of use of 3D modeling techniques affected by the precision with which points based on real-world content are defined?

4.1 Experimental Design

We conducted the study within-subjects, with marking technique (Geometric and VectorCloud) as the independent variable. We controlled the number of samples used by VectorCloud by requiring all participants to use 50 samples from each perspective. The order of techniques was counterbalanced to minimize any learning effects. For each technique, we conducted a small tutorial on its use, and then guided the participant through the main task.

The following objective dependent variables were analyzed: accuracy of the position of points that defined the new building (compared with 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.

We obtained ground truth point locations by first physically measuring the distance between the two points where users stood during the task. Then we performed the task ourselves twice using VectorCloud with 200 samples for each point. We took the average position of each point and plotted it on a floor plan of the real building. Finally, we aligned the points so that all line segments in the building formed right angles with each other.

Participants also completed three questionnaires: a **background questionnaire** at the beginning, which included demographic questions (age, gender, field, etc.); a **technique questionnaire**, which included questions about how the user rated the technique and application based on aspects such as precision, comfort, and ease of use; and a **final questionnaire**, with questions such as which technique they preferred and why.

4.2 Hypotheses

From our research question, we proposed two hypotheses.

H1. Marking initial points with a less-precise point marking technique will result in significant accuracy reductions for derived points when compared against equivalent points derived from a more-precise technique. We believed imprecise point marking would have a cascading effect on the accuracy of the model deriving from the marked points.

H2. Using a less-precise point marking technique will reduce the ease of use of the modeling tools. If H1 is correct, we believe that the lower precision of the marked points, in conjunction with incorrect occlusion and shading cues in AR, will lead to difficulty in understanding the model.

4.3 Procedure

The study was approved by the university's Institutional Review Board. The participant arrived in the study area and signed a consent form. We showed them a video of the application being used in the outdoors, to guarantee understanding of the application use cases. They answered the background questionnaire, and we presented the equipment to them. Before starting, the HoloLens calibration app measured and calibrated their interpupillary distance (IPD), and our application screened them for color blindness.

During each of the tutorials, the participant marked two points using the current technique. After the first technique's training session, they also received instructions about how to select and release existing objects, and how to undo or redo operations. In each of the main tasks, they created a specific building model following a sequence of well-defined steps presented by the experimenter. The participant could undo actions if they believed that something was wrong (e.g., the alignment, the position of the points) before moving to the next step. These were done at the participant's discretion and relied on their perception of the modeling.

After each main task, the participant completed the technique questionnaire. Then they would redo the training and main task for the second marking technique. After finishing the questionnaire for the second technique, the participant would complete the final questionnaire.

4.4 Environment and Task

The physical environment was a vast room of around 6 meters in height, which allowed us to try to replicate the distances and sizes of the use case of designing a new building. We decided to conduct the experiment in an indoor space to maintain a lower temperature and controlled brightness, allowing us to focus on the evaluation of the techniques rather than equipment limitations. The user could only interact from two pre-calibrated locations (L1 and L2 in Figure 2), to minimize the effects of tracking issues.

The main task consisted of nine steps . Together they would result in a model of a new building, as shown in Figure 1. We placed physical markers on the ground to indicate the exact points users were asked to mark. These steps were: (1) Mark two real-world points to create reference line 1. (2) Create reference line 2 based on one of the existing points and another marked real-world point. (3) Clone reference line 2 so that the new reference line 3 would be aligned with a column at the end of the space. (4) Clone reference line 2 again so that the new reference line 4 would be aligned with a second column at the end of the space. (5) Create a rectangular footprint based on points on reference lines 1, 3 and 4. (6) Divide the footprint in half by using the polyline tool. (7) Extrude half of the footprint to the height of the ceiling. (8) Extrude the other half manually to half the height of the ceiling. (9) Visualize the result and answer questions.

4.5 Participants

Twenty-two participants (aged 19 to 38, three female) from the campus population took part in the experiment in individual sessions of around 50 minutes. One was a professional, 12 were graduate students, and 9 were undergraduate students. All 22 used a computer daily for work. 3D modeling was at least somewhat familiar to 13 participants, and 9 had advanced experience with video-games. Three participants had VR experience, and only one had used AR.

4.6 Results

We calculated the distance between each point and the ground truth. In Figure 2, points with an absolute error of two meters or higher are painted red, while points with an absolute error between zero and two meters are painted on a scale from green to red.

4.6.1 *Quantitative Analysis.* We conducted a two-way ANOVA with replication for point position errors with factors being the points and the techniques. There was a significant difference (F(1,840) =106.77, $p<0.00001$) between Geometric (M=0.54, SD=0.39) and VectorCloud (M=0.16, SD=0.08). There was also a main effect of points (F(19,840)=7.50, $p<0.00001$), and an interaction effect between techniques and points (F(19,840) =1.69, p=0.03265). We performed post-hoc repeated-samples t-tests for each point (Figure 3). Although VectorCloud was substantially more accurate in most cases, after a Bonferroni correction due to repeated t-tests, only two points (P8 and P20) presented significant difference ($p<0.0025$).

We also wanted to understand if the footprint was skewed. We conducted a two-way ANOVA with replication for line segment orientation errors. There was a significant difference (F(1,294)=36.98, p

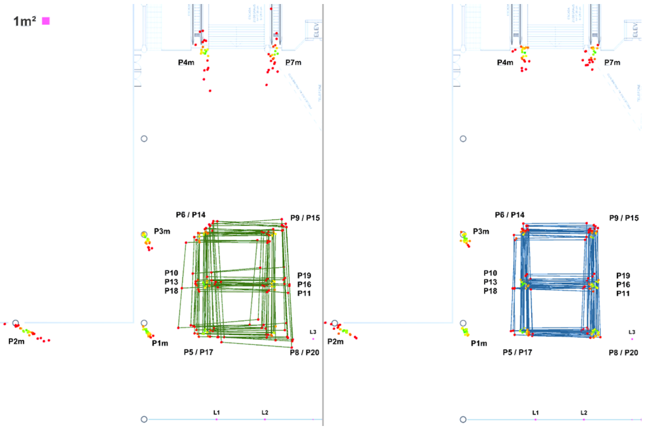

Figure 2: Models produced by participants while using the Geometric (left) and VectorCloud techniques (right).

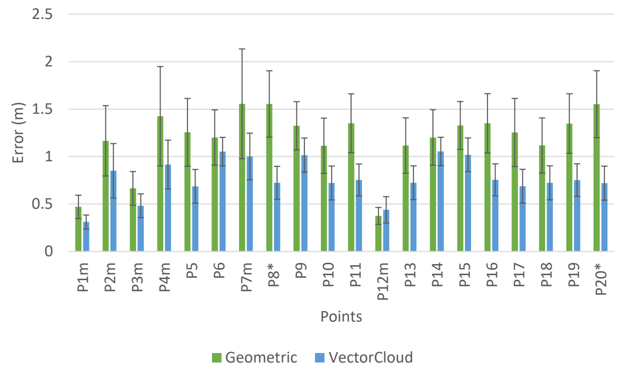

Figure 3: Average error for each point by technique. *Points with "m" were directly marked. Points with "*" were statistically different. Error bars indicates 95% confidence interval.*

< 0.00001) between Geometric (M=1.92, SD=0.24) and VectorCloud (M=0.65, SD=0.02). We also conducted a two-way ANOVA with replication for angular errors between pairs of line segments, and found a significant difference (F(1,168)=87.41, $p < 0.00001$) between Geometric (M=6.45, SD=0.13) and VectorCloud (M=1.36, SD=0.002). However, although VectorCloud resulted in lower error for every segment and angle, after applying the Bonferroni correction for multiple post-hoc t-tests, there were no significant differences for individual segments or angles.

4.6.2 Technique Questionnaire. The technique questionnaire included six questions to measure the perception of the point marking techniques on a five-point scale, with 5 being the best score. Questions are listed in Appendix A. We conducted Wilcoxon signed-rank tests to analyze the statistical difference of the results. For perceived precision, VectorCloud scored slightly higher (M=4.22, SD=0.75) than Geometric (M=3.81, SD=1.00), but the difference was not statistically significant. On ease of use, efficiency, naturalness, fun, and comfort, both techniques scored similarly, and no significant differences were found.

4.7 Discussion

In Figure 2, we can see a clear distinction between the accuracy of the models. The Geometric technique models are more spread out than the VectorCloud ones. Most of the Geometric points are red (indicating high levels of error relative to ground truth), while VectorCloud points have lower levels of error overall. It also shows the obvious skew of many of the buildings created by the Geometric technique.

These results are corroborated by the data analysis. VectorCloud resulted in higher accuracy than Geometric. Although the fact that we performed many comparisons made it difficult to achieve statistical significance after correction, we still found significant differences in derived points that were most distant from the directly marked points. This implies that the cascading effect that we hypothesized indeed happens: the small errors were amplified and accumulated with other markings. Overall, the evidence supports H1, that the precision of the point marking technique indeed influences the errors on derived points.

H2 was not directly supported by the results of the technique questionnaire. We did observe that many participants did not notice considerable errors in the alignment of references during steps 1 and 2, which later led to most of the angular errors in the model. Some did notice the problems much later. In a real-world application, the user would have to go back many steps to correct such errors. This suggests that problems with ease of use were primarily due to perceptual issues in AR systems without occlusion cues or opaque graphics. We do note, however, that using a precise marking technique like VectorCloud could make the modeling process easier by reducing the need for rework and improving users' confidence.

Considering all the results together, we claim that an application based on a less-precise marking technique would have reduced usefulness in domains where the model should be reliable, such as architectural modeling. 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.

5 CONCLUSIONS AND FUTURE WORK

In this work, we evaluated the impact of point marking precision on AR modeling in a realistic setting. By using techniques with different levels of precision, we were able to understand how errors propagate throughout the modeling process. Our results show that high precision of the point marking technique is essential to ensure the accuracy of the model, while also indirectly affecting the usability and usefulness of the system.

While our data demonstrate a better performance with VectorCloud, it also pointed to some possible usability issues. Participants complained about having to keep their heads still while using VectorCloud. A technique that maintains high precision but is less cumbersome on the user should be explored.

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