Enhanced Geometric Techniques for Point Marking in Model-Free Augmented Reality

Wallace S Lages[*]
Center for Human-Computer Interaction
Virginia Tech

Yuan Li[†]
Center for Human-Computer Interaction
Virginia Tech

Lee Lisle[‡]
Center for Human-Computer Interaction
Virginia Tech

Feiyu Lu[§]
Center for Human-Computer Interaction
Virginia Tech

Tobias Höllerer[¶]
Computer Science
University of California, Santa Barbara

Doug A. Bowman[‖]
Center for Human-Computer Interaction
Virginia Tech

Abstract

Specifying points in three-dimensional space is essential in AR applications. Geometric triangulation is a straightforward way to specify points, but its naïve implementation has low precision. We designed two enhanced geometric techniques for 3D point marking: VectorCloud, which uses multiple rays to reduce jittering, and ImageRefinement, which allows 3D ray refinement to improve precision. Our experiments, conducted in both simulated and real AR, demonstrate that both techniques improve the precision of 3D point marking, and that ImageRefinement is superior to VectorCloud overall. These results are particularly relevant in the design of mobile AR systems for large outdoor areas.

Index Terms: Human-centered computing—Mixed / augmented reality; Human-centered computing—Pointing; Human-centered computing—User interface design

1 Introduction

Specifying the three-dimensional (3D) location of points is an essential task in content creation for augmented reality (AR). We call this task point marking (or marking for short). 3D points in the real world can be used to attach annotations, place virtual objects, delimit areas, build real-world references, and arrange user interface elements. Marking is a different task than 3D selection in the sense that the target point is not necessarily a discrete object that can be selected from the background [3]. A *model-free* marking technique, in which points are specified without geometric information about the environment, may be required to mark distant outdoor locations in a mobile AR system.

A classic approach to model-free marking is to geometrically triangulate the target position from different viewpoints [1, 4]. However, the naïve implementation suffers from low precision due to technical and physiological limitations.

In this paper, we present two enhanced geometric model-free 3D point marking techniques. The *VectorCloud* technique uses multiple samples to reduce the influence of jitter and enables marking from multiple viewpoints. The *ImageRefinement* (IR) technique allows users to refine the direction of a 3D ray by manipulating a cursor on an image of the target region. We performed studies to understand the properties and limitations of these techniques in both ecologically valid real-world outdoor settings using a mobile AR display, and in more controlled simulated environments using a Virtual Reality (VR) system. Our experiments show that both VectorCloud and IR are more precise than the naïve geometric triangulation technique, and that IR is the best technique overall.

[*]e-mail: wlages@vt.edu
[†]e-mail: yli92@vt.edu
[‡]e-mail: llisle@vt.edu
[§]e-mail: feiyulu@vt.edu
[¶]e-mail: holl@cs.ucsb.edu
[‖]e-mail: dbowman@vt.edu

2 VectorCloud

2.1 Design

We implemented a naïve version of geometric marking on the Microsoft HoloLens. The user's head orientation is used to specify 3D rays that pass through the target position from two different viewpoints, and the target location is estimated by calculating their intersection. We observed accurate but imprecise results with this technique. As distances increase, small angular errors in head orientation due to head tremor and noise in the tracking data can introduce substantial errors in ray direction. This motivated us to reduce the influence of human and system jitter by casting many rays in a multi-sampling approach, which we named VectorCloud. The insight is that computing a location estimate based on the entire cloud of rays should lead to a better estimate of the target point.

2.2 Evaluation

To quantify VectorCloud's hypothesized performance benefits, we performed a within-subjects experiment comparing the naïve geometric technique with VectorCloud. Although we had implemented VectorCloud in AR on the HoloLens, we performed the experiment in an AR simulation using VR technology to avoid errors due to the HoloLens tracking system. The experiment task was to mark distant targets at distances of 12.5m, 26.7m, 40.2m, 55.2m, 70.3m, and 85.5m from two highlighted locations (1.92m apart) in the virtual environment. Each target was marked eight times with each technique, leading to 96 data points per participant. Ordering effects were eliminated by using the same randomized target sequence across all participants. For VectorCloud, we required users to collect 300 ray samples from each location.

Six graduate students and four undergraduate students (three females and seven males) participated in the study. The overall results are shown in Figure 1. Both techniques were highly accurate, although the naïve geometric technique showed a slight overestimation for the last target. However, variance for VectorCloud was significantly less than that of the geometric technique. The hypothesis of equal variances was rejected ($p < 0.008$) by a heteroscedastic version of the Morgan-Pitman test (using the HC4 estimator) [2].

The study confirmed that VectorCloud improved marking precision by computing a better estimate of the target position. While the improvement from the naïve geometric technique to VectorCloud is promising, we still observed several limitations of VectorCloud. Since it does not provide any feedback on the sampled rays, the user has no way to improve accuracy. The user does not know how many samples are needed or how still she must hold her head during

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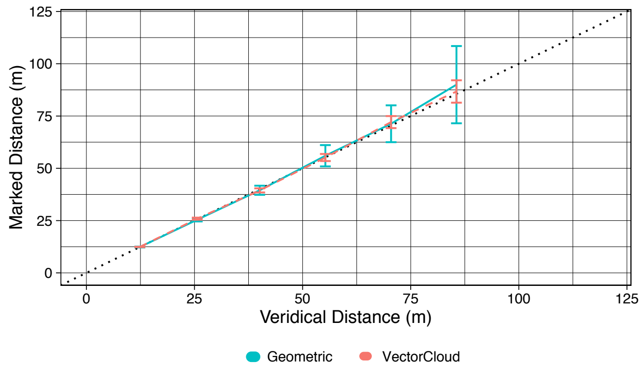

Figure 1: Marked distances with naïve geometric and VectorCloud techniques. Bars show the standard deviation at each target distance.

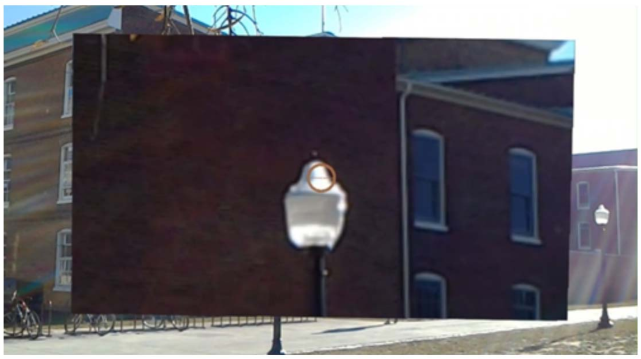

Figure 2: ImageRefinement implemented in AR. Once the image is taken, the user can adjust the ray by moving the cursor on the image with a controller.

marking. In addition, the user does not have fine-grained control of the final ray direction.

3 ImageRefinement

3.1 Design

The key determinant of accuracy in geometric marking is the precision of specifying ray directions. Thus, another way to enhance geometric point marking is to completely decouple the specification of ray direction from the users head, giving users fine control over the direction of each ray. In the IR technique, the user takes an image of the target position, then specifies the location of the target in the image. Based on the user's head position, a world-to-camera projection matrix, and the pixel coordinate on the image, we can reconstruct the 3D ray. We can also display a zoomed image so that the user can see the target even more clearly, as shown in Figure 2. We call this version of the technique IR, and the version without a zoomed image IRNZ. We hypothesize that IR and IRNZ will produce higher precision than VectorCloud due to their ability to make fine-grained adjustments to ray direction and their lack of reliance on head stability.

3.2 Evaluation

We implemented IR and IRNZ in the VR application that we used to evaluate VectorCloud, allowing comparison in a controlled setting. Since we knew distance affects performance, we used just three distances in this experiment: short (26.7m), medium (55.2m), and long (85.5m), leading to a 3 (technique) by 3 (distance) within-subjects repeated-measures experiment.

We collected data from 24 participants (five females, 19 male). Marking error is shown in Figure 3, suggesting that IR performed better than both IRNZ and VectorCloud. A linear fixed model on

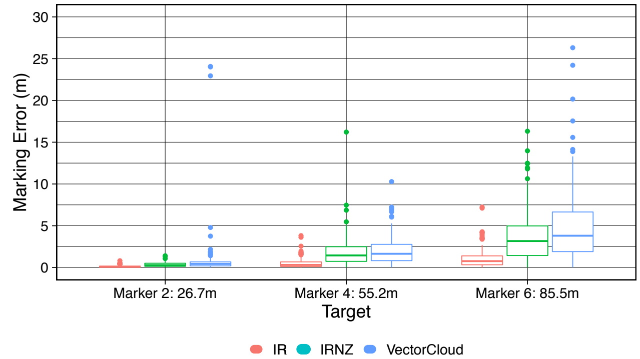

Figure 3: Marking Error in the AR simulation experiment

the data revealed significant main effects of technique ($F(2,34.5) = 35.85, p = 3.8e^{-09}$) and distance ($F(2,48.3) = 43.37, p = 1.7e^{-11}$). Post-hoc pairwise tests showed significant differences between all technique-target pairs ($p < .001$).

We also performed an outdoor experiment to explore how our enhanced marking techniques work in a real-world AR setting. We ported the code that we developed in the VR application, refactored it to work on the HoloLens, and repeated the same experiment with real-world targets at the same distances.

This study recruited 18 participants (four females, 14 males). With the same linear mixed-model, we found significant main effects of both technique ($F(2,28.4) = 6.35, p = .0052$) and target ($F(2,932.3) = 353.8, p = 2.2e^{-78}$). Post-hoc pairwise comparisons found that both IR and IRNZ were significantly more accurate than VectorCloud ($T(24.78) = 4.199, p = 2.93e^{-5}$); $T(24.78) = 2.5, p = .0126$).

Overall, we found that IR is more accurate than VectorCloud even when the benefit of zooming is removed. Zooming the image improved accuracy in the AR simulation experiment, but not with a real AR system. We believe this is due to limitations of HoloLens camera resolution and tracking..

4 Conclusion

The specification of 3D points is a fundamental task in AR systems. In this work, we explored three variants of the geometric triangulation approaches to model-free 3D marking. Our findings indicate that geometric marking can be reasonably accurate at distances up to 85m. VectorCloud is superior to the naïve geometric technique, but the lack of user control over the final ray direction leaves room for further improvement. Users perform even better with the ImageRefinement approach. Our results can be applied to indoor or outdoor AR applications where environment information is unavailable or unreliable. We are currently exploring the use of enhanced geometric marking in AR annotation and tour planning, architectural massing studies, and multi-user AR calibration.

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