VR Menus: Investigation of Distance, Size, Auto-scale, and Ray Casting vs. Pointer-attached-to-menu

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Abstract. We investigate menu distance, size, and related techniques to understand and optimize menu performance in VR. We show how user interaction using ray casting and Pointer-Attached-to-Menu (PAM) pointing techniques is affected by menu size and distance from users. Results show how selection angle – an angle to targets that depends on menu size and distance – relates to selection times. Mainly, increasing selection angle lowers selection time. Maintaining a constant selection angle, by a technique called "auto-scale", mitigates distance effects for ray casting. For small menus, PAM appears to perform as well as or potentially faster than ray casting. Unlike standard ray casting, PAM is potentially useful for tracked game controllers with restricted DOF, relative-only tracking, or lower accuracy.

1 Introduction and Related Work

VR and immersive visualization involve widespread use of projection-based displays. For such displays, ray casting is the predominant pointing technique. We investigate VR menu properties related to menu size and distance and show how they affect user performance for pointing with ray casting and PAM [1]. Our work shows:

– Performance degrades with decrease in selection angle (a circular menu's center-to-target angle). We show the shape of the degradation both for increasing user-to-menu distance and for decreasing menu size with constant distance.
– Auto-scale mitigates the effect of menu distance on selection times for ray casting.
– PAM, a technique that allows separation of selection angle from distance and visual size, also has decreased performance with decreased selection angle, with an additional effect of visual size. For small menus, PAM may outperform ray casting.

This study complements our earlier work on menu performance with ray-casting pointing and PAM in projection-based 3D environments. We previously studied menu properties like layout and location and found that contextually-located pie layouts are promising [1], consistent with other work showing a benefit of pie menus over list menus, e.g., [2], [3]. Only one (projected) menu size was considered in our earlier work, using an auto-scale feature intended to mitigate distance effects. Other methods to deal with distance include 3D variations of marking menu [3] or the rapMenu [4].

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Our new study considers distance-size properties of contextual pie menus and includes an evaluation of the auto-scale technique. We also further investigate the PAM pointing technique (the orientation-only variant, PAMO [1]), considering distance and size effects. In the previous study, standard ray casting performed better overall than PAM, but PAM was better in some cases and reduced errors overall. A benefit of PAM is that it supports a broader range of controllers than ray casting, requiring as few as 2 degrees of freedom with only relative tracking.

2 Characteristics Related to Menu Distance and Size

2.1 Distance, Size, and Auto-scale

Ray-casting pointing faces a known problem of distant or precise pointing [5] due to perspective foreshortening and tracking or hand jitter that amplifies over distance. When pointing at pop-up menus, this problem might be mitigated by scaling menu size according to distance from user [1]. We name this mechanism "auto-scale", where menus at varying distances have constant projected size. It is important to know how auto-scale affects performance. As an alternative to auto-scale, menus could be placed at a fixed distance. However, for contextually-located menus, this would make menus appear at a different depth than the object on which the menu is invoked. This can lead to visual discordance in a stereo immersive environment. We have also considered PAM as a way to separate interaction motions from distance and size [1], but we did not previously study distance and size effects on PAM.

Auto-scale maintains constant projected size, but it is not known what sizes perform best. For pie menus with ray casting, no evaluative studies have been carried out, to our knowledge, to optimize size. Since ray casting has a known problem with small distant objects requiring overly precise pointing, and considering cases of larger interface elements outperforming small ones with ray casting [5], [6], we expect that larger menus would be faster, at least up to some optimal size.

2.2 Selection Angle

For ray casting, pie menu size can be described by selection angle: the angle a hand would rotate to move a ray-menu intersection point from menu center to a menu item. We expect this angle, instead of pre-projected menu radius, to be a suitable measure of required motion, due to perspective effects of distance. Considering the geometry in Fig. 1, selection angle is $\Phi = \arctan(radius/distance)$. For results reported in this paper, we note our menus allow selection at a threshold distance of 60% of menu radius, so users need not move through the entire selection angle.

If we increase pie radius at a fixed distance, selection angle increases. Selection angle also increases with decreasing menu distance for a fixed pie radius. The optimal angle would depend on characteristics of human limb and wrist motor movement for rapid aimed pointing tasks. We consider the angle as the required movement, since angular motion is usually predominant for ray-casting pointing.

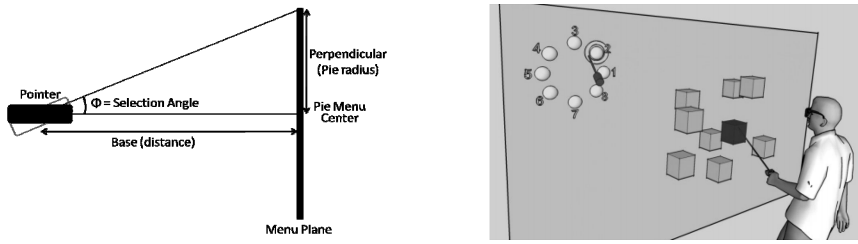

Fig. 1. *Left:* Side view of a pie menu and a pointer with selection angle. *Right:* PAM pointing: hand motions map to pointer (upper left) attached to a pie menu. The diagram, from [1], shows the menu at upper left, rather than contextually, for clarity.

2.3 PAM Selection Angle

PAM [1] is an indirect ray pointing technique that maps user motions to a ray selector that is local to the menu object. Specifically, as illustrated in Fig. 1 (right), PAM attaches a short menu-local pointer in front of the menu and maps wand motions to this attached pointer to aim a ray from attached ray origin to menu items. PAM separates menu visual size and distance from selection angle by calculating intersections disregarding menu visual size and distance. Selection angle can be controlled by changing a motion gain associated with the attached pointer – the higher the gain, the smaller the selection angle. This means that higher gain requires less angular motion to reach an item.

Changing selection angle in PAM by varying PAM gain might affect performance in a manner similar to changing selection angle for standard ray casting. If so, we could use PAM in a VR system where there is a restriction on menu visual size. PAM, with a (possibly optimal) large selection angle could then have faster performance than ray casting for small visual sizes or with high tracking jitter. However, a mismatch between visual angle and PAM selection angle may be distracting.

To avoid ambiguity, SRC angle (Standard Ray casting angle) is used to denote selection angle for ray casting. It also defines the visual size (screen-projected size) of a menu (auto-scaled or otherwise). For PAM pointing, SRC angle corresponds to projected visual size, not to PAM angle. PAM angle is used to denote PAM selection angle that depends on motion angle and gain but not on SRC angle. So, SRC angle can be used with a separate PAM angle for the same menu.

3 Pilot Study on PAM Angles

To estimate optimal PAM angle (that would be investigated further in the main study) we conducted a pilot study with varying PAM angles and visual sizes (SRC angles), on 16 subjects and a small number of trials (2 trials per PAM angle and SRC angle combination). The task and experiment settings were the same as what will be described in Section 4 (treatment type 2). Levels for SRC and PAM angles were also the same as in Section 4. Overall, the mean selection time with a PAM angle of 5°

was best. Results, shown in Fig. 2, suggested that menu visual size (SRC angle) does have an effect in addition to the effect of PAM angle.

A subjective tuning task was also given. Subjects adjusted selection angle for both standard ray casting and PAM and picked a value judged best for selections. For ray casting, menu size was changed to tune SRC angle. A tuning task was repeated three times, each with a different initial size: small (1.3°), large (9.7°), and the average of two previous subject-chosen sizes. The overall mean of best angle (average of 3 chosen angles) was 4.4° (σ = 1.5°). For PAM, subjects controlled PAM gain to change PAM angle. Three different menu visual sizes (SRC angles) were presented randomly – large (9.7°), small (1.3°), and intermediate (4.3°). Within each SRC angle, PAM angles were presented in the same manner as before – large and small randomly ordered, then average. The mean of best PAM angle was 5.4° (σ = 2.7°). So, subjectively-tuned PAM angle was roughly consistent with the overall best PAM angle (5°). The following study will show how this (estimated) optimal PAM angle compares against ray casting for various SRC angles.

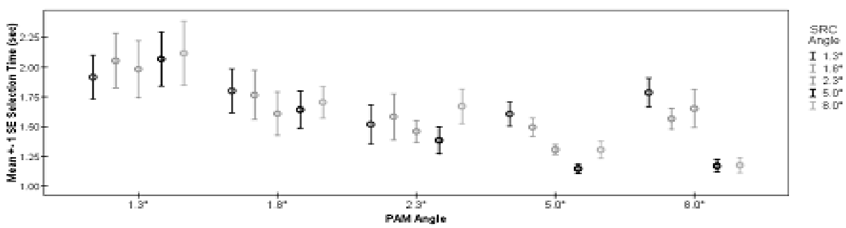

Fig. 2. Selection time (mean and SE) for different PAM and SRC angles from the pilot study.

4 Main Study: Methods

Hypotheses: We are interested in five hypotheses (and independent variables):

1. *Distance*: As distance between a user and menu increases, we expect user performance would degrade due to increase in required precision for the pointing task. Distance is measured between pie menu center and the hand position.
2. *Auto-scale*: We expect effects with distance would not be found if the menu selection angle is kept constant with auto-scaling.
3. *SRC Angle*: We expect user performance would get better with increasing SRC angle and that this effect would be similar for increases resulting from reduced distance (not auto-scaled) and increase in specified auto-scale size.
4. *PAM Angle*: We expect that changing PAM angle by changing PAM gain would show similar effects as changing SRC angle for ray casting.
5. *Pointing Method:* For small SRC angles, we expect that PAM pointing with an estimated optimal PAM angle would be faster than standard ray casting.

We varied selection angle in three different ways:

1. Varying distance of menu (un-auto-scaled) from hand. (SRC angle)
2. Varying auto-scale size, specifying projected menu size independently from distance. (SRC angle)

3. Using PAM and varying PAM gain. (PAM angle)

For un-auto-scaled menus, we chose a fixed menu size along with a set of distances such that projected sizes had SRC angles that we were also evaluating with auto-scale. This allowed direct comparison of distance-based SRC angles to equivalent auto-scaled ones. Evaluated PAM angles were the same as evaluated SRC angles. For fair comparison of PAM to ray casting, the same set of menu distances was used in PAM conditions as in standard ray casting conditions.

Specifically, we evaluated SRC and PAM angles of 1.3°, 1.8°, 2.3°, 5.0°, and 8.0°. Hand-to-menu distances were 11m, 8m, 6.2m, 2.9m, and 1.8m in the 3D space. Minimum SRC angle was chosen so that menu labels were barely readable, although target item was indicated by color. Maximum size was large but did not cover the entire screen, to allow randomized menu position in a reasonable range.

Apparatus: We used a 1.5m x 1.1m rear-projection screen with its lower edge 0.7m from the floor. An InFocus DepthQ projector displayed stereo 800x600 pixel images at 120 Hz, which were viewed with StereoGraphics CrystalEyes glasses. A wired Intersense IS-900 Wand was the 6-DOF input device and its button was used to indicate selection of target boxes and menu items. Head tracking was also done with the IS-900. Subjects stood about 1.2m from the screen center as in Fig. 3 (left).

Subjects: There were 20 subjects, 6 female and 14 male, with age from 19 to 41 years. Two were undergraduate students and 18 were graduate students. Four were left handed. 12 subjects reported no VR experience, 6 reported experience with 3D motion game controllers, and 2 reported experience with VR systems.

Procedure: Subjects performed targeted menu item selection. A target box appeared at a random location but at a specific distance from the hand, based on current conditions. Subjects had to select this box with ray-casting pointing to pop up a contextual pie menu. Subjects had to select a red item amongst white items on the menu. Since distance is an independent variable here, additional depth cues were rendered. Target boxes were displayed on pedestals with shadows in a large enclosed space with textured walls. Subjects were instructed to select target menu items as quickly as possible while keeping errors low as well. However, accuracy was enforced but speed was not, to prevent subjects from achieving high speeds at the cost of accuracy. If an incorrect selection was made, an error sound was played, the menu disappeared, and subjects had to bring up the menu again. Furthermore, to explain the feature of pie menus that selections are possible by pointing in a direction, subjects were told that exact pointing at menu item spheres was not required. Sessions lasted for about 30 minutes.

Trials and Treatments: A trial consisted of selecting the menu item on a single-level 10-item menu. There were 10 trials per treatment, each with a unique target item. Target order was randomized within a treatment. Per treatment, 2 menus appeared at each of the 5 distances, but at an otherwise random screen position. Treatments, consisting of combinations of the independent variables, were presented in random order per subject. There were 24 treatments (240 trials, excluding practice), divided into the following five types, presented in random order:

1. Ray-casting pointing and auto-scaled menus. There were five treatments of this type, each with one of the five levels of SRC angle.
2. PAM pointing without auto-scaling (menu size was 0.25m before projection). There were five treatment of this type, each with one of the five levels of PAM angle.

3. PAM pointing and auto-scaled menus. There were five treatments of this type, each with one of the five levels of PAM angle with the matching SRC angle.
4. PAM pointing with (estimated) optimal PAM angle 5° and auto-scaled menus. There were four treatments of this type, each evaluated with one of four SRC angles. The optimal PAM angle matching SRC angle 5° occurred in treatment type 3.
5. Ray-casting pointing without auto-scaling (menu size was 0.25m before projection). There were five treatments of this type. Ray casting at specific distances is of interest, but to keep the presentation of all treatments similar, distance varies within the treatment as well. We later separate results per distance (SRC angle).

Dependent Variables: Dependent variables were selection times (appearance of menu to selection, including time spent correcting errors), error count, and movement. Due to space constraints, we focus mainly on selection times in this report.

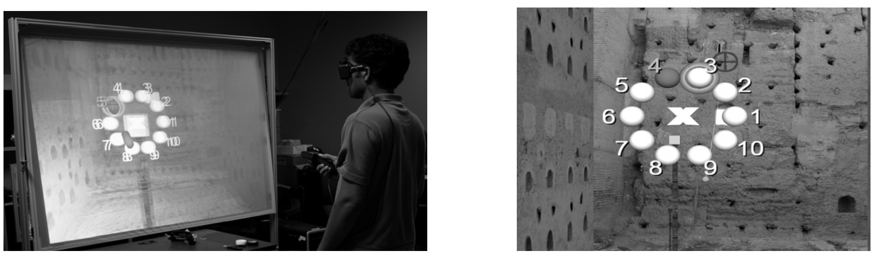

Fig. 3. *Left:* Experiment setup: rear-projection stereo display with 6-DOF head and wand tracking. *Right:* A screenshot of the experiment scene.

5 Results

Distance and Auto-scale: As seen in the leftmost box in Fig. 4, increasing distance in a un-auto-scaled menu with ray casting (treatment type 5) tends to raise selection times. A single-factor (distance) ANOVA on un-auto-scaled ray casting cases detects significant effect of distance on selection times ($F(4, 76)=46.102$, $p<0.001$). Pairwise comparisons with Bonferroni correction detect significance ($p<0.05$) except between the two closest distances. Similar effect of distance on selection times is not seen for menus auto-scaled to maintain specific SRC angle (Fig. 4, except leftmost box, treatment type 1). Note that auto-scaled conditions had 2 trials per distance, while there were 10 trials per distance in the un-auto-scaled condition. Single-factor ANOVAs for each auto-scaled SRC angle did not detect significant effect of distance on selection times. For auto-scaled menus at SRC angles of 1.3°, 2.3°, and 5°, the closest menu distance of 1.8 meters appears to take more time than further distances, but this was not detected significant overall.

SRC Angle: Fig. 5 shows how increasing SRC angle lowers selection times for ray-casting pointing. It also shows that SRC angle, changed either through varying menu distance without auto-scale (treatment type 5), or through changing menu size with auto-scaling (treatment type 1), has similar effect on user performance. A 2-factorial ANOVA on selection time with independent variables of SRC angle and auto-scale detects significant effect of SRC angle on selection time (F(4, 76)=51.848, p<0.001). All possible pairwise comparisons between different SRC angles, with Bonferroni correction, detect significance (p<0.05).

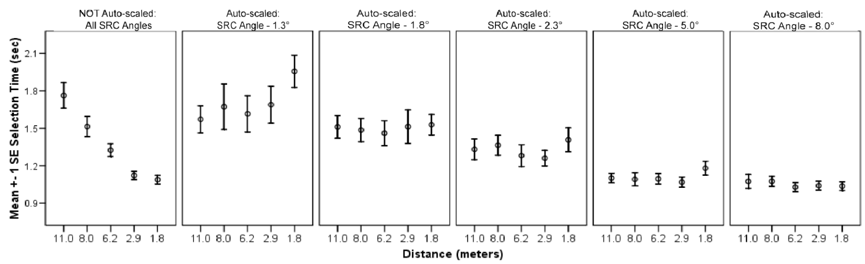

Fig. 4. Selection times (mean and SE) with ray casting at different menu distances without auto-scale in the leftmost panel (treatment type 5), and menus with auto-scale (except leftmost panel) having different SRC angles (treatment type 1).

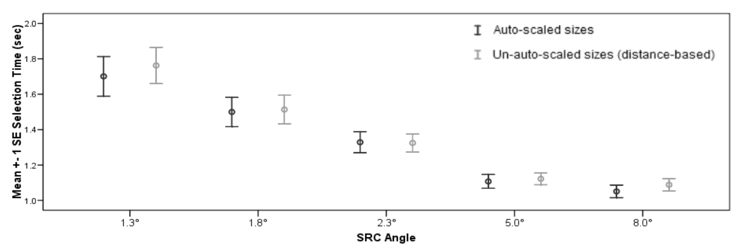

Fig. 5. Selection times (mean and SE) at different SRC angles clustered according to distance-based SRC angles and auto-scaled SRC angles. Distance-based SRC angles (right bar from each pair; treatment type 5) correspond to leftmost panel in Fig.4. Auto-scaled SRC angles (left bar from each pair; treatment type 1) are collapsed from error bars other than leftmost panel in Fig. 4 by averaging over menu distances.

PAM Angle: From Fig. 6 (right, treatment type 3) it seems that increasing PAM angle leads to lower selection times. If we compare 5° PAM angle cases (treatment type 4) to the SRC-angle-matched PAM angle cases (treatment type 3) at each of the four SRC angles, paired-sample t-tests detect significant effect of PAM angle at the smallest (t(19)=2.278, p<0.05) and largest (t(19)=2.513, p<0.05) SRC angle. It appears from Fig. 6 (left and right) that 5° PAM angle may perform better for smaller SRC angles (1.3°, 1.8°, and 2.3°) whereas matched PAM-SRC angles may perform better for larger SRC angles (5° and 8°). We can also see that increase of SRC angle leads to decrease in selection times (Fig. 6). An ANOVA on SRC angle for 5° PAM angle cases (treatment type 4), detects significant effect of SRC angle on selection times (F(4, 76)=37.536, p<0.001). Post-hoc tests with Bonferroni-adjusted pairwise comparisons show significance (p<0.05) between all pairs except for the two largest and two smallest SRC angles.

PAM vs. Ray casting: For smaller SRC angles, PAM seems to perform better with the estimated optimal PAM angle of 5° (treatment type 4) than ray casting (treatment type 1). It appears from Fig. 6 (left) that means for PAM at SRC angles of 1.3° and 1.8° are lower than for ray casting. Ray casting, however, performs better than PAM at larger SRC angles, particularly at SRC angle of 8.0°. A 2-factor (pointing method and SRC angle) ANOVA on selection times for auto-scaled menus did *not* detect significant effect of pointing method on times. Paired sample t-tests between pointing methods per SRC angle showed *near* significance at SRC angle 1.3° ($t(19)=1.975$, $p<0.063$) and significance at SRC angle 8.0° ($t(19)= 2.914$, $p<0.01$).

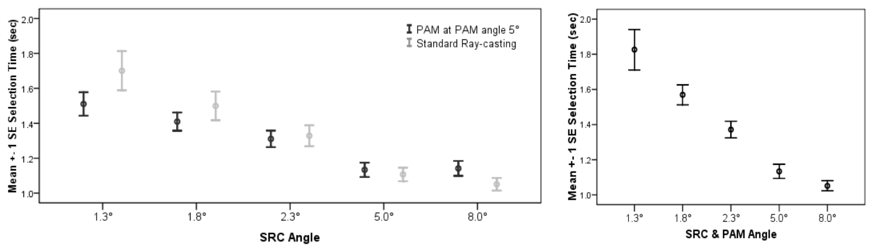

Fig. 6. Selection times (mean and SE) for auto-scaled sizes. *Left:* PAM with PAM angle 5° (treatment type 4) and standard ray casting at different SRC angles (treatment type 1). *Right*: PAM angle matched with SRC angle (treatment type 3).

6 Discussion

The hypotheses in Section 4 are largely supported by the observed results. An effect of menu visual size (SRC angle) in PAM pointing was also detected.

The basic effect of distance on menu selection with ray casting (Fig. 4, leftmost box) follows earlier studies of general object selection tasks [5]. Decreasing visual size with constant distance showed similar increase in selection times (Fig. 4, except leftmost box). Degradation of performance with increasing distance was mitigated by auto-scaling, which maintains a constant selection angle. Increasing selection angle decreased selection times, irrespective of how selection angle was varied – by changing auto-scaled size or by changing distance without auto-scale for ray-casting pointing, or by changing PAM gain for PAM pointing. These results show how selection angle can be used to understand user performance in ray-casting pointing.

Results suggest that larger menus should be used for faster pie menu selection with ray casting. However, from a practical standpoint, restrictions on size may be imposed by the display or application. For hierarchical menus, traveling through a sequence of large offset child menus could move a user's focus far from their object of interest. For the studied environment, we estimate optimal selection angle between 5° and 8° (for ray casting and PAM). The tuning study suggests users prefer selection angle closer to 5°. Note this optimal angle could vary depending on a selection threshold (60% of radius, in our study), as selection distance and area vary with it.

Higher selection times at small PAM angles may correspond to increased perceived sensitivity (by large C-D gain). Subjects may find it irritating to see the visual attached pointer move large amounts for small hand motions. In PAM pointing, visual size (SRC angle) has an effect on user performance, even when PAM angle is constant at 5°. From Fig. 2 and Fig. 6 we see that larger SRC angles typically led to lower selection times in PAM, especially for large PAM angles. Besides the performance increase with larger PAM angles, a likely reason that large SRC angles work well with large PAM angles is that subjects experience more consistency between visual effect and required motions.

Comparing PAM with estimated optimal PAM angle (5°) to ray casting at specific SRC angles (Fig. 6 left) suggests that PAM performs about as good as or better than ray casting at smaller SRC angles of 1.3° and 1.8° (ANOVA did not detect overall significance, but there was a near-significant t-test result at 1.3°, so we also consider overall plotted trends and note this result is less conservatively stated than others). PAM may be a good alternative to ray casting when menu visual sizes must be small, when jitter is large, or with limited-DOF tracking devices.

Selection time decreases with higher angular motion. That means users moved more rapidly towards a larger or a distant target. This follows from human motor performance for rapid aimed movements [7], where greater target distance results in faster motion. Also, as target size (pie-slice area) increases in a pie-menu with increasing distance to target, users need not spend much time on the slower corrective submovement [7] that occurs for precise pointing.

From results, we speculate that selection times may be modeled by a logarithmic function involving the inverse of selection angle [8]. However, such a model may not work well at very large or very small selection angles where additional factors such as tracking jitter become critical. A difference between visual target size (spheres drawn at visual menu circumference) and actual selection size (pie-slice with radius thresholds) may further complicate the model. A well-known logarithmic model for pointing is Fitts's law applied to 1D or 2D translation [9] or rotation [7], where an index of difficulty is a logarithmic function of the ratio of target distance to target width. Relating our results to Fitts’s law may seem counterintuitive, as selection times decreased with an increase in distance, and our environment is 3D with interaction primarily involving rotation. However, both target distance and target width increase with increase in selection angle, and the effect of target width seemingly dominates. This may be explained by modeling target width as target area (e.g., resembling [9]), which would be proportional to the square of the pie radius [8]. Since distance-to-target is a fraction of the pie radius, this would predict a decrease in movement time for increase in pie radius (or selection angle).

7 Conclusion

We showed several properties related to menu distance and size and how these affect user performance in menu interaction. These findings can help UI designers optimize menu interaction in projection-based VEs. We confirmed that auto-scaling mitigates the effect of distance on menu pointing tasks. Auto-scaling could also work well with other user interface elements such as toolbars, list menus, etc. that afford auto-scaling (e.g., temporarily invoked widgets), where it could be used for more consistent user performance with widgets located at different distances. User performance was found to vary with selection angle: increasing selection angles lowered selection times. An estimated optimal selection angle of 5° is suggested for environments such as ours. We also observe that using PAM with a PAM angle of 5° can get performance as good as or faster than ray casting for small interface elements. In any case, inspection of results shows that performance differences between 5°-PAM and ray casting are not very large percentagewise, so PAM is a promising ray casting alternative for controllers that are supported by PAM but not ray casting.

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