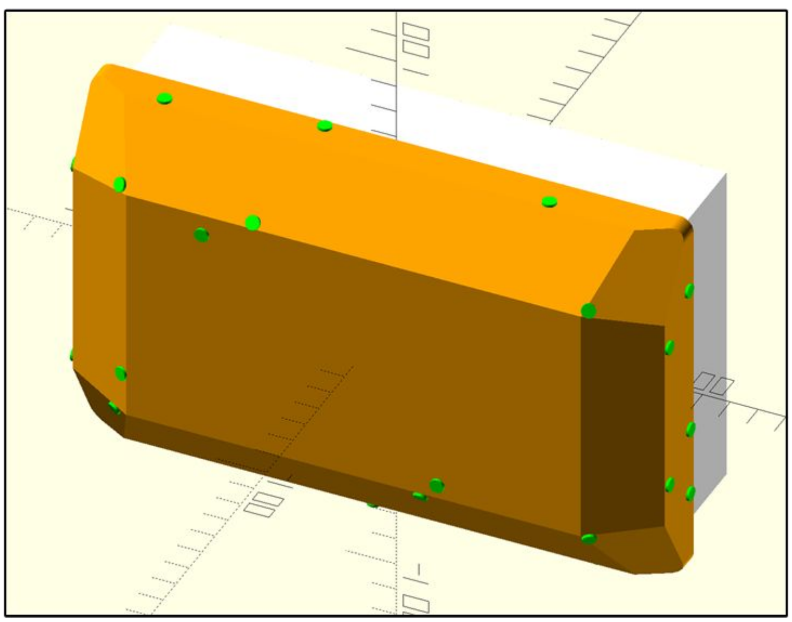
Interpreting Simulation Output

SteamVR™ Tracking

Introduction

Predicting the tracking performance of an object through simulation reduces design time and cost. Iterating on design concepts to improve performance before building prototypes increases the chance that a prototype has acceptable performance when it is built. The simulation tools produce 2D and 3D performance plots, which indicate the Number of Visible Sensors, Initial Pose Possible?, Pose Rotation Error, and Pose Translation Error for every object orientation. These graphs predict the ability of the object to begin tracking and continue to track as the object rotates into different orientations and translates in different directions relative to the base station. A solid understanding of how to interpret simulation output is necessary to get the most benefit from the simulation tools. This document describes how to navigate the 2D and 3D plots, recognize problem areas, and draw conclusions about how to improve the design. For complete instructions on running the simulation tool to generate the plots explained here, see the **Simulation User Guide**.

The plots presented in this document were generated from a rudimentary shape that represents an initial attempt at an HMD design. A simple masking shape was added to the rear of the HMD sensor object to simulate the occlusion of sensors by the binocular display of the HMD. The sensor placement on this shape was generated from the simulation tools, and is a best attempt by the tools to place 32 sensors on the shape.



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Input to the Simulation

The simulation uses the following information:

- The positions and normals (facing directions) of each sensor,
- The expected field of view of each sensor (usually assumed to be 60 degrees),
- The occlusion caused by the surfaces of the object the sensors are mounted on, and
- The occlusion caused by other attached or nearby components that you supply.

You can do a simulation without including the occlusion surfaces, but the simulations will be overly optimistic about what performance can be achieved. You can also add additional occluding surfaces, like hand models, optional accessories, or even entire posed human models. These will help you visualize where coverage of your object is naturally blocked, so you can avoid focusing on those areas for improvement.

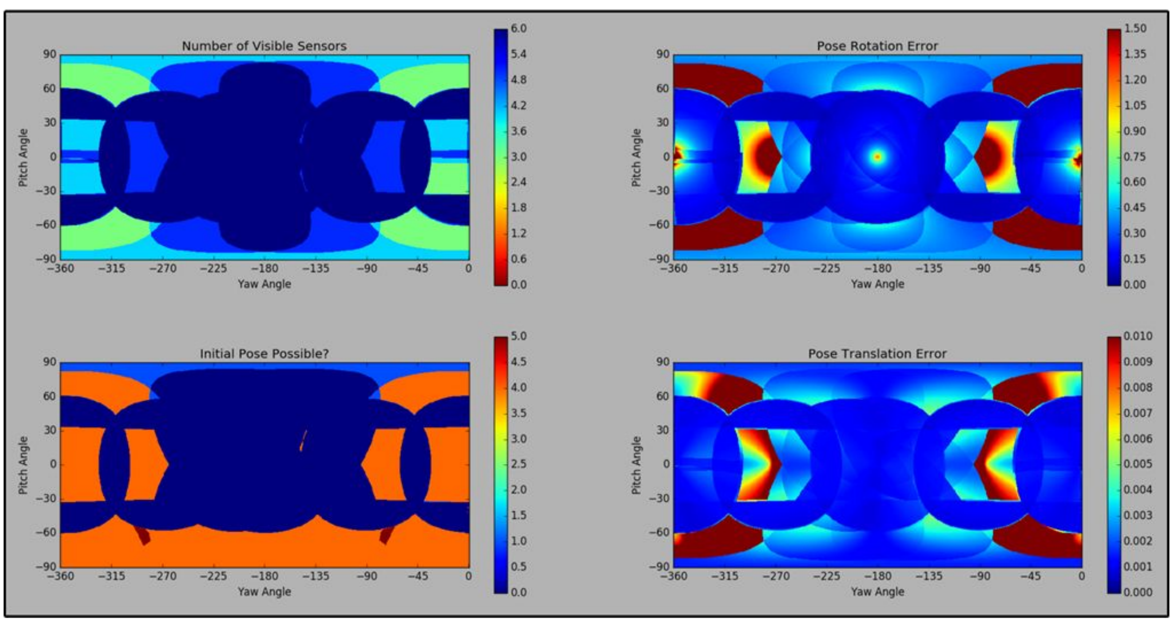
2D Output

The 2D plots are very useful for comparing designs at a glance, sharing via email, and copying into documentation. They include output plots for the Number of Visible Sensors, Initial Pose Possible?, Pose Rotation Error, and Pose Translation Error. All poses, characterized by a sphere, are mapped onto a two dimensional plot using an equirectangular projection, with Pitch and Yaw axes. Simulation values are represented in the color gradient on the plot.

Navigating the Plots

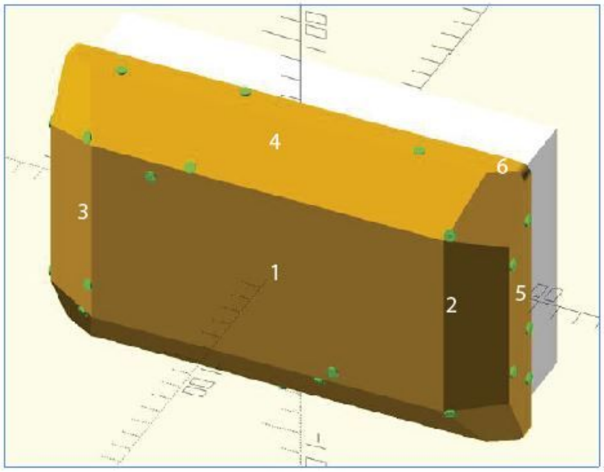
The 2D plots are presented side by side, in a single PNG image file. Each metric is plotted against Pitch Angle and Yaw Angle. On every plot, colors on the blue end of the spectrum represent better performance, while colors on the red end represent poor performance. If you compare the graphs for two objects, the relative performance is represented very accurately. If a region of the graph is more blue for an object, it will work better when that area is facing the base station. If it is more red, it may not work as well. There is no fixed number requirement for rotation or translation error that guarantees acceptable performance. The best way to evaluate a simulation is to compare against simulation results from an object with known performance.

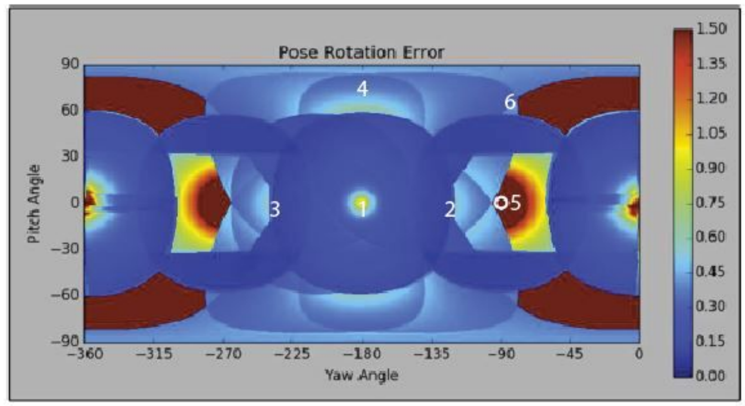
Most objects are refined until they achieve medium to dark blue performance in the error charts for the directions where it makes sense. Every object will have regions where self-occlusion or common usage will block the laser signals, so it is expected that those areas will never achieve the best performance.



Note: Including an axis for Roll Angle is not required, because from the base station's perspective there is no change in baseline with changes in Roll Angle.

Recognizing problem areas on a 2D plot is relatively easy, by identifying the red and brown areas on the plot. Translating that plot location onto the actual 3D object can be challenge. Understanding how the 2D coordinates map onto 3D axes makes that translation easier. The 3D axes are indicated on the 2D plot below





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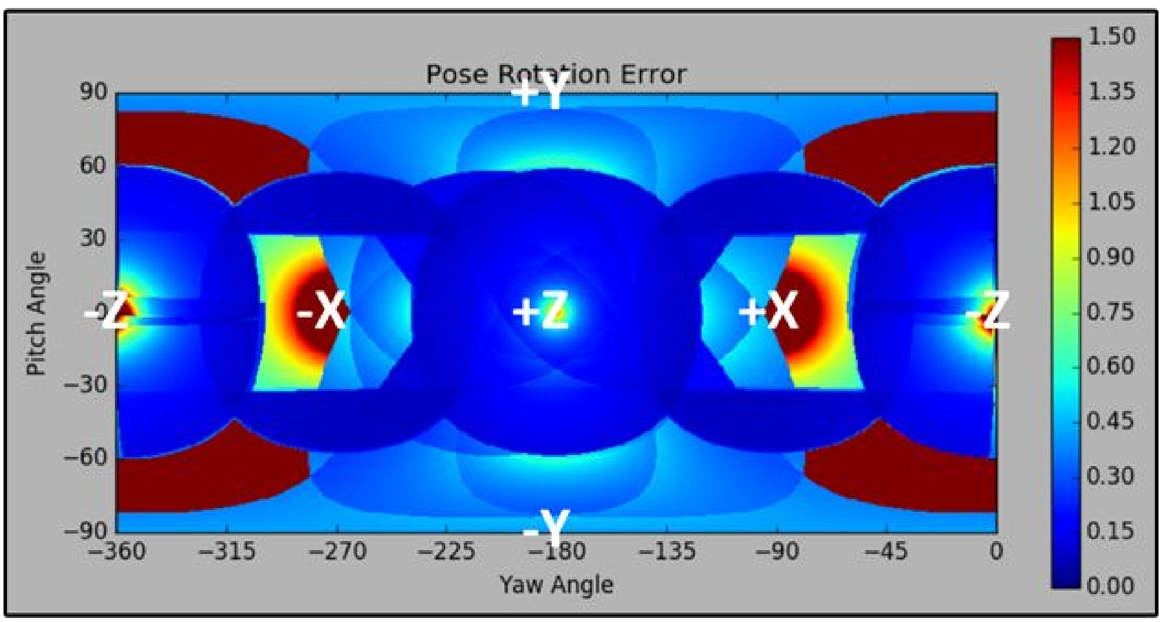
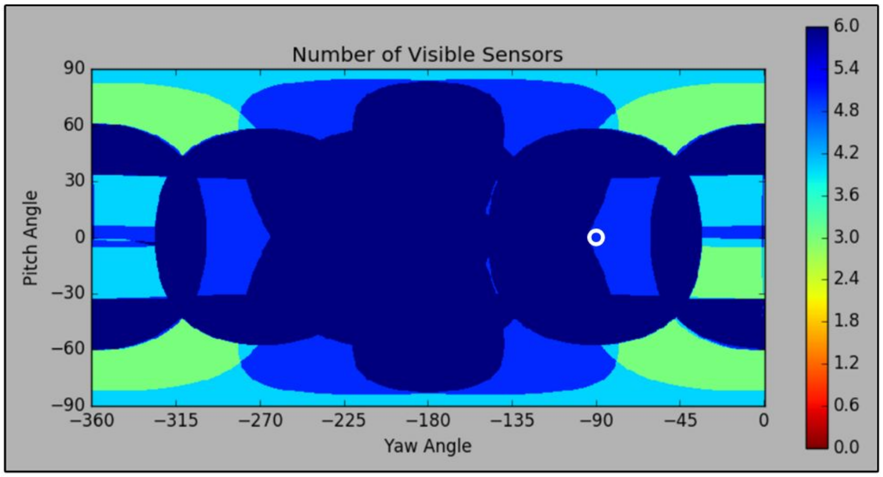


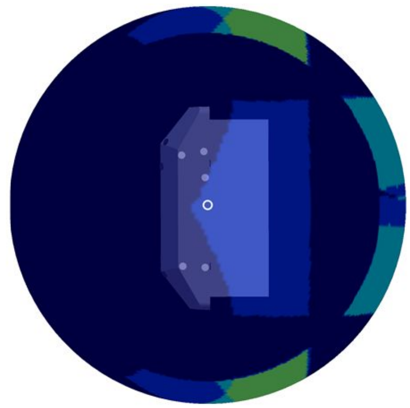
3D Output

The 3D plots are very useful for pinpointing poses that exhibit low tracking performance. Hmd_designer_viewer displays the same four plots available in the 2D output: Number of Visible Sensors, Initial Pose Possible?, Pose Rotation Error, and Pose Translation Error. The plots are displayed as a bubble around the object.

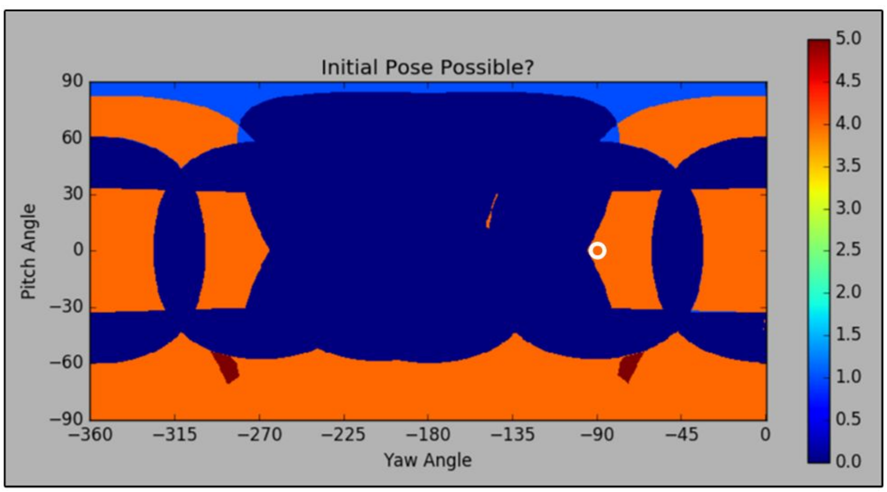
Navigating the Plots

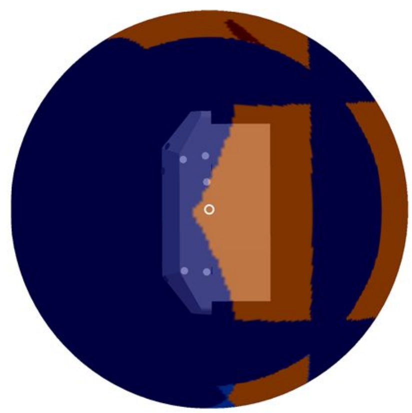
The number keys 1 - 4 toggle the associated plot on and off. Clicking on the plot and dragging the mouse rotates the object and plot to a new point of view. Compare the 2D plots above to the 3D plots below, oriented in the +X direction.



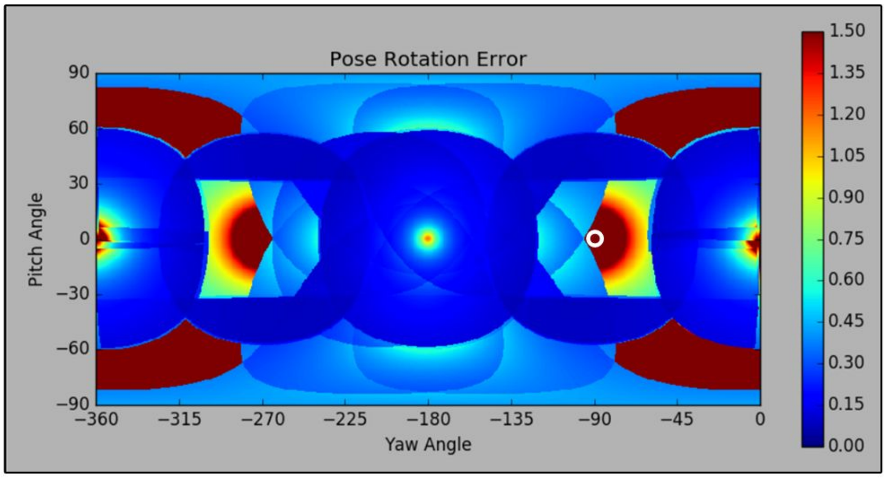


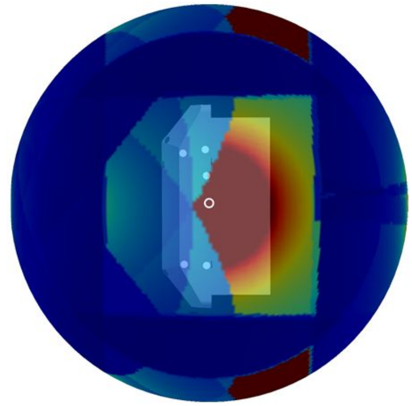
1: Number of Visible Sensors



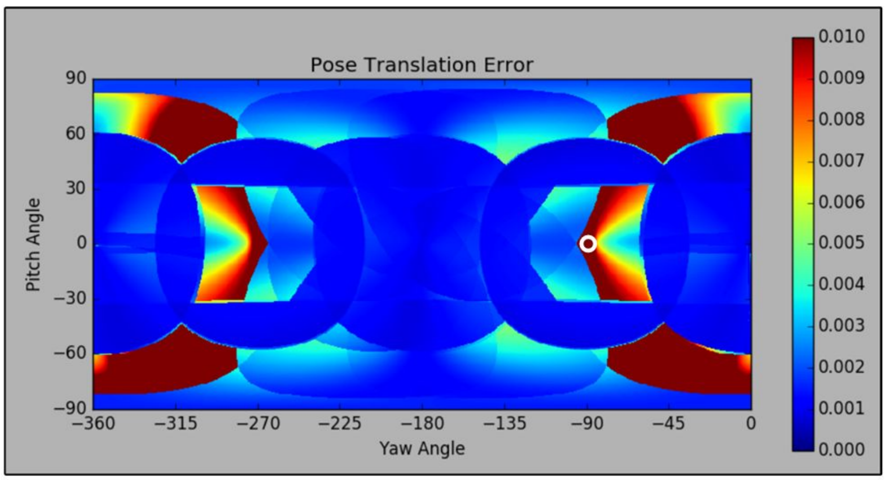


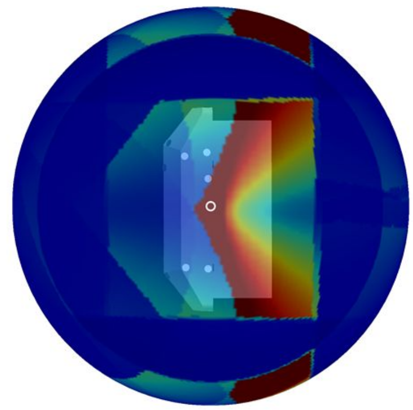
4: Initial Pose Possible?





2: Rotation Error

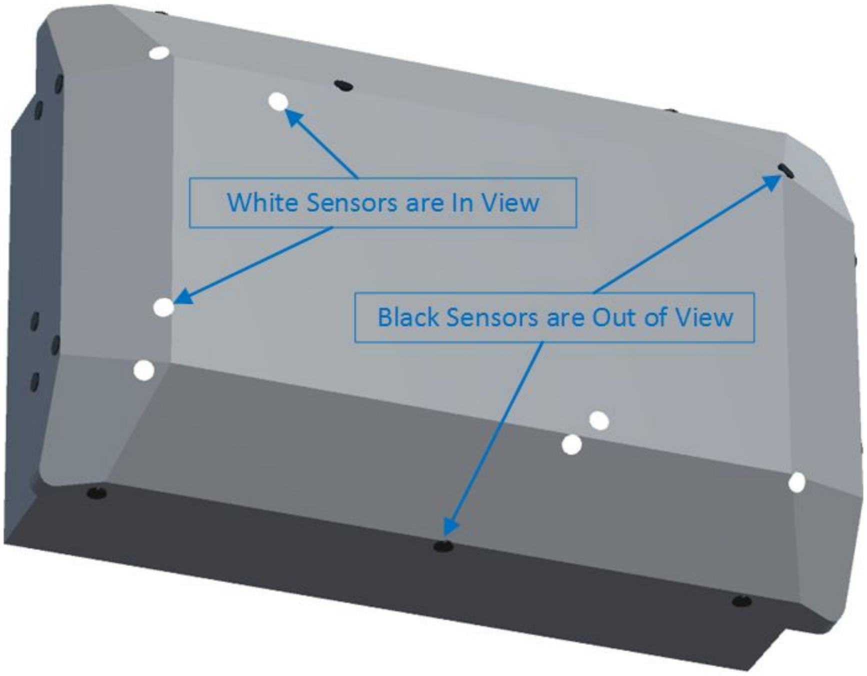




3: Translation Error

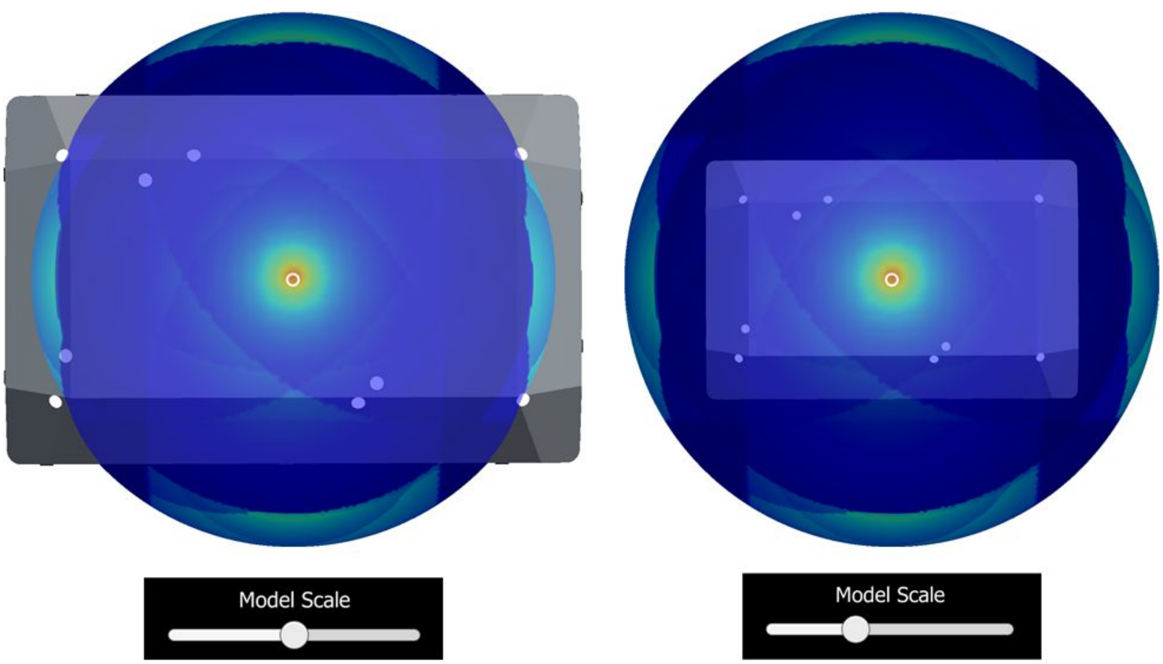
Active Sensors

HMD Designer Viewer highlights sensors when they are within ±60° of the point of view.



Model Scale

If the model is much larger than the bubble displaying the plot, use the Model Scale slider shrink the model into the bubble.

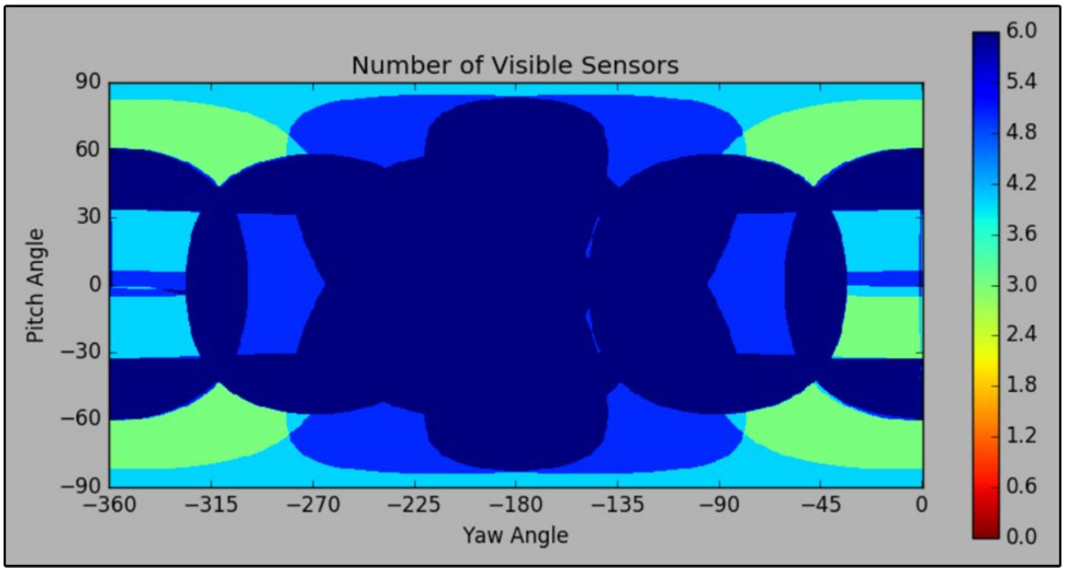


Number of Visible Sensors

The number of visible sensors for a pose is a good starting point for determining the trackability of that pose. Four visible sensors are required to begin tracking. Initiating tracking is also referred to as “bootstrapping” or “booting”. Less than four sensors may continue tracking with assistance from the IMU.

Inspecting the 2D Plot

Blue areas of the plot indicate poses where four or more sensors are visible. Darker blue means more visible sensors. If an area displays green, yellow, or red there will not be enough sensors to begin tracking. An object can track with fewer than four sensors by using IMU measurements to fill in the gaps, but the design goal is at least four visible sensors.

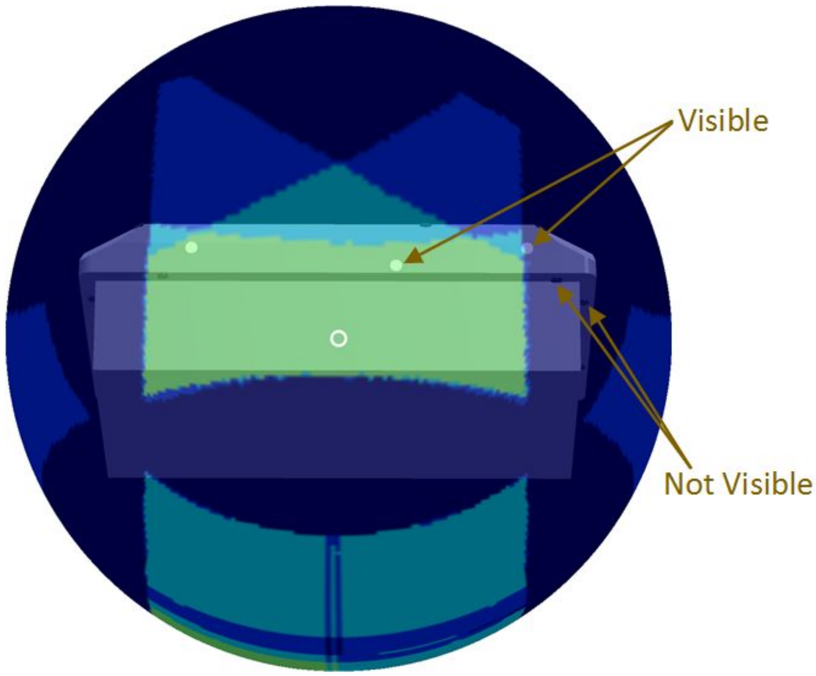


At first glance, this simulation above shows sufficient sensors visible from the +Z, +X, and -X directions, but becomes marginal in the +Y and -Y directions. From the -Z direction, pitched up and down by 60° to 80°, and rotated almost ±90°, the plot has large green areas representing only three visible sensors. We would expect to find problems in these areas for initial pose, rotation, and translation. It is possible that the human eye could see more than three sensors in these problem orientations. However, it is important to remember that the sensors have a ±60° viewing angle. Accounting for the viewing angle may be the reason that only three sensors are visible to a base station. The 3D plot is a great way to diagnose the exact cause of the green areas on the 2D plot.

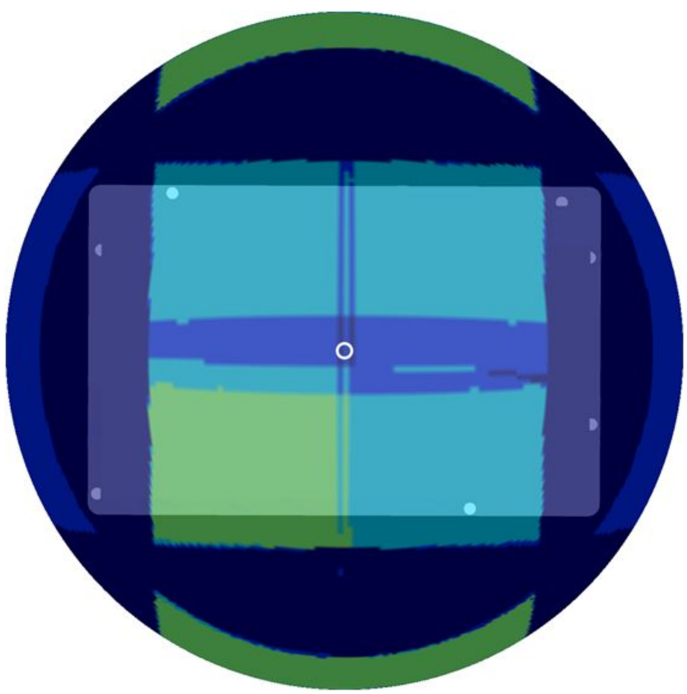
Inspecting the 3D Plot

Opening the 3D plot in HMD Designer Viewer shows the problem areas, while highlighting sensors that are within their ±60° viewing angle.

Rotating the 3D plot in the -Z direction, and then pitching the object 70° in the +Y direction lands the point of view marker in the green area shown in the 2D plot above. From this perspective, HMD Designer Viewer clearly shows three visible sensors, highlighted white. Looking closely, it is possible to see other sensors along the back and front faces of the object. However, these sensors are colored black because the point of view is not within the ±60° viewing angle of the sensor. One clear way to improve this design would be angling the rear face to tilt the sensors in the +Y direction, adding two more visible sensors to this pose.



Another problem area in the design is seen from the -Z direction. There are four patches around -Z that look marginal. The question to ask in this situation, is whether it matters that there are not enough visible sensors in this orientation. If this object is an HMD, the user's head will occlude the rear of the object. Increasing the number of visible sensors in these poses is likely to make no actual improvement in practice.



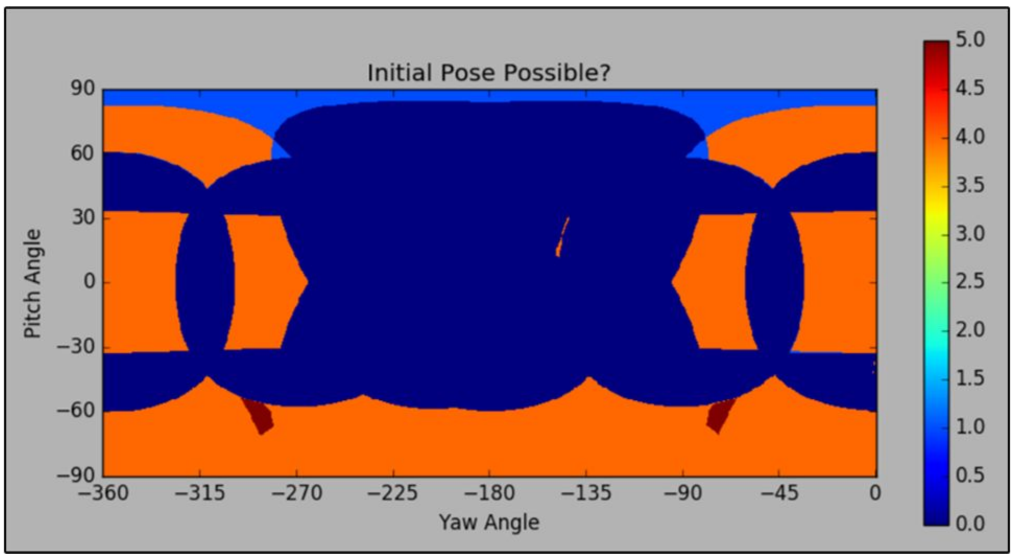
Initial Pose Possible?

Although the Number of Visible Sensors is a good place to start. Tracking performance also depends on the distance between sensors and their coplanarity. For an object to begin tracking in SteamVR™, i.e. boot, four visible sensors are required, but they must also be non-coplanar. Adding coplanarity criteria gives a more detailed simulation of whether a pose may be used to start tracking. The “Initial Pose Possible?” plot represents the object’s ability to begin tracking from any orientation.

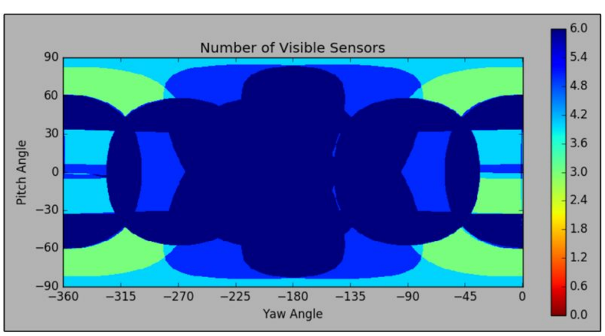
Inspecting the 2D Plot

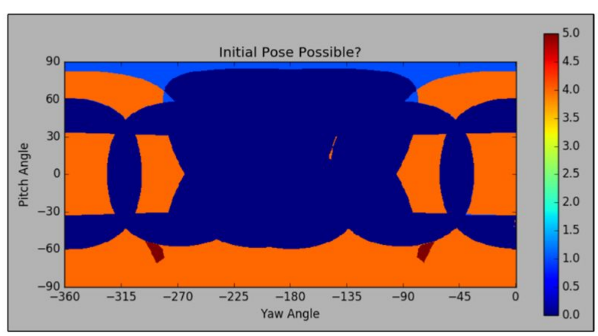
The object will either boot or not in every given orientation. The object can boot wherever the plot is blue, and cannot wherever it is orange or red. Dark blue areas have five or more sensors. Light blue areas have less than five sensors but can still boot by satisfying other conditions. Similarly, brown areas are far from meeting the criteria for booting, while orange areas meet some of the criteria but are excluded by violating the coplanarity rule.

The ability to bootstrap in a given orientation requires having at least four visible sensors with sufficient non-coplanarity. Three sensors always determine a plane. The fourth sensor must be at least 8 mm out of the plane for the object to boot.



Because four visible sensors is a necessary condition for an initial pose, the “Initial Pose Possible?” plot often looks similar to the Number of Visible Sensors plot.



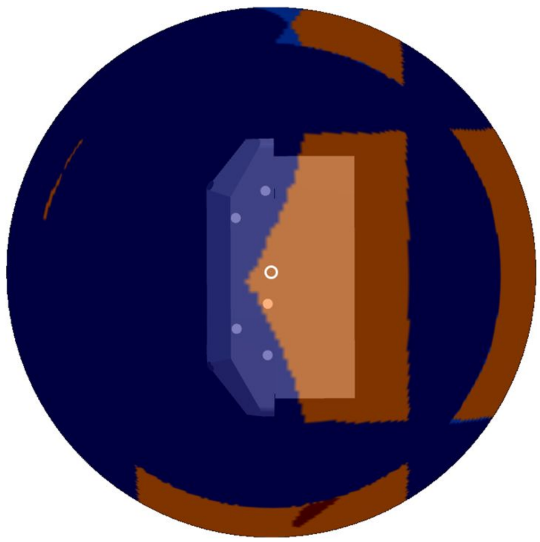


Comparing the two plots presents some interesting differences. The chevron shapes near the +X and -X orientations appear blue in the Number of Visible Sensors plot, suggesting that four sensors are visible. However, in the Initial Pose Possible plot, those chevrons are orange, indicating that the object could not boot from that pose. The same is true of the -Y axis. Four or more sensors are visible, but an initial pose is not possible. Differences in these two plots come from the hard limit between three and four sensors for initial tracking and the additional non-coplanarity requirement. Visualizing coplanarity is easily done using the 3D plot.

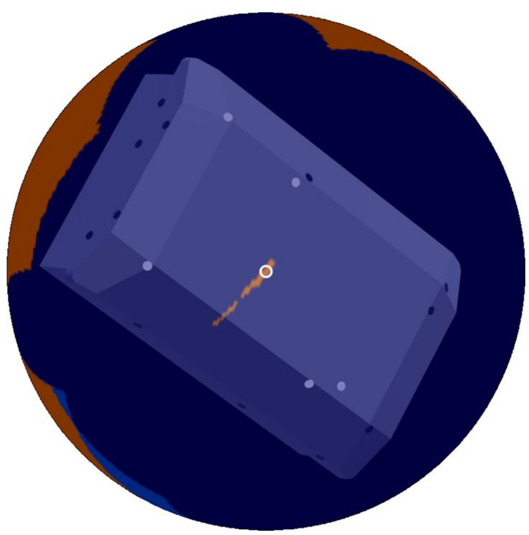
Inspecting the 3D Plot

Opening the 3D plot in HMD Designer Viewer and orienting the plot to the +X axis displays the area of the 2D plot that indicated more than four visible sensors, but still fails as an initial pose.

The cause of the failure is clearly coplanarity. All five visible sensors are placed on the same surface of the object. Without at least one sensor more than 8 mm out of this plane, the object cannot begin tracking. Adjusting the angle on the rear or front facets could bring front or rear sensors into view from the side. At that point, some of the sensors on the side face could be moved to other places that need improvement.

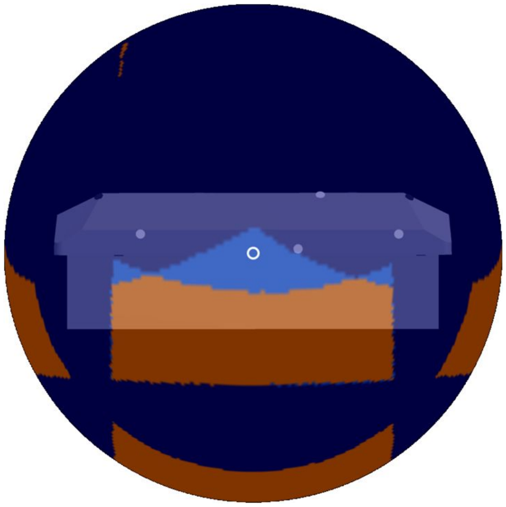


When all the sensors are placed on the same surface, coplanarity is easy to see. However, any cross section of the shape is a plane. Spotting coplanarity at odd orientations is a powerful feature of the 3D plot. Pointing the view at a sliver of poor performance on the front of the object reveals a pose that aligns five sensors in the same plane, even though they are on different facets.



To solve this problem, a good tradeoff could be moving at least one sensor down the facet toward the edge of the shape. If sensors were reclaimed from the side of the device, more sensors could be added on the front facets to create depth.

As an example, the pose shown below is capable of booting using only four sensors. Three sensors are clearly in the same plane, as they are placed on the side surface of the object. The fourth sensor is located on the front facet, but is still visible due to the sensor's viewing angle. The depth of the fourth sensor is sufficiently out of the plane of the top surface, making this a valid initial pose.

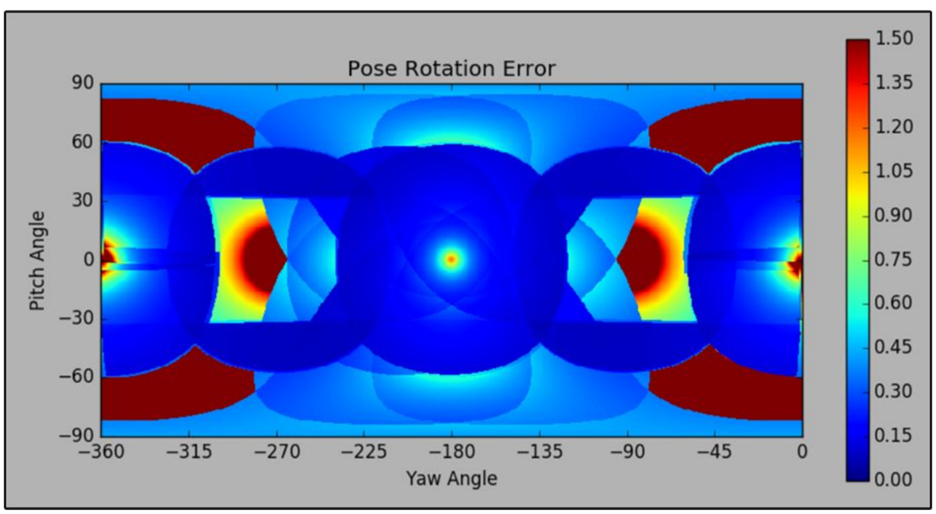


Pose Rotation Error

Sufficient depth in three axes is necessary for an initial pose, but is also a key determinant of rotation error. As described in the **System Overview**, baseline in all three axes amplifies the change in relationships between sensors for a given degree of rotation. When sensors are mostly coplanar, rotation around any axis within the plane does not result in significant X or Y displacement between sensors. The Pose Rotation Error plot maps the rotation error against all object orientations.

Inspecting the 2D Plot

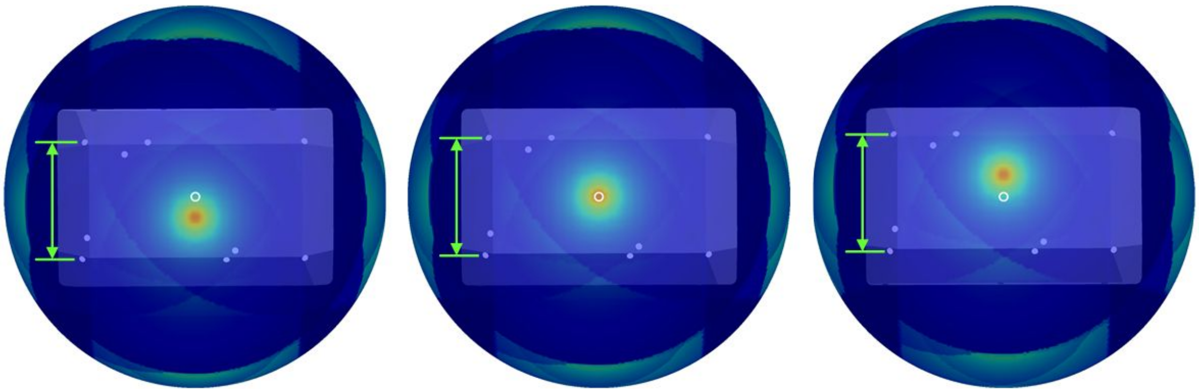
Again, blue represents good performance and brown is bad. Good rotation performance is determined by multiple, visible, non-coplanar sensors, with sufficient baseline between them. Brown areas of the Pose Rotation Error plot are typically good indicators of object poses with high sensor coplanarity.



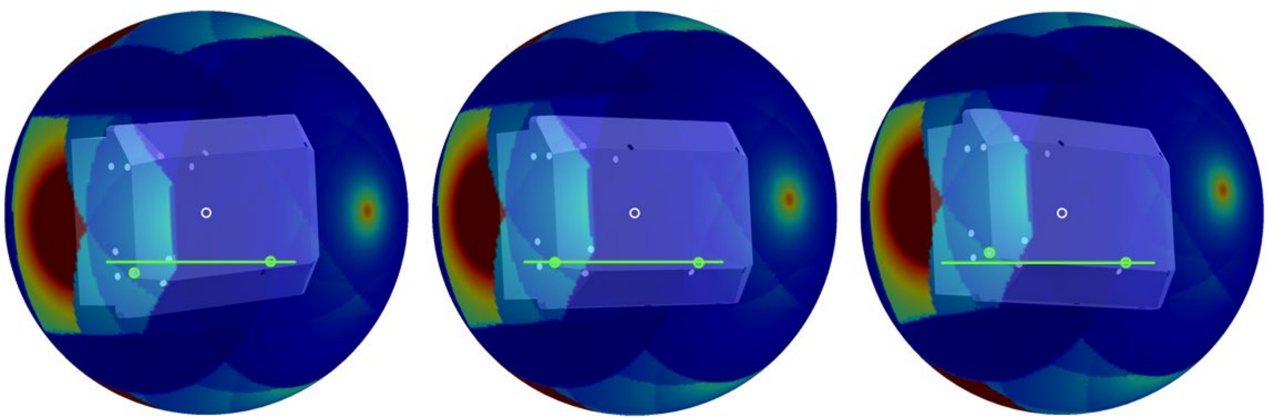
The plot above shows poses with high rotation error in areas that we already expect from our previous inspection of the Initial Pose Possible plot. The surfaces one the sides of the object, +X and -X orientations, expose only coplanar sensors. However, there is also a bull's eye in the center of the object on the +Z axis that exhibits rotation error. The bull's eye is not due to lack of baseline in the X and Y dimensions, but lack of depth in the Z dimension. The 3D plot makes this very clear.

Inspecting the 3D Plot

Focusing on the bull's eye on the +Z axis, we can show why rotation error increases for coplanar sensors, even when they have good baseline within the plane. Consider the orientations below. The change in pitch only changes the distance between sensors by -0.3% or -0.8%. The distance between sensors decreases with pitch toward +Y and -Y. Without another sensor out of the plane, the direction of pitch is ambiguous.



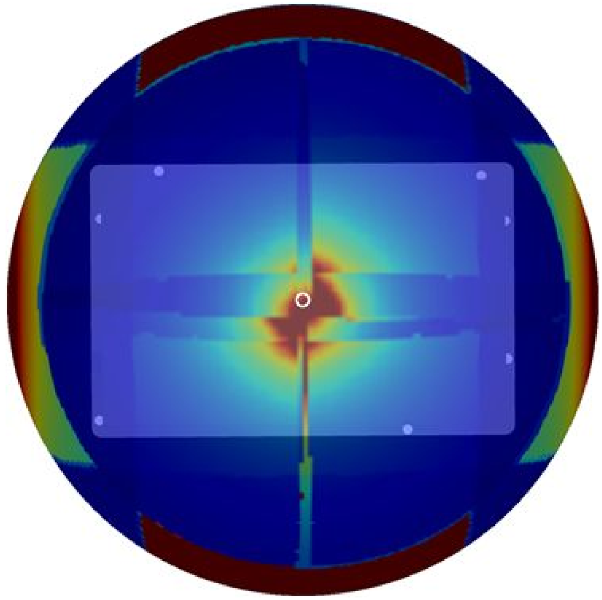
Contrast the pose above to that pictured below. The plot below focuses on a pose with very low rotation error. The sensors are not coplanar and there is depth between the two highlighted sensors. As a result, even small changes in pitch are amplified. The displacement between the two sensors even changes from negative to positive as the pitch changes only slightly.



Eliminating the rotation error along the +Z axis could be accomplished by moving some sensors down the facets toward the edges of the object. Creating baseline along the Z axis reduces coplanarity by adding depth, and the rotation error would decrease.

This design has other problem areas in the +X, -X, +Y, and -Y directions due to coplanarity of sensors on the side, top, and bottom faces of the object. Adjusting the rear facets outward or adjusting the angle of the front facets to make their sensors visible from the sides, top and bottom would add depth in the X and Y axis to reduce rotation error.

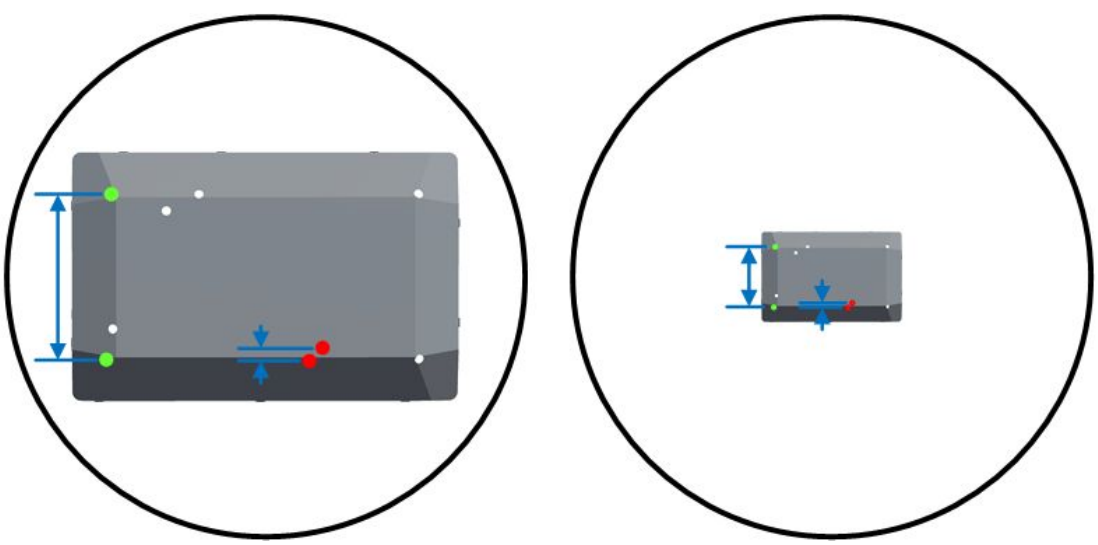
Another problem spot exists at the rear of the object, looking from the -Z direction. However, it is always important to consider use cases for the object. If the rear of the object is completely occluded by the user's head, there is no reason to improve the error in that pose.



Pose Translation Error

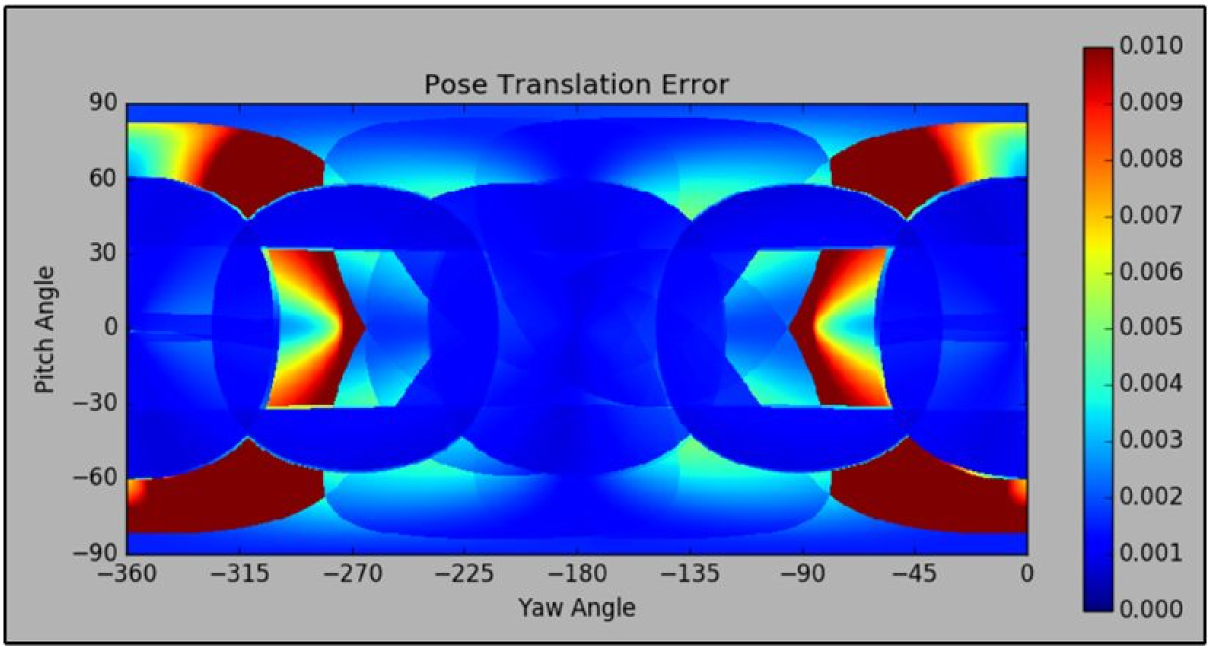
Translation error is dominated by translation away from the base station. As the object moves away from the base station, the perceived distance between sensors foreshortens. If there is not sufficient baseline between sensors at the start, the object cannot move away from the base station without running out of baseline.

Consider the two translations pictured below. The green sensors have significant baseline. Moving the object away from the base station results is a significant change in the perceived distance between the two sensors. The two red sensors have very little baseline to start. Translation away from the base station quickly reduces the baseline between the two red sensors to nearly zero.



Inspecting the 2D Plot

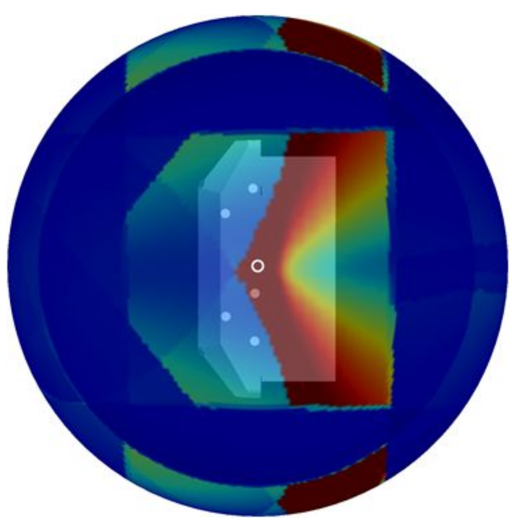
The Pose Translation Error plot maps translation error against all possible object orientations. Blue represents good performance and brown is bad. Good translation performance is determined by multiple, visible sensors with sufficient baseline in at least two axes. Brown areas of the Pose Translation Error plot are typically good indicators of object poses without sufficient baseline in at least two axes.



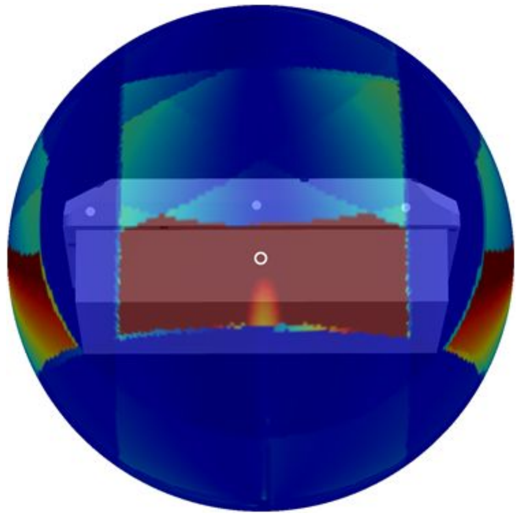
Unlike the Pose Rotation Error plot, there is no problem in the +Z orientation. Although the sensors visible in that pose are coplanar, they have significant baseline in the X and Y axes. Problem areas do still exist in the +X, -X, +Y and -Y orientations. The object is fairly large, which makes it easy to obtain baseline. However, baseline is required in two axes. The 3D plot shows how sensors on the sides of the device only have baseline in one axis.

Inspecting the 3D Plot

Adjusting the point of view to the +X orientation shows the side of the object, with five visible sensors and baseline in the Y axis, but very little baseline in the Z axis. Adjusting the facets on the front or rear to make sensors on their surfaces visible from the side would add baseline in Z, and reduce the translation error.



A similar problem exists from the -Y orientation, but it is even more pronounced. The three sensors on the bottom face are arranged almost linearly, nearly eliminating baseline in the Z axis. Again, expanding the Z axis baseline by adjusting facet angles on the front and back to bring those sensors into view would extend the Z baseline from the rear facet to the front facet and could be a solution to the translation error problem.



Summary

The 2D and 3D simulation plots are very useful for evaluating how well an object and its sensor placement achieve the criteria for high performance tracking in all possible orientations. For detailed instructions on generating and viewing these plots using the simulation tools, see the **Simulation User Guide**. On all plots, blue represents good performance and brown represents bad performance. The Number of Visible Sensors plot gives an initial indication of blind spots on the object. Keep in mind that a minimum of four visible sensors is required to initiate tracking. Initiating tracking also requires that at least one of the four visible sensors exists out of the plane created by the other three by at least 8 mm. Adding coplanarity criteria to the visible sensors and putting a hard threshold between good and bad at four sensors, creates the Initial Pose Possible? plot. The Initial Pose Possible? plot indicates the object's ability to boot at each orientation. Once the object is tracking in VR, it may exhibit errors in rotation or translation. Rotation error is driven by coplanarity of visible sensors and is represented in the Pose Rotation Error plot. Brown areas in the Pose Pose Rotation Error plot likely indicate poses that present coplanar sensors to the base station. Translation error is dominated by translation away from the base station, due to the foreshortening of baseline between sensors. Sufficient baseline is required in two axes to overcome translation error. Brown areas of the Pose Translation Error plot indicate areas of insufficient baseline. Adjusting the number of sensors, angles of facets, or spacing between sensors in problem areas are all potential ways to increase baseline and break coplanarity to improve tracking performance.