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Introducing the "Cut-out Star Target" To Evaluate the Resolution Performance of 3D Structured-Light Systems

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ABSTRACT

Structured light depth map systems are a type of 3D system where a structured light pattern is projected into the object space and an adjacent receiving camera is used to capture the image of the scene. By using the distance between the camera and the projector together with the structured pattern you can estimate the depth of objects in the scene from the camera.

It is important to be able to compare two systems to see how one compares to another. Accuracy, resolution, and speed are three aspects of a structured light system that are often used for performance evaluation.

It would be ideal if we could use the accuracy and resolution measurements to answer questions such as how close two cubes can be together and be resolved as two objects. Or, determine how close a person must be to the structured light system in order to determine how many fingers this person is holding up.

It turns out, from our experiments, a systems ability to resolve the shape of an object is dependent on a number of factors such as the shape of an object, its orientation and how close it is to other adjacent objects. This makes the task of comparing the resolution of two systems difficult.

Our goal is to choose a target or a set of targets from which we make measurements that will enable us to quantify, on the average, the comparative resolution performance of one system to another without having to make multiple measurements on scenes with a large set of object shapes, orientations and proximities to each other.

In this document we will go over a number of targets we evaluated and will focus on the "Cut-out Star Target" that we selected as being the best choice. Using this target we will show our evaluation results of two systems. The metrics we used for the evaluation were developed during this work. These metrics will not directly answers the question of how close two objects can be to each other and still be resolve, but it will indicate which system will perform better over a large set of objects, orientations and proximities to other objects.

INTRODUCTION

1.1 Background

Structured light depth map systems are a type of 3D system where a structured light pattern is projected into the object space and an adjacent receiving camera is used to capture the image of the scene. By using the distance between the camera and the projector together with the structured pattern you can estimate the depth of objects in the scene from the camera.

There are different types of structured patterns that can be projected into a scene. Most of the patterns types are described in [1]. Some possible patterns are binary coded, color coded, gray scale coded, pseudo-random binary dots and patterns made up of mini-patterns that form coded words. In practical applications, we may want to know how well a structured light system is able to resolve, for example: two cubes placed close to each other, two fingers someone is holding up or the shape of a small object (e.g. whether the object is square or round).

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It is important to be able to compare two systems to see how one compares to another. There are three aspects of a structured light system that are often used to evaluate the performance of a system [1]:

- **Accuracy:** Refers to how accurate the measured x, y and z values are with respect to the "ground truth" [2], where z is the depth coordinate and x and y are the horizontal and vertical coordinates, respectively. The "ground truth" is the actual x, y and z location of a point in the object space. Accuracy, therefore, is the deviation of the measured value as compared to the actual ground truth values. For each 3D image captured by the structured light system one can express the errors of all measured locations in terms of mean error, standard deviation, maximum error and etc.
- **Resolution:** Refers to the ability of a system to resolve a point or as set of points in the object space. One approach to measure this is by determining the number of reported depth pixels provided by a system [1], but you may find such a measure is not a good way to determine how close two objects can be to each other and still be resolved as two objects. Special targets can be constructed for the purpose of measuring how close two objects can be and still be determined by the system to be two objects. Other methods can also be used, such as comparing the shape of a known object, such as a cube or sphere, to the shape obtained in the depth map provided by the structured light system [2]. There are other 3D methods of measuring the shape of an object using optical methods, such as Time/Light in Flight, Laser Scanning, Interferometry and etc. [3]. Structured offers advantages, among them are the ease of implementation and fast full field of view measurements [3]. For our work we will be concerned with how to measure resolution for a 3D structured light system.
- **Speed:** Refers to the rate at which the system is able to capture and process a depth map image. Some systems can achieve 30fps or more. This facilitates tracking the movement of objects.

Some systems use post-processing to improve the accuracy of the depth map information it measures. For example, a system can look at each depth map point it measured and compare it with the neighboring points. If the measured depth of that point is far in distance from the neighboring points, then the system could consider this measurement erroneous. In which case, it could use the neighboring measurements to correct the point it thinks is erroneous. Such type of post-processing can make it difficult to find a target that will not bias the results. For example a 3D target system made up of two small cubes close together could produce results different than that for a target system with just one small cube. For the target with two cubes, the post-process can cause the gap between the two cubes to merge together forming one object instead of two; whereas the post-processing may not have as much of an impact if only one cube is used. This is because a point or set of points that separates two objects can be considered erroneous and the system will replace this point or set of points with depth distances somewhere in between the two objects.

Another issue is the need to know the "ground truth" in order to measure the accuracy, resolution and speed. One way to do this is to use accurate depth measurement equipment in order to measure the ground truth. This could be tedious and time consuming. It would be good if we could find a target that will enable comparing two systems without requiring efforts to determine the ground true.

The orientation of an object can also influence the results. For example the results can be different if you rotated a cube 45 degrees with respect to the three x, y and z axes. It therefore becomes important to consider how the orientation of an object or objects will affect the accuracy and resolution of a system. One could take a series of measurements where a cube, or a different 3D target, is rotated by a quantized amount, but the process of taking many such pictures could become overwhelming. It would be good if we could find a target that would minimize such an effort.

One of the goals of our research was to find a target, or set of targets that can be used to compare the resolution of two systems without the need to know the ground truth and without having to assure the orientation of the target is the same for both systems.

1.2 Our approach

Our goal is to develop a set of metrics based on targets that will enable us to quantify the resolution performance differences between two or more structured light systems. We need to be able to quantify the performance as a function of depth along the z axis and along the x and y axis. Our criteria for such a test system is to be able to use a

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flat test target that is perpendicular to the z axis, where this target can be moved from the systems closest operating distance to the farthest distance. The idea is to determine how well the system can resolve flat objects that reside on a plane perpendicular to the z axis. We can then make measurements at a specific set of distances from the system measured along the z axis. For each distance we want to use metrics that do not require knowing the ground truth and are insensitive to the orientation of objects found in the plane of the target.

We have developed a test target and methods to evaluate the ability of a structured light system to resolve objects and edges. Our objective was to make a set of measurements that would enable us to assess how well a system performs.

2. TEST TARGET

2.1 Target Design criteria

The two areas we are focusing on are the ability of a system to resolve two separate objects that are near each other and how well a system can resolve the shape of an object. Ideally we want a target that does not require knowledge of the ground truth and does not require tedious alignment procedures. The target should also provide for a way to removed dependencies on the orientations of an object or objects.

2.2 Test target considered during the design process

During our research we tried a number of targets. The target that we ultimately selected is called the "Cut-out Star Target" and is shown in figure 1. We looked at other targets as well. Some of these targets are described below and shown in figures 2, 3, 4 and 5.

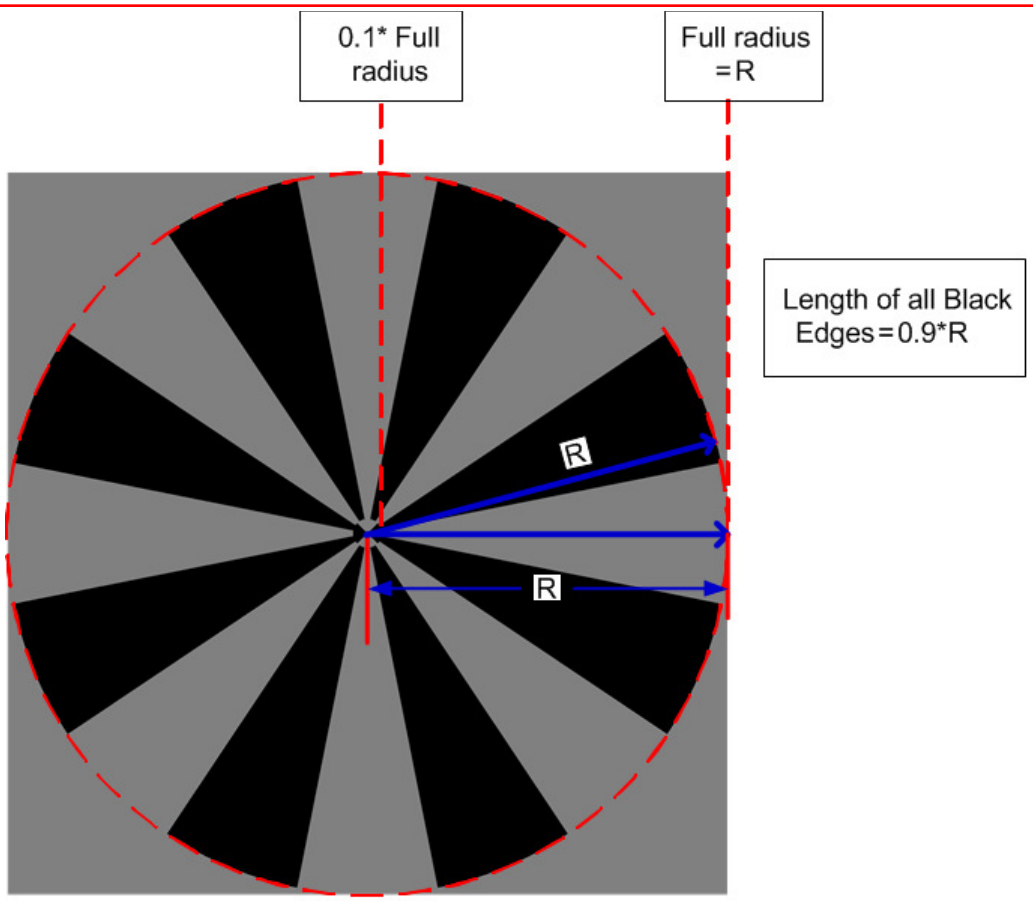
2.2.1 Cut-out Star Target

Figure 1 shows a target that is commonly referred to as the "Star Chart" and is used to measure resolution in typical 2D pictures [4]. The Star Chart has light gray areas and black areas as shown. The target we propose for testing a structured light system is the same, except the black areas are cut out, which creates holes that look like pie wedges. All gray pie shape wedges and black pie shape wedges are exactly the same in shape. It is important to point out that in the center there is a circle that has 10% of the full 100% radius shown in the picture. The area within this 10% circle is not cut out. This center circle area is used to attach the gray spokes together in the center.

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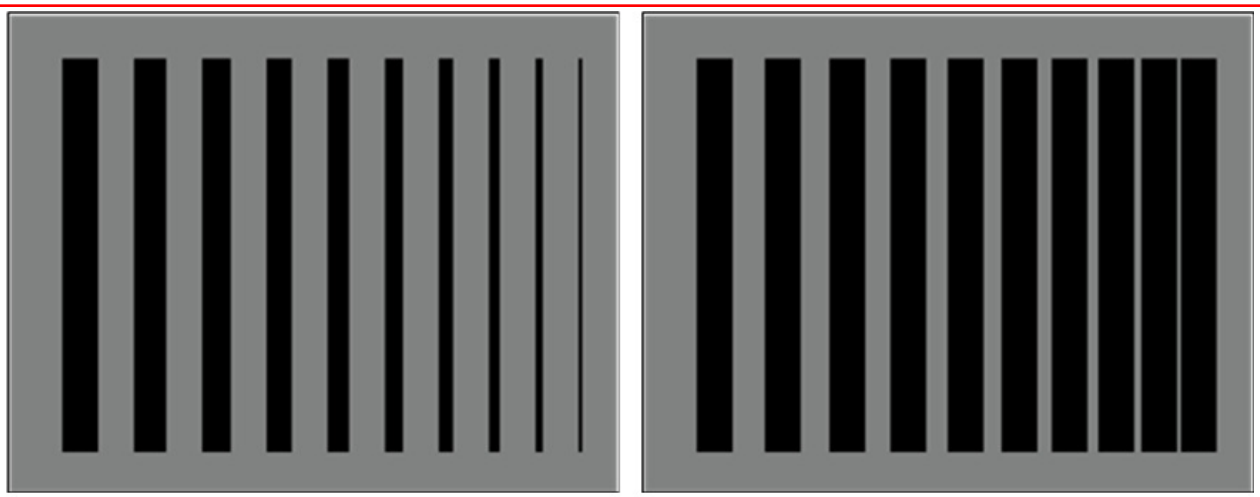
Figures 1 show the Cut-out Star Target.

2.2.2 Cut-out bars of decreasing widths and its complement

Figure 2a and 2b show two complementary targets. For both, the black areas are cut out creating holes. The smallest hole width shown on the left target is 1/10th of the adjacent bar widths (in gray), where all bars are of the same width. Likewise, the smallest bar in the right target is 1/10th of the adjacent hole, where all holes are of the same width.

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(a) (b)

Figures 2a and 2b show complementary targets. **2a** shows a board that is gray with black cut-out areas, where the gray areas between the cut-out areas are referred to as "bars". The thinnest black cut-out is 1/10th of the adjacent gray bar, where all gray bars are equal in width. The next thinnest cut-out area is 2/10ths of the gray bar width and 3/10ths for the third thinnest and so on. **2b** shows a gray board with equal width black cut-out areas, where the thinnest gray bar is 1/10th the width of the adjacent black cut-out width. The next thinnest bar is 2/10ths. The third thinnest is 3/10ths and so on for the remaining gray bars.

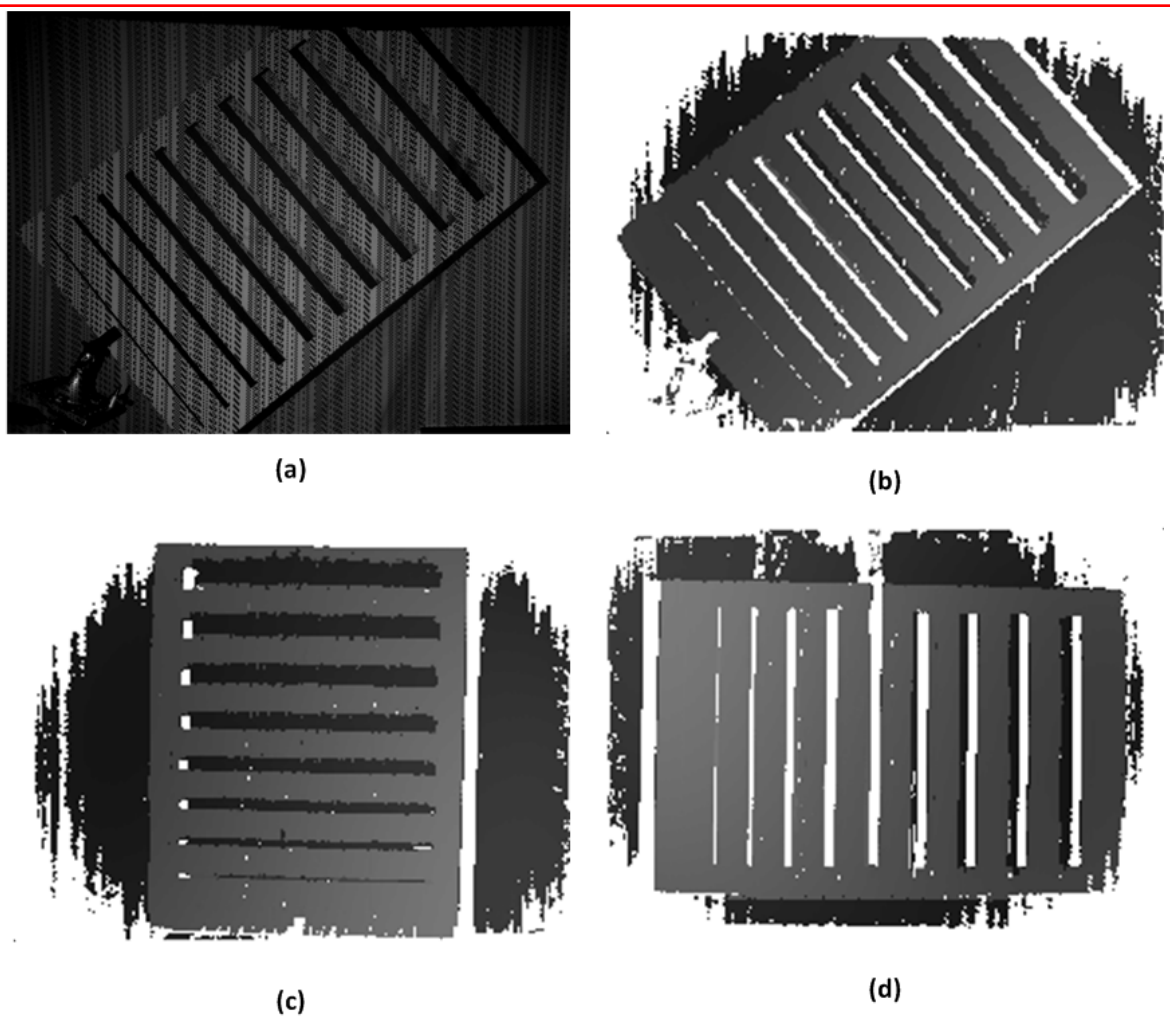
In order to use this target to compare two structured light systems we need to find a way to assure each structured light system projects the same number of depth pixels on the target. We could do this by aligning the target so it fills the full Horizontal Field of View (HFoV) and then measure from the captured depth map picture the number of horizontal depth pixels across the target. We can do the same for another system. Using this information we can figure out where to place the target for one system relative to the other system in order to assure the same number of depth pixels are used across the target for each system. Once we know the same number of depth pixels cover the target between two systems we can determine and compare the smallest bar or hole each system can detect. Next we will need to rotate the target by 45 and 90 degrees and make the same measurements. It is possible these three orientations will yield different results. If the results are different we will need to develop a merit function to determine which system performs better overall independent of orientation.

Figure 3a shows a picture of the target shown in figure 2a. This picture is the actual picture captured by the camera use in a 3D structured light system. In this picture you can see vertical patterns that shift in position as a function of depth. The structured light system detects these patterns and estimates the depth based on the separation distance between the projector and the receiving camera that captured this picture. Figures 3b, c and d show the structured light depth map captured for three different orientations of the target. The depth map is represented by shades of gray, where the board in the foreground is a lighter shade of gray than the background. The white areas in b, c and d are the shadows caused by occlusions. The black areas in figure 3a are the shadows. These are the areas the camera can see, but pattern is not present because it is occluded by the target.

In Figure 3b, c and d the system was able to detect hole 2/10ths of the bar width or greater. Using this information you can say something about the resolving capability of the system. It will tell you something about how big a hole can be before it is detected, but it will not tell you how close holes can be before it merges into one hole. The situation is further complicated by the fact the 2/10th hole in figure 3b seems to be closed more than that for 3c and 3d. The edges between the bars and the holes are also different for figures 3b, c and d, where figure 3b looks like the jagged edges of a wood saw blade, figure c looks like vertical box like edges and figure d looks like clean straight edges. Our goal is the find a target that will enable us to say something about the resolution of the system independent of the target orientation. So to used target 2a, we will need to develop metrics that take all orientations into account. Our selected target is the Cut-out Star Target shown in figure 1. So, we will not concern ourselves with the bar targets further.

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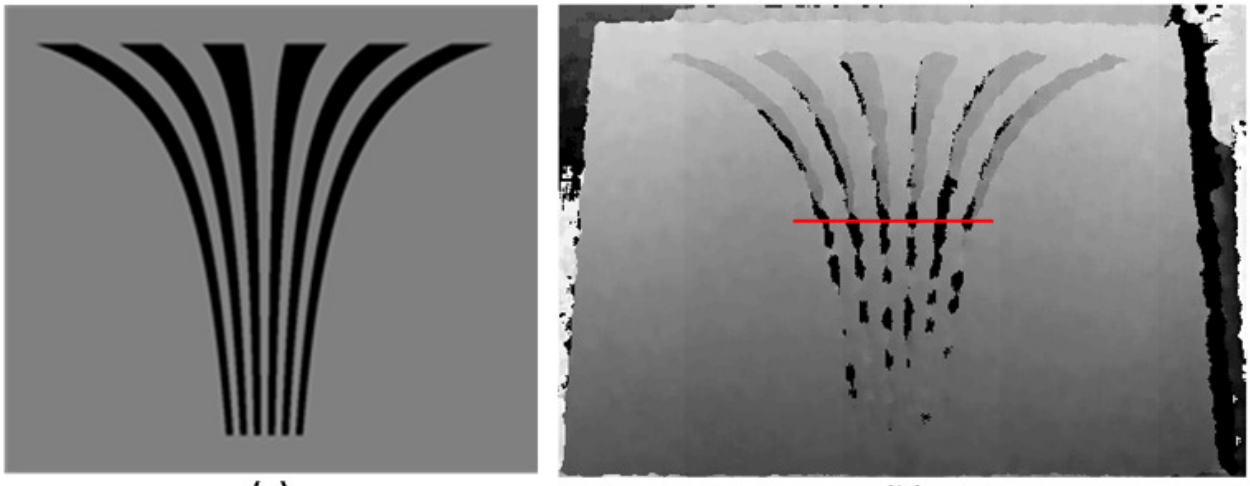
Figures 3a shows the actual picture captured by a structured light system, showing the pattern projected into the object space and reflected back to the receiving camera. **3b** shows the captured 3D depth map, where the shades of gray indicate the depth. The board is the same target described in Figure 2a. The board, in the foreground, is a lighter shade of gray as compared to the background, which is darker. The white areas are the shadow areas caused by occlusions. **3c** and **3d** show the depth map when the target is rotated 90 degrees and zero degrees, respectively. You will notice the thinnest cut-out in (a) is not shown in b, c or d. You will also notice roughness along the cut-out edges are different for all three orientations shown in b, c and d.

2.2.3 Cut-out Curved Lines of Variable Width

Figure 4(a) shows a pattern that progressively decreases in width from the top to the bottom. The black areas are cut out creating holes. If you draw a horizontal line across the bars at any vertical location you will find the holes and bars (in grey) will have the same width at that location. The idea behind this target is to find the horizontal line location where the system is just barely able to detect all holes and bars along that line, like that shown in figure 3(b). This figure shows the depth map picture captured by a structured light system, where the different gray levels represent relative depth. The red line shows the horizontal line where the system is just barely able to detect all the holes and bars along this line. For each system we can then find the average number of depth pixels along that line that fit in the holes and the average number that fit over the bars. The next step is to rotate the target by 45 an 90 degrees and make the same measurements. If there are dependencies based on orientation a merit function will need to be developed in order to compare two structured light systems.

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(a) (b)

Figures 4a and b, show the "Cut-out Curved Lines of Variable Width" target. 4a, show the target were the black areas are cut out creating holes. 4b, shows the structured light system picture, where gray levels are used to indication relative depth. The lighter gray represents the depth of the target. The darker areas are depths behind the target.

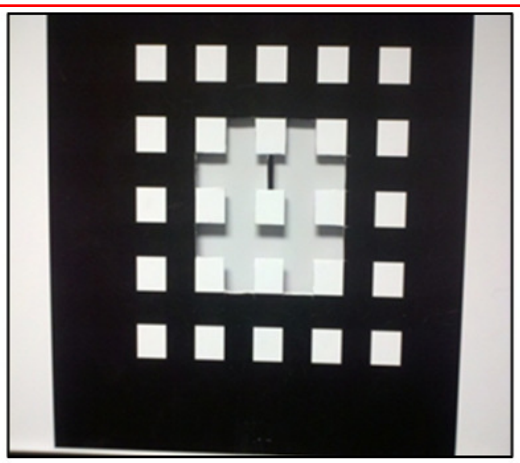
2.2.4 The Cut-out Checkerboard Target

Figure 5a shows a checkerboard pattern, where the center most black areas have been cut out. The idea is to create holes around the center most white square. Using this chart allows us to investigate how well the structured light system under test is able to distinguish the center square as being square. Figure 5b shows the gray level depth map picture from one system and 5c shows the same for another system. Notice that 5b is better able to detect the square shape than that of 5c. While this is the case for this orientation, it may not be the case if you rotate the target.

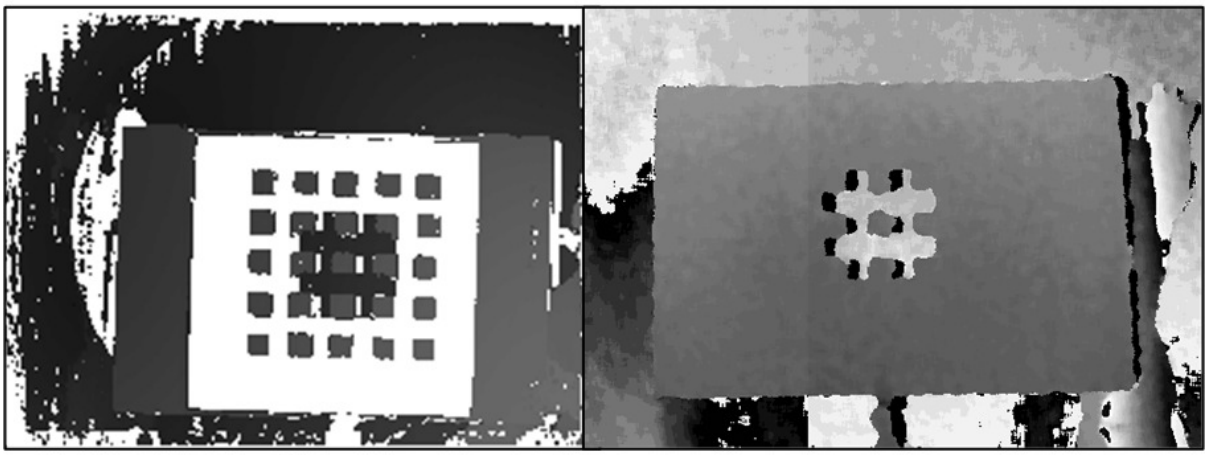
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(a)



(b) (c)

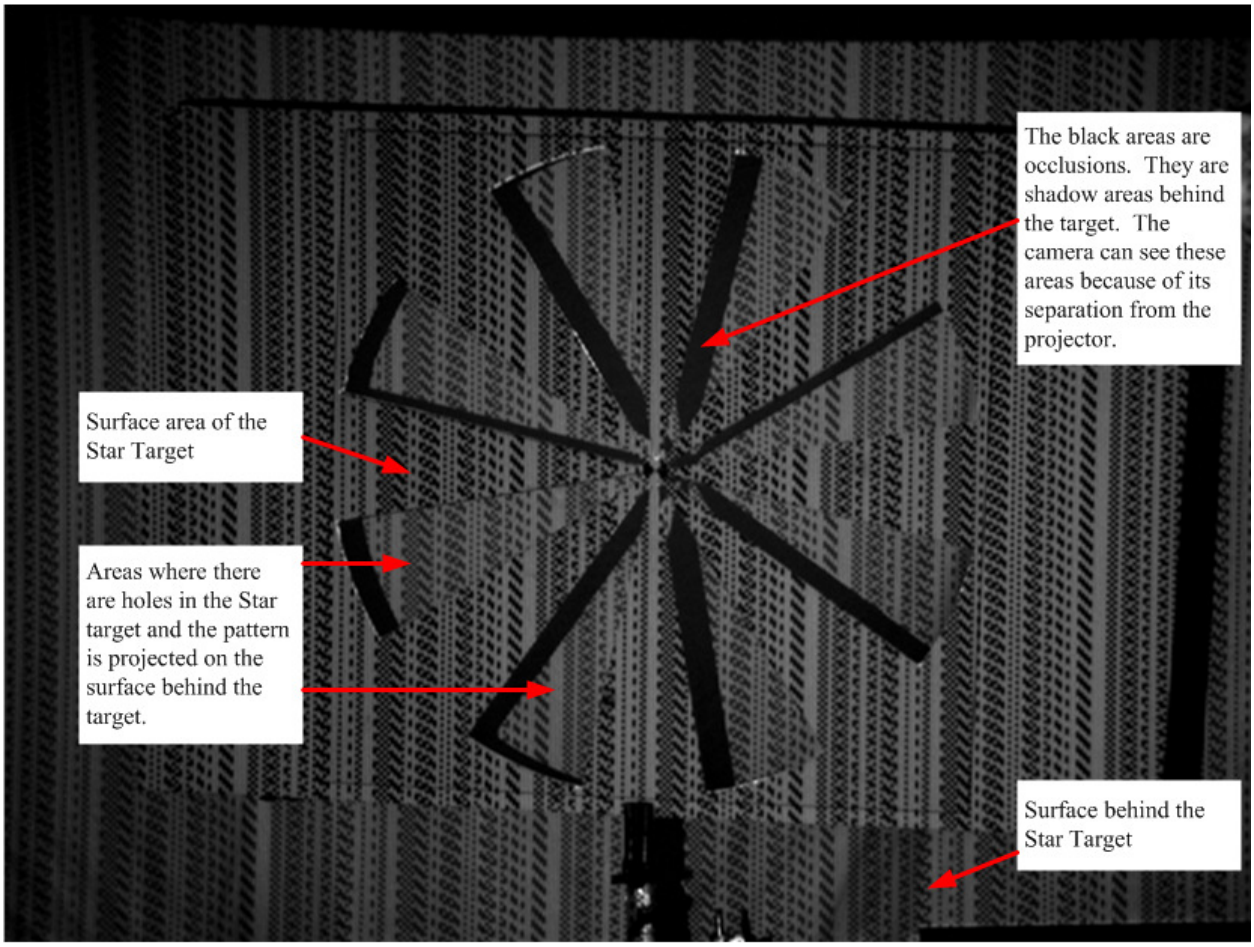
Figure 5a shows a target with a center square and a black narrow bar that holds it in place. The idea is to look how a single square in the presence of near-by squares will look like using a systems depth map. 5b, shows the gray level depth map from one system and the same from another 3D structured light system in 5c.. We need to concern ourselves with the shape of the center square. In 5b the shape looks square, whereas for 5c the shape is not as distinct as it is in 5b. It is also worth pointing out that 5b shows white areas where the target is black, whereas 5c does not. This indicates system for 5b is less able to detect dark objects than that for 5c. The system that captured 5b will show white areas for locations it could not detect a depth, such as shadows caused by occlusions.

2.3 Selected test target: The Cut-out Star Target

Based on the target requirements set forth in section 2.1 above, we have found that the Cut-out Star Target, shown in Figure 1, is the one that better fits our requirements. This will be explained in section 3.

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Figures 6 shows an image of the Cut-out Star Target captured by the camera used in a 3D structured light system. It shows the projected structured light pattern on the star target and the surface behind the star target. Notice that the cutout pie wedges show the pattern on surfaces behind the target. The black areas are shadows caused by the target occluding the pattern with respect to the camera.

Figure 6 shows a pictured of the Cut-out Star Target taken by the camera in a structured light system that projects vertical lines, like that shown in figure 7a. Figure 7b shows a structured light pattern that uses dots. Both systems project mini-patterns that form coded words. In fact these patterns form the same code words, the difference is one uses dots and the other uses lines. If you look closely you will see the patterns are similar.



(a) (b)

Figures 7a shows a structured light pattern made up of vertical lines. Within this pattern are mini patterns that make up coded words. Figure 7b shows a structured light pattern that uses dots. Both systems project mini-patterns that form coded words.

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3. MEASUREMENTS MADE USING THE Cut-out STAR Target

3.1 Performance metrics

The ideal Star Target is shown in Figure 1. The image has been cropped so that the distance from the center of the picture to the horizontal or vertical edges will be the same length from the center to the end of the black areas in the picture. The length of any black edge is equal to 90% of the Full Radius, R, in depth pixels.

Let's assume:

- Each pixel in this picture represents a depth pixel
- The gray areas are depth pixels found on the targets surface
- The black areas are holes. These pixels when captured by the camera will be either in shadows, on surfaces behind the target, or depth errors made by the structured light system.

With these assumptions we can compare the number of gray pixels, "Pg", laying on the target surface and on a circle with a radius Rz:

$$Rz = Z*R, \text{ where Z is scalar from 0.1 to 1.0} \quad (1)$$

We can then calculate the percentage

$$Y = 100*(Pg/(\pi*Rz)) \quad (2)$$

Ideally we would expect Y to be equal to 100% for all radial distances Rz. This is because in the ideal case, for Figure 1, Pg should equal one-half the circumference of the circle with radius Rz.

Figure 8 shows the results of computing Y for the target shown in Figure 1. As you can see the Y turns out to be 102.2 percent. This is because the target in Figure 1 has 2.2% more gray pixel than black pixels along any of the circles with radius Rz, where $Rz > 0.1*R$. It turns out this difference is not as significant as it may seem; this will become more evident as we describe the actual test results.

Let's use the symbol X to represent the numbers on the abscissa of Figure 8.

$$X = [(Rz - 0.1*R)/(0.9*R)]*Xmax, \text{ where Xmas is the largest value for X in Figure 8} \quad (3)$$

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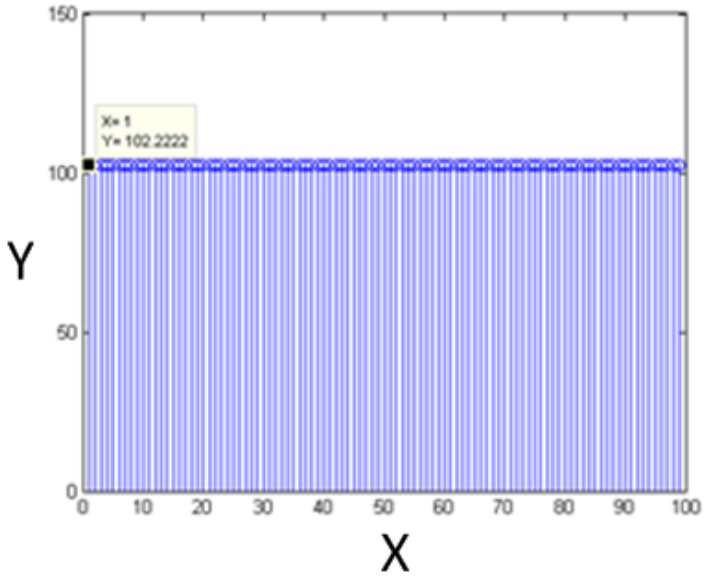


Figure 8: Evaluation results for target in Figure 1

3.2 Performance evaluation of 2 systems

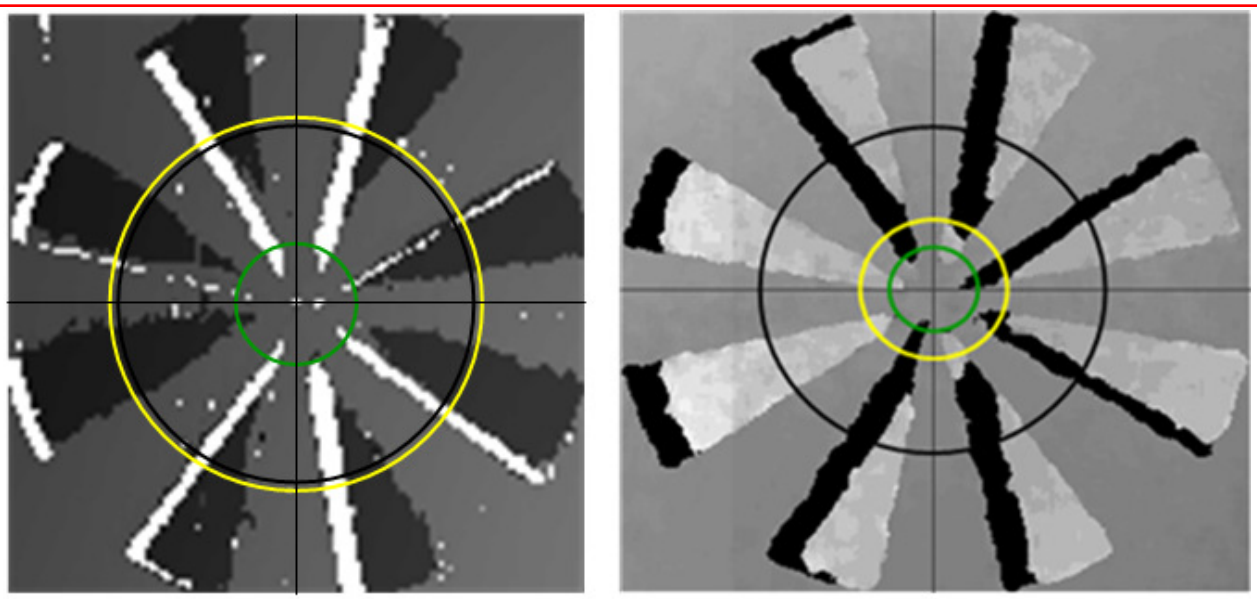
The two systems we used for comparison are:

- A system that projects line patterns with code words, which we will refer to as the B-Line System
- A black box system that projects an unknown dot pattern, which we will call the C-Dot System

In Figure 9, cropped depth map images are shown for the B-Line and C-Dot systems. The depth map images used for Figures 9a and 9b were cropped so that the horizontal and vertical edges of the pictures are about twice the radius of the circle encircling the outer edges of the pie wedge holes. By cropping the pictures in this way we can make the assumption that the center of the captured target is in the center of the picture. Granted, it is not likely to be, but taking care to align the target perpendicular to the optical axis of the camera and having the center of the star target very closely aligned with the optical axis you should get a good enough picture to make meaningful measurements.

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(a) (b)

Figure 9 Depth Map: (a) B-Line System, and (b) C-Dot System

The results using our evaluation program, for both the B-Line and C-Dot Systems, are shown in Figure 10.

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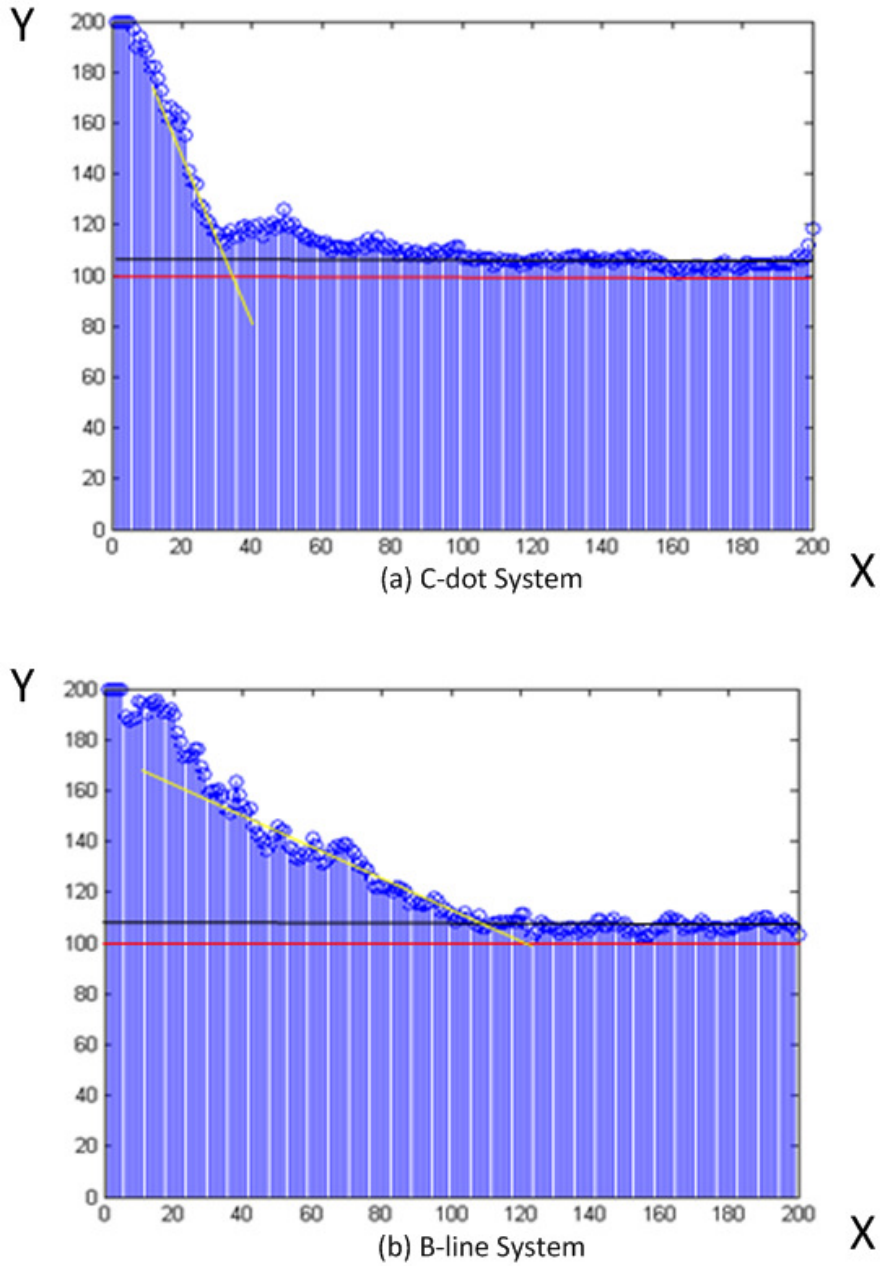


Figure 10: Performance metric: (a) C-Dot System and (b) B-Line System

The B-Line system depth map picture shown in Figure 9a has been cropped to 126x126 depth pixels and the C-Dot system picture shown in figure 9b has been cropped to 278x271 depth pixels. We can estimate the average radius R for both pictures to be:

Rc(C-Dot) = (278+271)/4= 137.25, as the radius for the C-Dot system
Rb(B-Line) = (126+126)/4= 63, as the radius for the B-Line system

Throughout this section it is important to keep in mind the number of resolution pixels across the same target image are:

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C-Dot System = 75338 Depth Pixels
B-Line System = 15876 Depth Pixels

The C-Dot system uses 4.75 times more pixels than the B-Line system. What we want to show is how we can use the Star Target and draw comparative information without having to go through elaborate lab setups and alignment procedures. Granted, it is reasonable to argue that comparative results would be more accurate if it used the same number of depth pixels across the target. So, it would still be good to try to capture pictures that are approximately the same, but it does not have to be exact when you use the Star Target.

By entering these radius values in equation (3) above, and solving for Rz we can establish a relationship between the Star Target photos in Figure 9 to the graphs in Figure 10. The relationship equation is:

$$Rz = [(X/Xmax)*0.9 + 0.1]*R, \text{ where} \quad (4)$$

Xmax is the largest X value shown on the graph.
And R is Rc or Rb for the C-Dot and B-Line systems, respectively

In each of the Figures 10a and 10b, you will see three different color lines. There is a yellow line that follows the descending slope of Y as X goes from zero to Xmax. The horizontal red line drawn across the graph represents Y equal to 100. The horizontal black line is the mean value of the flat area for Y. Both the yellow and black lines are drawn manually based on visual judgment.

Notice the yellow line intersects the black line around the value of 30 for the C-Dot system and 110 for B-Line system. Let use “Xy” as the value of X where the yellow line and the black line intersect in figures 10a and 10b.

It is helpful to place a circle on the pictures shown in figures 9a and 9b that represent the location where the yellow and black lines intersect. Let’s used a yellow circle with radius “Ry” to represent the location where the yellow line intersects the black line in Figures 10a and 10b. The values of Ry for both systems turn out to be:

For the C-Dot system (X=30) Ry(C-Dot) = 32
For the B-Line system (X=110) Ry(B-Line)= 38

The black circle in 9a and 9b represents the radius at which the Y value in the respective graphs, shown in figures 10a and 10b, begin to rise above the black line as you go from Xmax to zero. Let’s use “Xb” as the location in figures 10a and 10b where the Y value begins to rise above the black line as you go from Xmas to zero. The Xb value for the C-Dot system is 100 and 105 for the B-Line system. We can now calculate the radius, “Rb”, of the black circles in figure 9a and 9b. For each of the system the value of Rb is:

For the C-Dot system (X=100) Rb(C-Dot) = 75
For the B-Line system (X=105) Rb(B-Line)= 36

We can now look along the edges in figure 9a and 9b where Rz is greater than Rb. It may be difficult to recognize the edges along the pie wedges. What you need to look for is the gray level associated with the surface of the Star Target. You need to look for this gray level as you look around the edges. Keep in mind all other levels of gray are part of the cut-out area. That cut-out region can represent surfaces behind the Star Target or shadows cause by occlusions. If you now look at the edges in figures 9a and 9b you can see the roughness of the 16 edges where Rz is greater than Rb.

Ideally, we would like to obtain a set of metric values from all 16 edges that will tell us something about how reliable the systems depth map will match the shape of an actual object. We will refer to these metrics collectively as Edge Fidelity. In our future work we will deplore ways to define Edge Fidelity and explore what metrics provide the most information on factors related to Edge Fidelity.

For now we can make these general observations:

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- For B-Line system in Figure 9a:
  - The edge roughness for 16 edges where Rz is greater than Rb, looks to be rougher than the C-Dot system.
  - There are edges that look like a jagged wood-saw blade edge and others that look more random, indicating the orientation of the object, can affect the edge fidelity.
- For the C-Dot system in figure 9b:
  - The edge roughness is not the same for all 16 edges, but there is not as much difference between each of the 16 edges as compared to the B-Line system.

While these are general observations, what we need is to find a set of metrics that will give us an idea of how well one system, on the average, compares to another.

Let's start off by defining a new set of metric values referred to collectively as the "Average Edge Consistency" (AEC). The motivation for this metric will become more evident below. For the Average Edge Consistency metric values we will calculate the Mean, Standard Deviation, Min and Max values for Y, as shown in figures 10a and 10b, as X goes from Xb to Xmax. For the B-Line and C-Dot systems these metric values are shown in Table 1.

Table 1: Shows the Average Edge Consistency Metrics for the B-Line and C-Dot Systems

	Mean "Ymean"	Standard Deviation "Ysdv"	Min value below the Mean "Ymin"	Max value above the Mean "Ymax"
B-Line System	106.8	1.95	-5.2	4.8
C-Dot system	105.1	1.75	-4.6	2.7

Note that in the C-Dot graph in figure 10a, the Y values between X=190 to X=200 are above the mean. We consider these values as outliers and removed them when we calculated the Mean, Standard Deviation, Min and Max values shown in Table 1.

Table 1 shows the metric values for the C-Dot system is slightly better than that for the B-Line system. Given that the C-Dot depth map picture has 4.7 times more pixels than that for the B-Line system, you should try to capture depth map pictures that match more closely in resolution to draw a more accurate conclusion.

For both the B-Line and C-Dot systems the Ymean is above 100 percent. This means the system's depth map is showing a wider wedge surface area than that of the actual Star Target. The cause of this may not be clear, but it is possible a post processing algorithms is doing some edge processing and thereby widening the edges for Rz radial lengths longer than Rb.

Let's look more closely at graphs in Figures 10a and 10b. From these graphs, one can consider the Y values from Xb to Xmax to represent the area of the graphs that would model the behavior of the system if there was one long edge, like that shown in Figure 3b, 3c and 3d above. The difference is the Star Chart has 16 different angular orientations captured in one depth map picture, whereas the targets shown in Figure 3 only have one.

It is useful to try to explore what else we may learn from Figures 9 and 10. Let's start by looking first at what Y=180 may tell us. The motivation for this will become evident below.

For Y=180, we can make the following assessment:

- For the C-Dot system Y=180 corresponds to X=10 and Rz=19.9, where a green circle is drawn in figure 9b to represent Rz=19.9.
  - $2*\pi*19.9 = 125$ pixels around the green circle in figure 9b
  - 125/16 is equal to 7.8 pixels per 16 wedges (8 for the pie shaped hole wedges and 8 for the gray wedges)
- For the B-Line system Y=180 corresponds to X=20 and Rz=11.97, where a green circle is drawn in figure 9a to represent Rz=11.97.
  - $2*\pi*12.97 = 75.2$ pixels around the green circle

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- 75.2/16 is equal to 4.7 pixels per 16 wedges

Let's look more closely at the green circle in Figure 9b. This green circles is very close to touching all 16 wedges (8 wedges on the Star Chart Surface and 8 Wedges on the pie shaped holes). The green circle could be thought of as representing the minimum Rz radius threshold where the system is able to detect all 16 wedges. With these observations we can define a new metric called "Threshold Resolution" (TH) using the Star Target shown in Figure 1. A complete definition of TH is given below in section 3.3.

Let's look at the yellow circle in figures 9a and 9b. This circle represents the intercept of the yellow line with the black line in figures 10a and 10b, respectively. The slope of the yellow line in figures 10a and 10b provided a way to judge how quickly Y drops to the mean value represented by the black line. In Figure 10a, you will notice the actual value of Y does not reach Ymean. So there is another measure of the peak value of Y between Xy and Xb. We can think of these two observations as providing us information about the rate of settling as X goes from zero to Xb. So it would be a good idea to include these measurements when assessing a systems response. Let's refer to this metric as Settling Rate (SR), by using two values:

SR-Slope = $2*\pi*Ry/16$

SR-Peak = Peak Value of Y between Xy to Xb

Table 2: Showing the Settling Rate for the B-Line and C-Dot Systems

	SR-Slope (Depth Pixels per 16 Wedges)	SR-Peak (Peak Y value between Xy and Xb)
B-Line System	14.7	0
C-Dot system	12.7	125

Table 2 shows that the C-Dot SR-Slope is better. What it tells us is the B-Line system requires, on the average, 16% more depth pixels to settle than the C-Dot system (14.7/12.7 = 1.16). In our future work on Edge Fidelity we will explore how to use concepts related to Settling rate to see what this will tell us about how well a systems depth map can represent the actual shape of an object.

3.3 Metrics

Now that we have made a set of observations about the Cut-out Star Target and carried out some measurements. We can at this point define these metrics:

Average Edge Consistency (AEC)
The Average Edge Consistency metric values are by definition the Mean, Standard Deviation, Min and Max values for Y as X goes from Xb to Xmax. Table 1 above serves as an example of such measurements. The idea behind AEC is to measure the variations of Y where the values of Y are more constant.

Threshold Resolution (TH)
TH is the minimum number of depth max pixels needed in order to resolve all 16 wedges. TH value can be different for planes placed perpendicular to the camera's optical axis at different distances along that optical axis.

To calculate the value of TH for the plane where the Star Target is located, draw a green circle on the star target depth map picture, like that shown in figures 9a and 9b, so that the circle has the smallest radius possible and touches at least one depth pixel in each of the 16 wedges (i.e. 8 wedges on the star target surface and 8 pie like hole wedges).

Determine the radius of the green circle, "Rg", and then calculate:

TH = $2*\pi*Rg/16$

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The TH threshold can be thought of as a figure of merit for the Star Target. It provides a way to compare two systems based on the Star Target alone.

Settling Rate (SR)

The Settling rate has two values:

SR-Slope = 2*π*Ry/16
SR-Peak = Peak Value of Y between Xy to Xb

It is a figure of merit used to compare two systems

It would be convenient to be able to use the values of AEC, TH and SR to provide sufficient information to help us say something about the comparative Edge Fidelity of two systems. Edge Fidelity will be the subject of our future work. For now we can use AEC, TH and SR as figures of merit when comparing two systems.

4. CONCLUSIONS

Our goal was to find a target, or set of targets, that will allow us to compare how well two systems are able to resolve flat objects that reside in a plane perpendicular to a system's z axis. Above we have introduced the 16 wedge Cut-out Star Target and defined metrics for AEC, TH and SR. One can use these metrics to compare, on the average, how well one system performs with respect to the other.

In our future work we will be investigating how to make measurements that will help us predict how well a system is able to resolve the shape of an object.

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