Brightway Depth Sensing System Calibration - Manchen Hu, Zixin Huang, Xueqi Chen

team members: Zixin Huang, Xueqi Chen, Manchen Hu

Introduction:

Depths sensing is the technique of sensors to measure the distance between a device to an object. It acquires multi-point distance information across a wide Field-of-View(FoV) as a 3D range finder. It can be increasingly important for the development of many computer vision applications. It changes the way a digital system understands the real environment. With accurate reconstruction, the systems would acquire information that typically needs human observation. Three key tasks that depend on each other are needed for the success of depth sensing which are image acquisition, processing, and analysis. Integration of depth sensing devices can help improve techniques like 3D model reconstruction, advanced driver assistance system(ADAS), gesture recognition, and facial analysis. For the new age's autonomous driving vehicles, depth sensing can help them picture the surrounding environment clearly so that they can navigate safely. In our case, the Brightway depth sensing sensor (Figure 1) is built aim to collect depth information for vehicles. Besides the camera to take images and a processing unit connected to the camera, the device also has two infrared lights that simulate the headlights of a car. In a real application, the camera would be put in the middle of the front of the car to collect information, and the two lights would be replaced by the original headlights of the car.

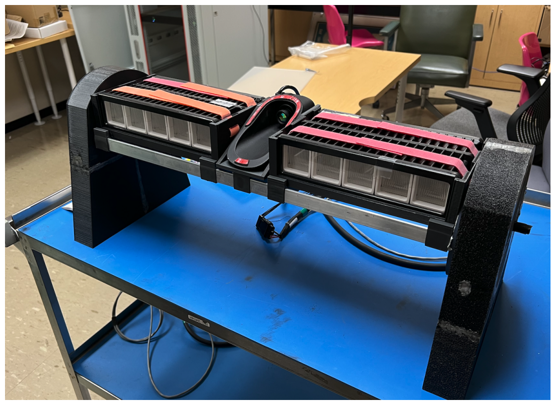


Figure 1. The Brightway Depth Sensor

Background:

Depth sensing theory

As background, the common types of depth sensing technique and their working principles would be discussed here. There are three most popular and commonly used types of sensors today. They are stereo vision, time of flight, and structured light. [1]

Stereo Vision

Stereo vision sensors rely on binocular vision as a principle which is the same as what human eyes are based on. As a human, our vision uses stereo disparity which is the apparent motion of objects between a pair of stereo images to measure the depth of an object. In the case of a camera, the difference in an object's location captured by two sensors is the key to forming stereo vision. An explanation of the theory is shown in Figure 2. The left image and right image are two images that capture the same object from two points of view and by taking both images into account, we can utilize the difference in the two images to calculate the stereo disparity. With disparity, algorithms are used to help form the stereo vision. On the other hand, great details and textures are often required to form accurate stereo vision with this method.

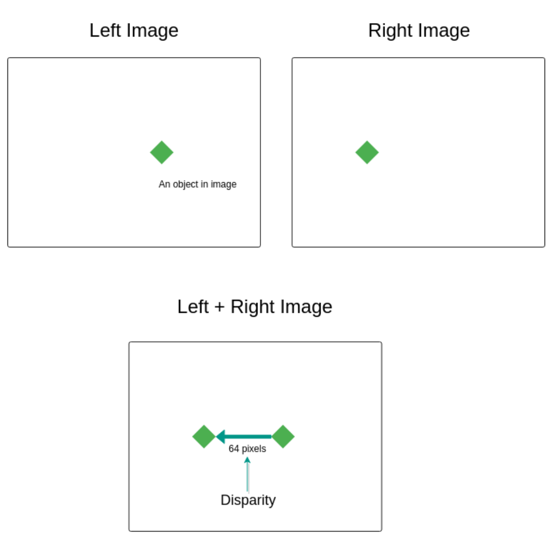


Figure 2. Stereo Disparity to form Stereo Vision

Time of Flight

Time of flight here means the time taken by light to travel a given distance. This type of camera work as they estimate the distance to an object based on the time taken by the light emitted to travel back from the object's surface. This type of camera is composed of a laser sensor, a light source and a depth processor so that it can capture the reflected light from the object. The light source, such as a laser or an LED, is responsible for actively illuminating an object. A sensor that is sensitive to the laser's wavelength is used to capture the reflected light. It would also measure the time delay between emitting light and receiving light and this delay is proportional to twice the distance between the camera and the object. Figure 3 is an illustration of this type's camera.

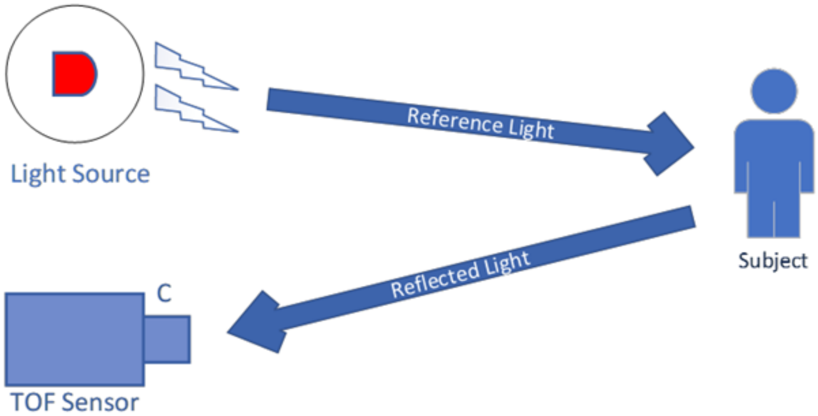


Figure 3. Illustration of ToF Camera

Structured Light

The structured light method would project light patterns(usually striped patterns) to the object by using laser or LED light. As shown in Figure 4, it would then capture the image and calculate the depth information based on the distortion of the pattern. This method is very suitable for 3D model reconstruction and capturing details of relatively close objects.

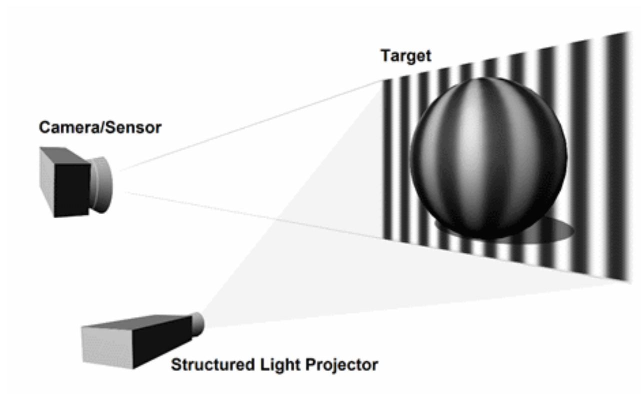


Figure 4. Illustration of Structured Light Modeling

Active Gated Imaging

Active gated imaging is based on 1) pulsed illumination and 2) a fast gated camera. Via synchronizing these two parts in time, we are able to selectively capture the images from some certain distance.

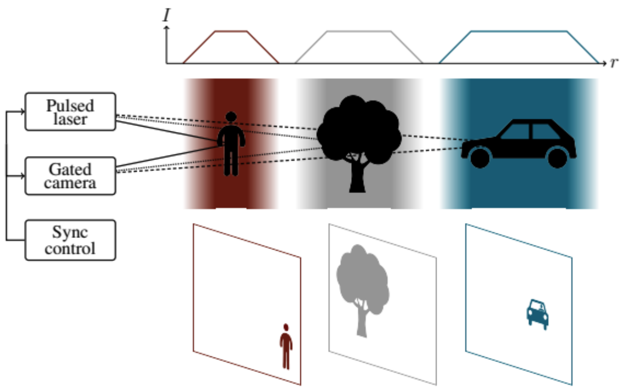


Figure 5. Diagram of the active gated imaging system Ref 3.

As shown in Figure 5, the illumination system will generate a near-infrared laser pulse. Considering the speed of light is known, precisely controlling the gate of the camera, we can only capture the reflected near-infrared light within a controllable and small window. In this way, by careful design of the synchronization, images of different known distances can be obtained.

Sharpness

Sharpness would be one important parameter we utilized to quantify the clearness of the object in our captured images. Sharpness describes the clarity of details in a photo and can be a valuable tool to judge textures. Sharpness is usually defined by the boundaries between zones of different colors. It is a parameter that is mostly visible on objects' edges in images and can be measured by edge response. [2] In our case, we would calculate the sharpness as a function of its Laplacian and normalize it by the local average luminance in the surrounding pixels.

$$SH = \sum_{x,y} \frac{LP(x,y)}{\mu_{xy}}, LP(x,y) = \frac{\partial^2 L}{\partial x^2} + \frac{\partial^2 L}{\partial y^2}$$

Sharpness would be one of the parameters we rely on to determine the clearness of objects captured at different depths by the Brightway sensor in this project. Figure 6 shows an example of the comparison between brightness and sharpness images.

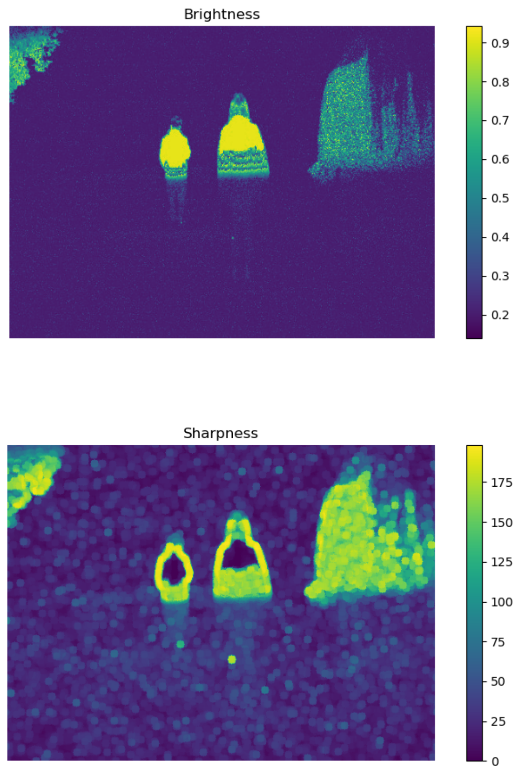


Figure 6. Example: three people separated by 6 meters with the center person located at 10 m away from the camera (captured at 10-46 range).

The upper image is the brightness while the lower image is the corresponding sharpness image

Contrast of Brightness of the Object to the Background

Brightness is the measurement of how much light appears to shine from objects. For depth sensors, objects at different distances away would reflect different amounts of light and thus result in different brightness in the images. For example, further away objects would look darker(small brightness) compared to closer objects as shown in Figure 7. We can see that the three people on the right are closer to the camera compared to the two people on the left since they have a brighter color in the image. On the other hand, since different textures of objects(three people wearing different clothes in our case) would influence the reflecting of lights and thus cause the relationship between distance and brightness to change a lot, we would set up the background's brightness as a basis. What we would eventually use to compare brightness is actually the contrast of an object to its background. In our case, the background has a relatively constant color and thus brightness as well.

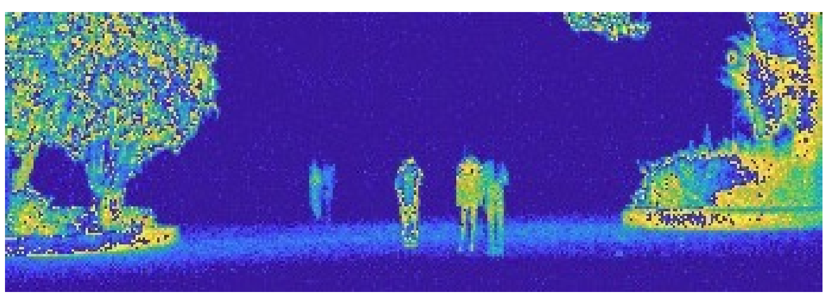


Figure 7. Example of Different Brightness at Different Distances

Brightway Depth Sensor Principle

The Brightway Depth Sensor, the device we experiment within this project, is one of the time of flight depth sensors as introduced above. Figure 8 shows the manual mode panel of the Brightway Vision System Control, which is the software that can be used to adjust the depth sensed by the camera. The system has an automatic sensing mode which the software would adjust the depth aim to measure based on the image it captures continuously. In this case, since we want to calibrate the sensor, we would manually select the distance range. The range slicing has minimum distance and maximum distance as two of its parameters. For example, for the first slicing which is 0m to 36 m, the sensor would adjust its time of flight accordingly to sense objects from 0 to 36 meters apart from the camera. It would send out a light, wait for the time light travels to the object within this range and then travel back, then let the camera capture image quickly and then record the image. By repeating this behavior constantly, the sensor can capture video within this distance.

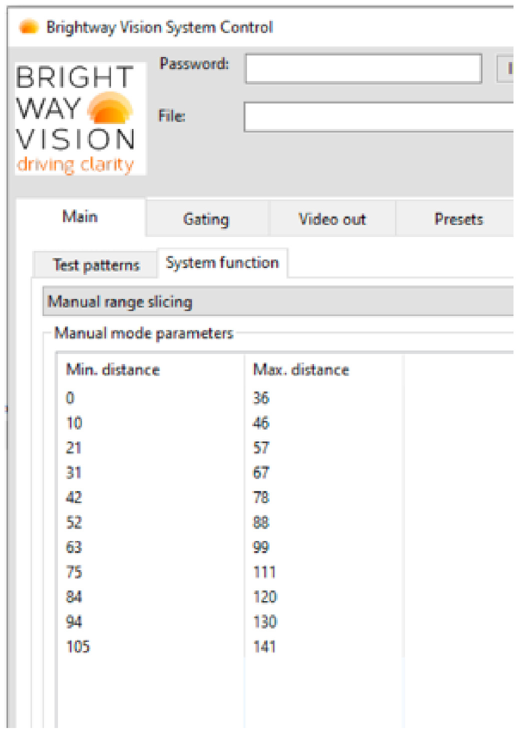


Figure 8. Brightway Vision System Control Manual Mode Panel

Results

There are three tests we performed to experiment with the accuracy of depth sensing and the performance under the fog condition of the device. They are distance test, depth range accuracy test and fog test. The introduction and results of them are shown below.

Distance Test

We filmed one person with one whiteboard in front of him at a distance of 30 m away from the camera with all manual range selections chosen once to see plot the depth spread spectrum of the sensor (in the center of Figure 9, there was one person holding a whiteboard). Figure 9 was taken by camera from the phone. Figure 10 was taken by the Brightway sensor with a sliding option from 0-36m to 94-130m ranges separately. We can see that compared to the photo taken by the phone camera, the sensor's camera seems to have s smaller wide angle and thus maximizes the objects a bit. The object in the sensor's images seems to be closer compared to the one in the first image. Besides that, we can also see that the object has the highest contrast with the background in the image with a 21-57 depth range. It has lower contrast in the 0-36m range and disappears in the 42-78m range one. In the last image, the object is still there as we can see the shape of the person. However, its brightness is the same as the background as the sensor is trying to ignore it and film the objects within a further range.

Figure 9. Object Scene Taken by Phone Camera

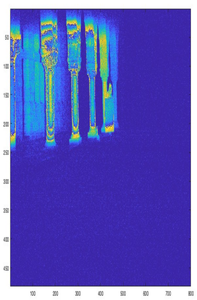
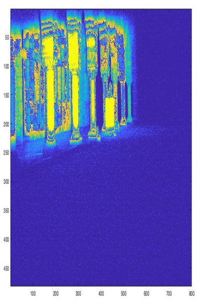
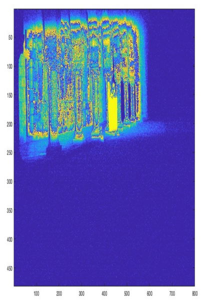
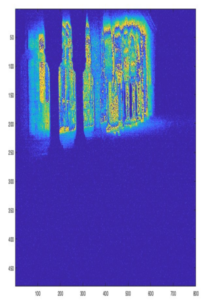
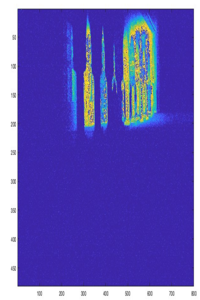
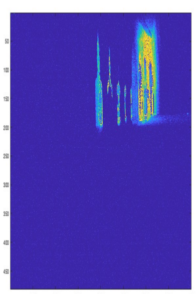
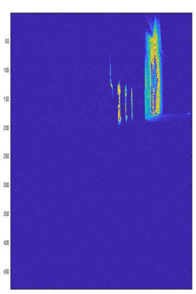
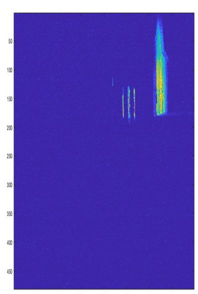
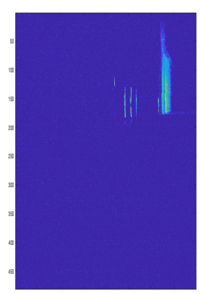
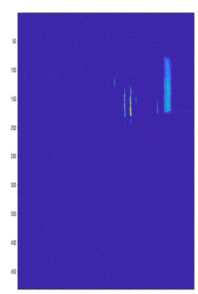
0-36m	10-46m	21-57m	31-67m	42-78m
				
52-88m	63-99m	75-111m	84-120m	94-130m
				

Figure 10. Imaged captured at different gating ranges

We would also plot the depth spread spectrum to demonstrate the object's contrast with the background's change as we change the depth slicing, which are shown in Figure 11 and Figure 12.

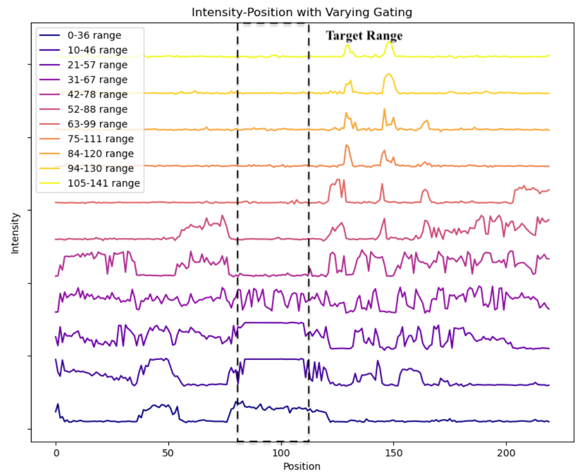


Figure 11. Intensity-Position relation at different gating ranges. The black dashed line denotes the position range of the whiteboard.

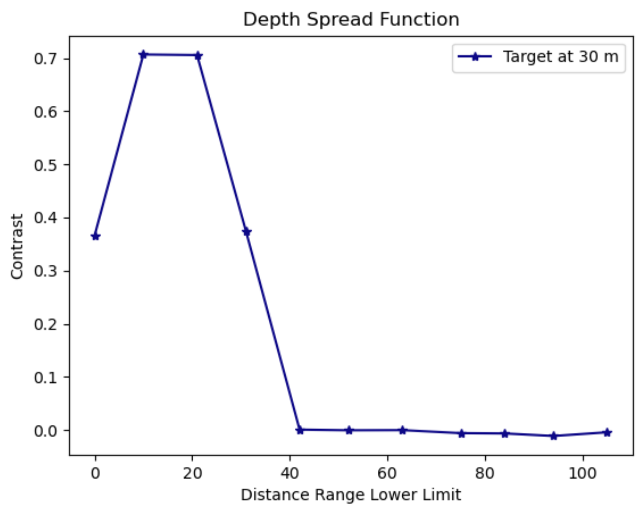


Figure 12. Depth spread function: the relationship between the contrast of the whiteboard and the lower limit value of the distance range.

The contrast is calculated by [(*the average intensity of the whiteboard*) - (*the average intensity of the background*)] at different distance ranges.

Depth Range Accuracy Test

The goal of the depth range accuracy test is to see how hard and accurate the manual selecting ranges are. We filmed two different groups of photos for this test. The first one is that we picked several ranges from the list, let one person stand at a distance within the edge of the range, let another two people stand a certain distance a bit closer or further away from the first person, and then took the photo. For example, when we picked the range 10-46m, in our first image (Upper picture of Figure 13), we let one person stand 10 meters away from the camera and two other people stand 7 meters and 13 meters away from the camera. So, ideally, if the depth range is super accurate and hard, we should be able to see the people 10 meters and 13 meters away but not the person 7 meters away at it is out of the range. We have also widened the distance between people to 6 meters to test the range accuracy. The upper picture of Figure 13 is people standing 13m, 10m and 7m away with 10-46m mode selecting. The other picture of Figure 13 is people standing 16m, 10m and 4m away. We can see that as a person standing at 4m, the image becomes much vaguer as it is out of the range.

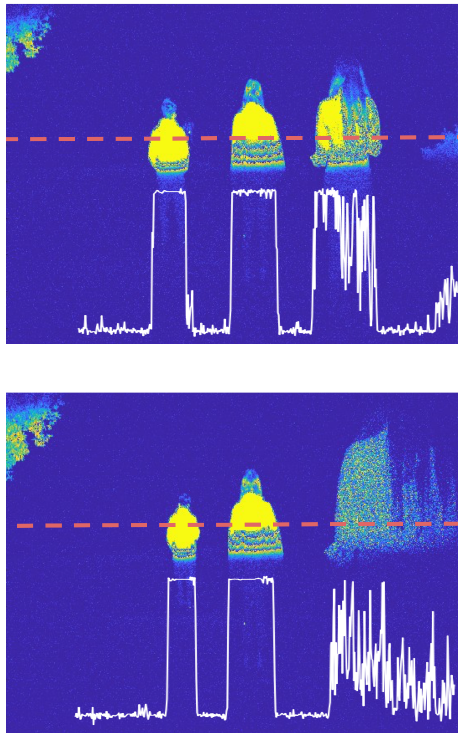


Figure 13. The first image is with 3 m separations while the second one is with 6 m separations.

The white lines illustrate the intensity at the red line level.

The second group of images filmed (Figure 14) is the images of the pillars and arches at the quad of Stanford. These pillars are separated by 4.27m(14') from each other and they are strictly aligned in a standard way which makes them great objects to the film. Figures of filmed pillars with different ranges selected are shown below.

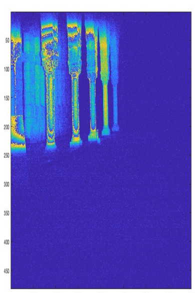
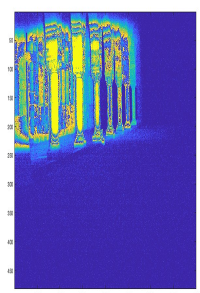
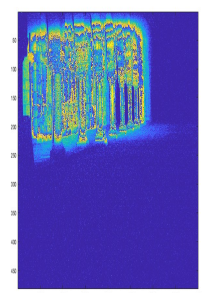
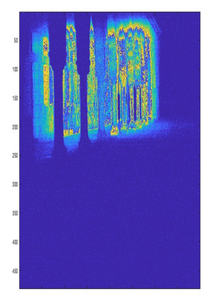
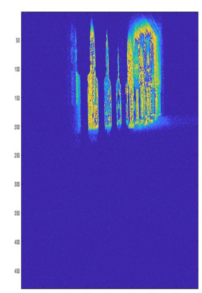
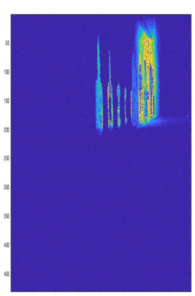
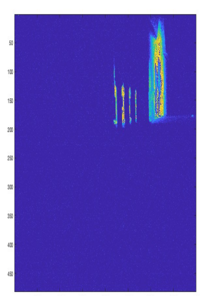
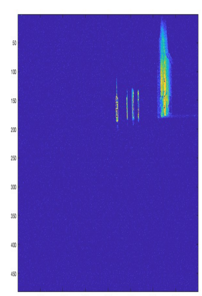
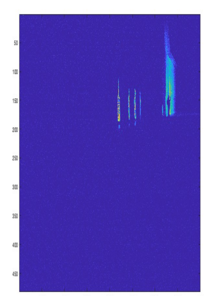
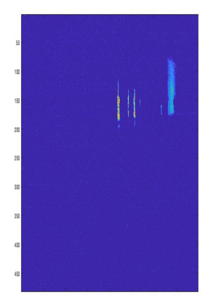
0-36m	10-46m	21-57m	31-67m	42-78m
				
52-88m	63-99m	75-111m	84-120m	94-130m
				

Figure 14. Images captured at different gating ranges.

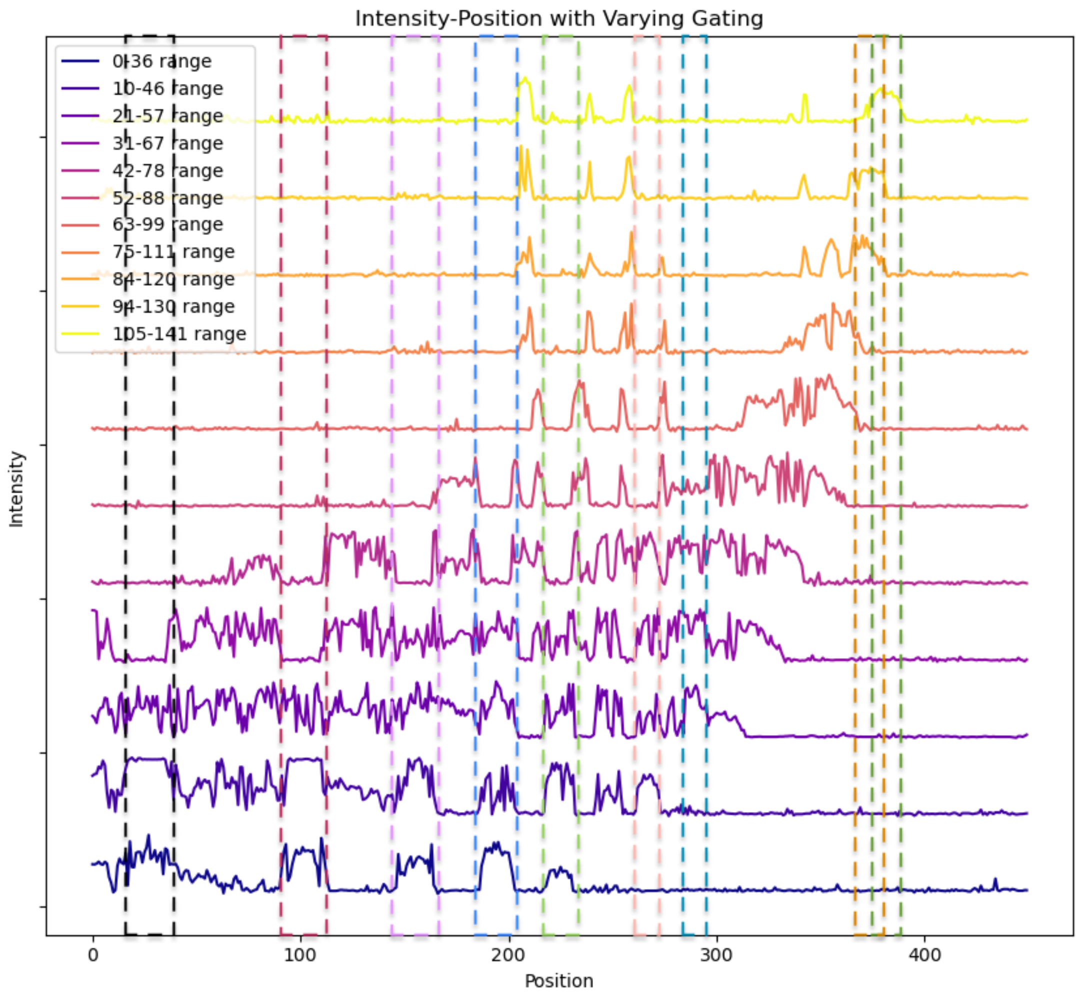


Figure 15. Intensity-Position relation at different gating ranges. The different colored dashed line denote the position ranges of different columns. The distance as increasing from left to right.

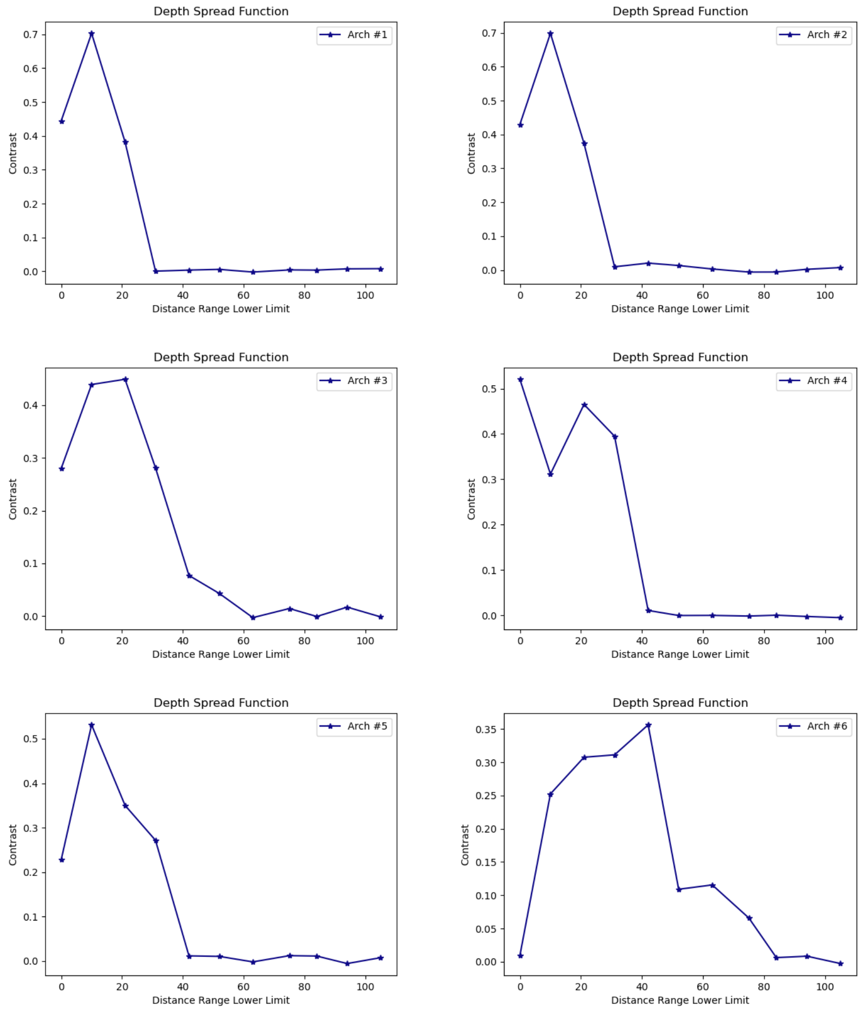


Figure 16. Depth spread function for the first six columns. The definition of contrast is the same as in Figure 12.

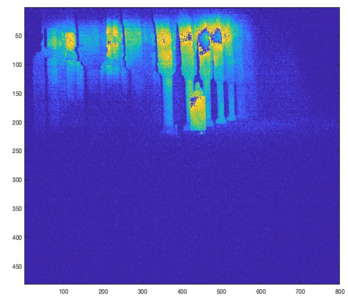
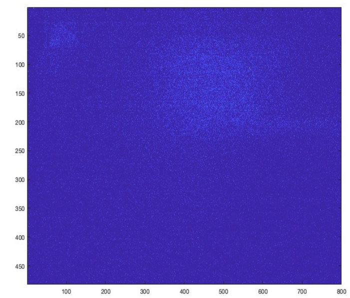
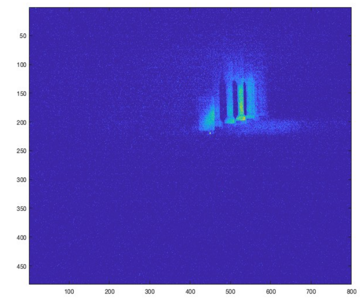
Fog Test

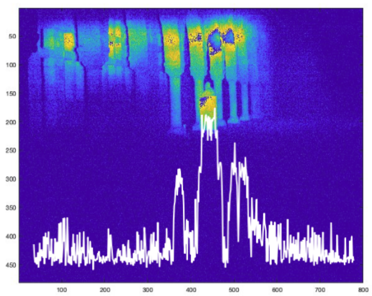
Lastly, we also performed a fog test by creating fog in front of the camera to see how the sensor performed under fog conditions. Fog Worx$_{TM}$ was used to generate fog in front of the camera. Figure 17 is a phone photo showing the fog in front of the illumination system and camera.

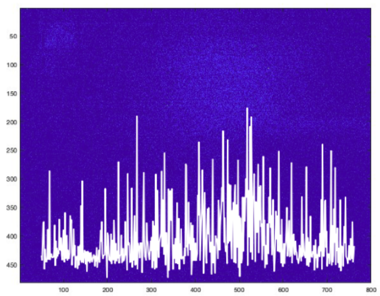
Figure 17. Phone image of the fog situation.

Active gated imaging system intrinsically has the advantage of minimal interference by scattering effect that will increase the light path and travel time accordingly. This is to say, for some extreme weather conditions (e.g., fog, smoke, etc.), theoretically, this active gated imaging system will perform the same. As an application, when the device is actually applied on vehicles, being able to identify objects under fog conditions can help with computer vision a lot.

We filmed one person as an object within the time that the fog machine start to create some fog, lots of fog was created in front of the camera and the fog disperse but has not disappeared lately. We also plotted the intensity on the IR images. When fog starts to form or fog is dispersing, there is still some decent signal from the object. However, when there is a lot of fog in front of the imaging system, the image almost captures nothing, as shown in the middle figure.

Fog Start to Form	Lots of Fog	Fog Disperse but not Disappear
		





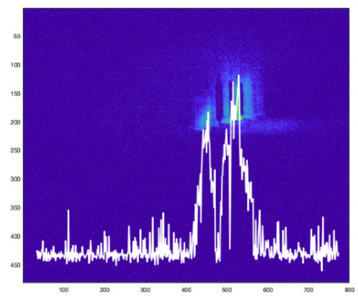


Figure 18. Images captured at different fog densities and the corresponding intensity lines.

Limitation of Device and Experiment

Discussion of some limitations of devices we found during the experiment.

Indoor Sensing

When we test taking a photo indoors in a corridor, the image is quite over-saturated everywhere. The reason is that the small space reflects the infrared light a lot so the sensor has no idea how long it takes for each light to come back. An example indoors with strong saturation is shown below.

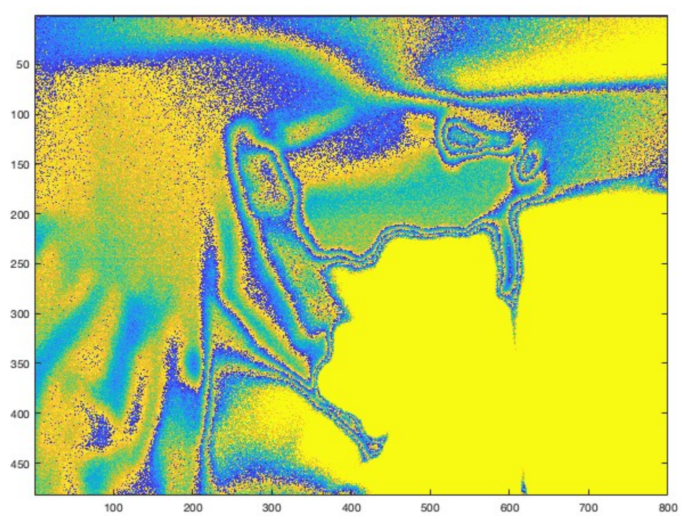


Figure 19. Indoor Experiment Image

Control of Fog

We use a small fog machine to create fog to simulate a foggy environment. However, since the machine can only create a small amount of fog in a small space, in our fog experiment, we only create fog in front of the camera. This is not ideal to simulate the fog environment and the fog we created each time is different due to the wind. As we can see from the following two photos, we can't control the fog to be identical in each round.

Figure 20. Fog Conditions

Conclusions:

The Brightway Imaging System is an active gated camera with pulsed near-infrared laser illumination. When we tested it on campus at night, it has a depth resolution of around 10 meters and an imaging range of around 10 - 140 meters. Compared to traditional RGB camera, the near-infrared active gated camera demonstrates the huge advantage of depth sensing and the ability to see in extreme weather conditions. This imaging system will capture more information on the road for the vehicles. However, there is still one big problem needs to address: the interference of near-infrared light. This interference can happen in different conditions: 1) reflected infrared light from itself. For example, if the system is used in a tunnel, the reflected/scattered infrared light will greatly decrease the signal-to-noise ratio. 2) infrared light from others. For example, if there are many vehicles using the same system that pulses near-infrared, it will become problematic for the computer to process the images.

In general, Brightway is a relatively novel imaging system that gains some depth information at the cost of intensity. We believe active gated cameras just need a proper niche to fully take its advantage before it can thrive in the market.

Reference:

1. https://www.e-consystems.com/blog/camera/technology/what-are-depth-sensing-cameras-how-do-they-work/#:~:text=Depth%2Dsensing%20means%20nothing%20but,to%20it%20on%20the%20go.

2. https://www.imatest.com/docs/sharpness/#:~:text=Image%20sharpness%20can%20be%20measured,distance%3B%20see%20Figure%203).

3. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8569590