

Sensor Performance Characterization for Use on a Micro Aerial Vehicle

Anish Raghavan

Advisors: Frank Shen, Dr. Vijay Kumar

This paper details the characterization of the Hokuyo UTM-30LX and the Xbox Kinect for use on a Micro Aerial Vehicle (MAV). The MAV is to be used for the exploration of unknown territories, and thus must be able to localize itself in various different conditions. To accomplish this, both the indoors and outdoors performance of the sensors are examined with different objects in their immediate surroundings.

The characterization begins with tests using objects with different surface properties and in different indoor lighting conditions. Furthermore, tests are conducted indoors to see how the data received by the sensors is distributed. Hence, the results show how the data can be interpreted using a probability distribution in software to aid exploration algorithms.

The same characterization is carried out outdoors to compare the data. The effects of sunlight on the sensors is noted. Then, further experiments allow us to determine the conditions in which the data from each sensor are not likely to be trustworthy. We can make the quadrotor ignore these values when exploring.

Finally, we show the initial part of an experiment conducted to test how information gained from the characterization can be used to optimize motion estimation. We continue to work on the the rest of the experiment beyond the submission of the paper.

1. INTRODUCTION

Autonomous aerial vehicles require much more control than autonomous ground robots. The movement of ground robots is generally only in the x-y plane and has three degrees of freedom $\{x, y, \theta\}$. On the other hand aerial vehicles travel in three-dimensional space. Due to the extra dimension, aerial robots have six degrees of freedom to contend with. The extra degrees of freedom are problematic and no one sensor is able to determine 3D movement with high degree of accuracy. This means that the robot needs to fuse data from multiple sensors in order to get a view of its pose and surroundings.

In order to get a sense of the pose of the robot, we use six variables. The variables are x-displacement, y-displacement, z-displacement, roll, pitch and yaw $\{x, y, z, \theta, \varphi, \psi\}$. The quadrotor we are using contains three sensors: a laser range finder, a Kinect sensor and an inertial measurement unit (IMU). As each sensor has a different mode of operation, each gets a reading of a different subset of the six variables. Since no sensor can be 100% reliable in all the measurements it makes, there is an overlap between the values measured by each sensor.

The laser range finder measures distance of objects in its local 2D frame. When fused with data from the IMU, these measurements can be used to calculate the $\{x, y, \varphi\}$ positions of the robot indoors. The Kinect gets data in the form of a depth point cloud. When this is fused with the IMU data, it can calculate the $\{x, y, z, \theta, \varphi, \psi\}$ positions of the robot. Since there is no sensor like a GPS on the quadrotor to provide global coordinates, mapping and localization will all be relative to the origin. This is not a problem in most situations as the origin is usually known. The data can then be translated from the robot's frame into the world frame.

The IMU measures the displacement and tilt of the robot directly. It has an accelerometer to measure the linear displacements, a gyroscope to measure the roll & pitch and a magnetometer to measure the yaw. The problem, however, is that the IMU measures the changes of the various variables. Therefore, any errors in the change of the variables are added to the measured variables. As a result, though the errors are only small, they are incremental and after a few seconds the state of the robot cannot be determined accurately using the IMU alone. For this reason, data from the IMU must be fused with data from the other sensors as shown by Grzonka et al.[1]. While this paper does not deal with characterizing the IMU, it is important to know that the aim is to characterize the laser scanner and Kinect for use in conjunction with the IMU.

As explained earlier, data from a number of sensors must be fused to form a unified view of the pose of the robot. Since there is overlap between the sensors, we must be able to build a model of how accurate each sensor is under different conditions. With this information the robot will be able to determine which data makes sense in which conditions.

From the point of view of the robot, raw data is received and must be interpreted based on the behavior of the sensors programmed into it.

Thrun[2] proposed a model for robots to interpret data from range sensors. The model (shown in Figure 1) proposes that given a measurement from a sensor, the probability of the distance from the robot can be divided into four parts.

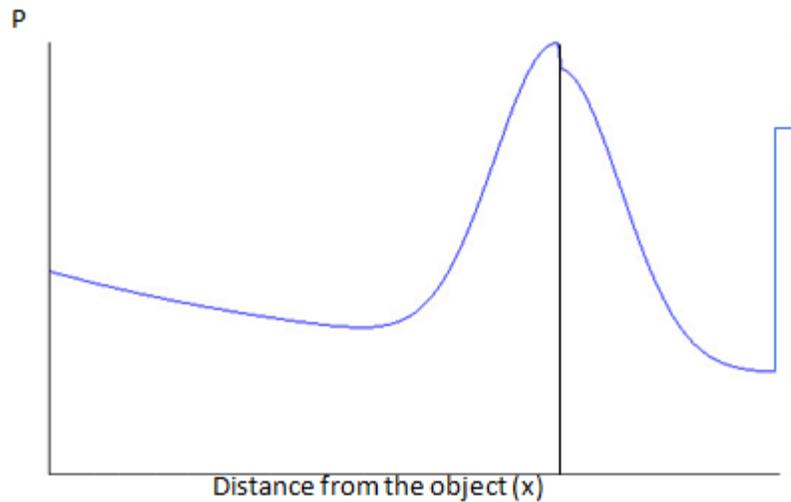


Figure 1: Thrun's beam model

- A Gaussian curve around the distance of the object
- A small distribution at z_{max} where the sensor misses the measurements
- A random element contributing equally to all values
- An exponential decay portion for unexpected obstacle

We aim to make models like Thruns to enable our sensors to interpret data correctly.

In this report, we aim to characterize the performance of two sensors (the Hokuyo UTM-30LX and the Xbox Kinect) on the quadrotor to improve its pose estimation. In Section 2, we discuss the operation of the sensors and the usual method used for sensor fusion. Section 3 shows the results from previous works, Sections 4, 5 and 6 contain the results of our experimentation and Section 7 introduces one way we used the data collected to help in motion estimation.

2. BACKGROUND

2.1. The Hokuyo UTM-30LX Laser Range Finder

The Hokuyo laser range finder consists of a laser emitter and a rotating mirror as shown in Figure 2. The rotating mirror rotates by 270° with a resolution of 0.25° to send the laser at all those angles to obtain a full view of the area in that part of the view of the sensor[3].

The laser beam reflects off objects and

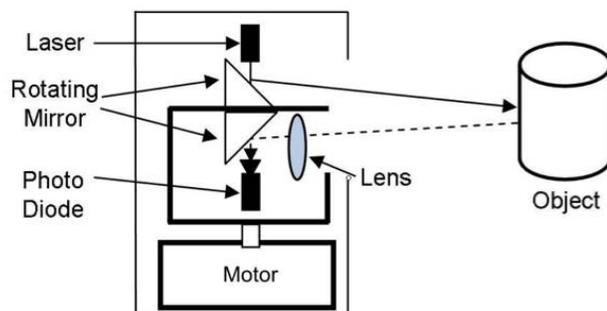


Figure 2: Operation of Hokuyo range finder[4]

returns to a photo diode in the Hokuyo sensor. The sensor measures the time taken for the beam to return. Since the speed of the beam does not change much (it remains at the speed of light), the time of flight is proportional to the distance of the object.

The readings from the laser range finder depend on the conditions of the measurements. Depending on the medium, the laser will travel a different way. Under normal conditions, the laser beam will travel straight through the medium. However conditions like smoke, rain and snow can cause dispersion of the beam[5]. This reduces the intensity of the beam and the reflection might not be able to reach the photo diode. As a result there would be no reading for this measurement.

Theoretically, the laser beam transmitted has no thickness and the angular deflection off it is zero. The beam would reflect off the object and return to an infinitely small receiver. This does not prove to be the actual case. When the laser beam leaves the emitter, it has a slightly conical shape. When it strikes the surface, the beam has an elliptical interaction with it [6]. The entire elliptical part of the beam reflects off the object to return to the diode. The value measured by the diode is the average of the distance to all points in the ellipse.

As a result of the conical feature of the laser, the further the object is, the bigger the ellipse will be. A larger ellipse causes the range of measurements made to increase as well. Consequently, the standard deviation of the range data will increase as the distance to the object increases. The other factor that increases with distance is the number of failed measurements. A failed measurement is caused when (for some reason) the reflected laser beam does not reach back to the diode. This could be due to the fact that the object is too far away causing the laser to diminish before returning or the return of the beam is being obstructed by an obstacle.

Overall, the laser scanner produces a relatively accurate depth image of the surroundings. However, the image will just be a 2D depth image. the quadrotor would have no knowledge of its height and what is above or below it. In order to provide the quadrotor with this information, the laser range finder is fitted with mirrors on either side. One is turned 45° to send the laser upwards and the other is turned 45° the other way to send the laser downwards. With these, some of the laser beams will reflect off the mirrors to give the quadrotor an idea of the distance to the floor and ceiling.

2.2. The Xbox Kinect

The Xbox Kinect works on the principle of binocular disparity in order to find depth data. The Kinect has an infrared(IR) projector that projects a dot pattern of IR light on objects in its field of view. An IR camera positioned a slight distance away is separate from the projector and views the position of the dots. Depending on where the dots are formed, the disparity (d) is detected.

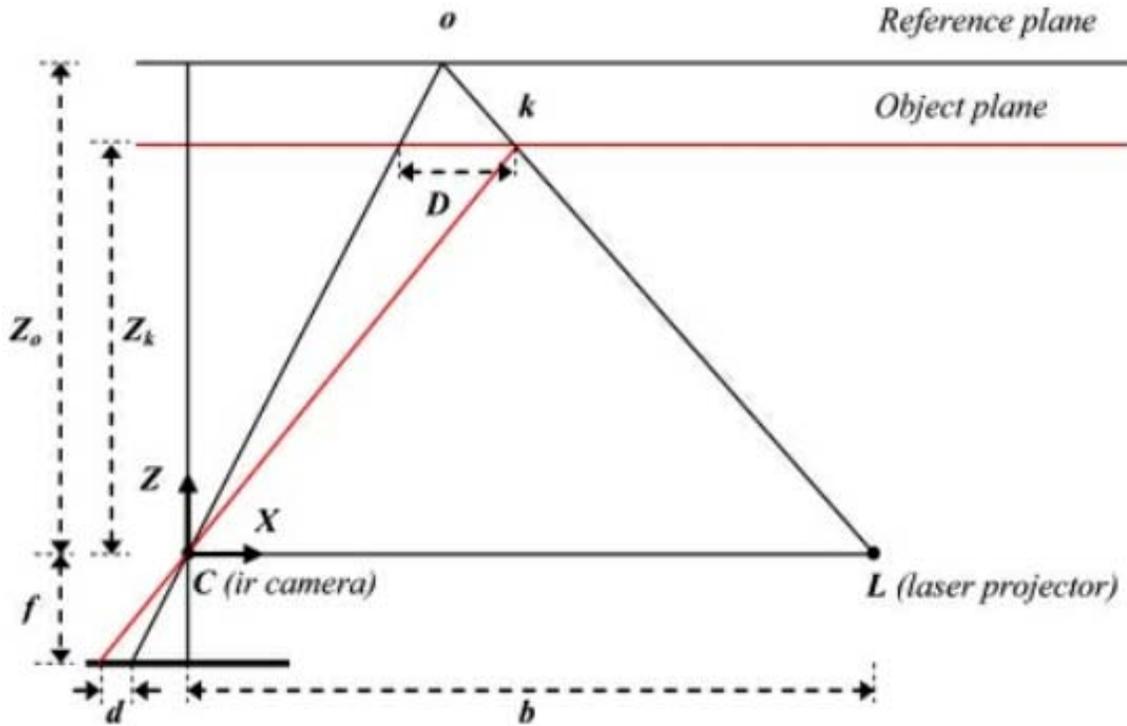


Figure 3: Distance measurements from disparity[7]

To calibrate the Kinect, there is a reference plane at a specified distance from the Kinect. At that distance, the IR camera observes each dot at a certain point, a distance f behind the surface of the camera. This is kept as a reference point for that dot. When a new object is to be sensed, the IR camera will see the IR beam hitting the object at a different point as shown in Figure 3. At f behind the camera, the reflection is created d away from the reflection of the same point off the reference plane[7].

From the diagram in Figure 3, we can see the depth information (Z_k) can be resolved mathematically. There are two sets of similar triangles. From them we can state[7]:

$$\frac{d}{D} = \frac{f}{Z_k}$$

$$\frac{D}{b} = \frac{Z_0 - Z_k}{Z_0}$$

Therefore, the depth data (Z_k) can be expressed in terms of the calibration parameters and d

$$Z_k = \frac{Z_0}{1 + d \left(\frac{Z_0}{fb} \right)}$$

As seen from the calculations above, the Kinect strongly relies on calibration with a reference frame. All depth data received from the Kinect is relative to this reference depth

Due to the limited width of view of the camera, there will only be a limited range of disparities that can be measured on either side of the reference depth. This means that the Kinect can only get a short depth measurement and is rendered useless in wide open spaces.

2.3. Sensor Fusion

The data from the laser range finder and the Kinect are particularly useful if used in conjunction with the IMU. A common tool used for sensor fusion is the Kalman filter[8]. When the quadrotor moves, the robot will make a prediction of its location using the IMU. Then, the measurement taken by the laser range finder or the Kinect is used to adjust the prediction to get a better prediction of the location of the robot.

3. PREVIOUS WORK

3.1. Effect of Surface Properties of an Object

The surface properties of an object have a greater effect on the laser range finder readings than the Kinect readings. The following experiments have been conducted by others for laser scanners. While their experiments have not been conducted using the same Hokuyo sensor that we are using, they still describe the nature of the interaction of the laser beam with different surfaces.

3.1.1. Roughness

Rough objects cause reflections in all directions, while smoother objects cause only direct reflections. Direct reflections do not work well for the laser range finder. When the laser beam impacts the object at an angle, very little light would reflect back to the object. We deal with a very smooth surface (glass) in Section 6 and see that the laser range finder only has a limited field of view when pointed towards the glass.

3.1.2. Reflectance

The reflectance of an object has an effect on the intensity of the reflected laser beam. Luo et Al.[5] explain that when the laser hits a highly reflective object, specular reflections are caused. This saturates the photo diode which causes the object to appear to be closer than it is. On the other hand when an object is not reflective, it slows down the return beam and causes the object to appear to be further away.

In the context of exploration using our quadrotor, object reflectance does not play a huge part as most objects encountered have a dull finish. This will be discussed in more detail in Section 6.

3.1.3. Color

Knierp et al.[3] have done experiments with different color sheets to show the difference in the laser range finder measurements. As can be seen from Figure 4, the mean measurement from all the three color sheets shows the object as being closer than it actually is. We can also see that the spread of the measurements is different for the three colors.

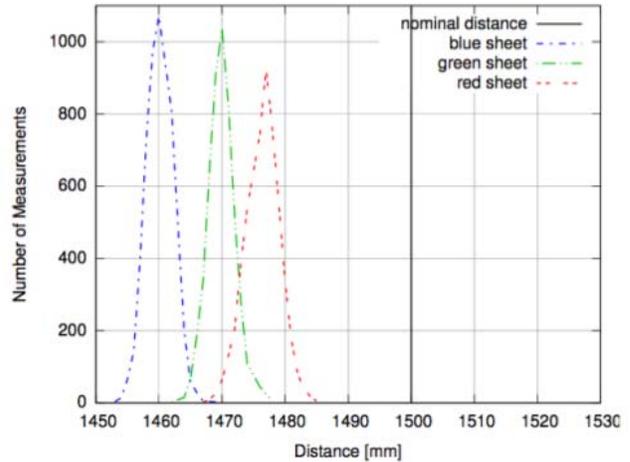


Figure 4: Difference measurements to different color sheets[3]

3.2. Effect of Angle of Incidence

When the laser beam strikes an object at an angle, the main part of the beam deflects away from the photo receptor of the laser scanner.

Smaller reflections are caused in all directions. Hence, the standard deviation of the distribution around the measured point increases. Knierp et al. thoroughly describe how the angle of incidence impacts the laser measurement. Depending on the surface, the laser range finder only has a certain field of view (outside that field of view the laser beam deflects away and the value returned is not accurate). The field of view reduces as the smoothness of the object increases.

We performed an experiment to see whether the angle of incidence of the laser beam affects the mean measurement using our laser range finder. The set up of the experiment can be seen in Figure 5. We used a typical indoor wall. The measurement that strikes orthogonal to the wall is taken to be the actual measurement (z_0). If this result is accurate, when the incident angle on the same wall is θ , the measured distance should be:

$$z = z_0 \cos(\theta)$$

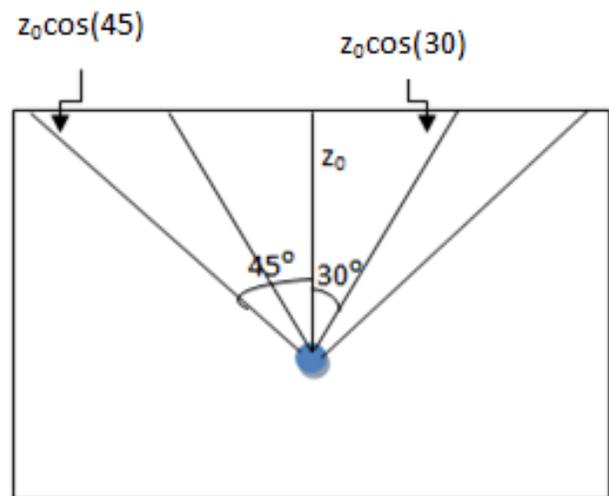


Figure 5: Experiment setup to test the effect of angle of incidence on the laser range finder

Figure 6 shows the measurements (the 'x's) plotted upon the theoretical distance enumerated using (4). Since we used a small distance from the wall (70cm), and the wall was not a very shiny surface, we did not see any significant deflection of the actual measurement from the expected measurement. However, from previous work, we can see that it would make a difference for longer measurements and on shiny surfaces.

Our work with windows in Section 6 confirms this.

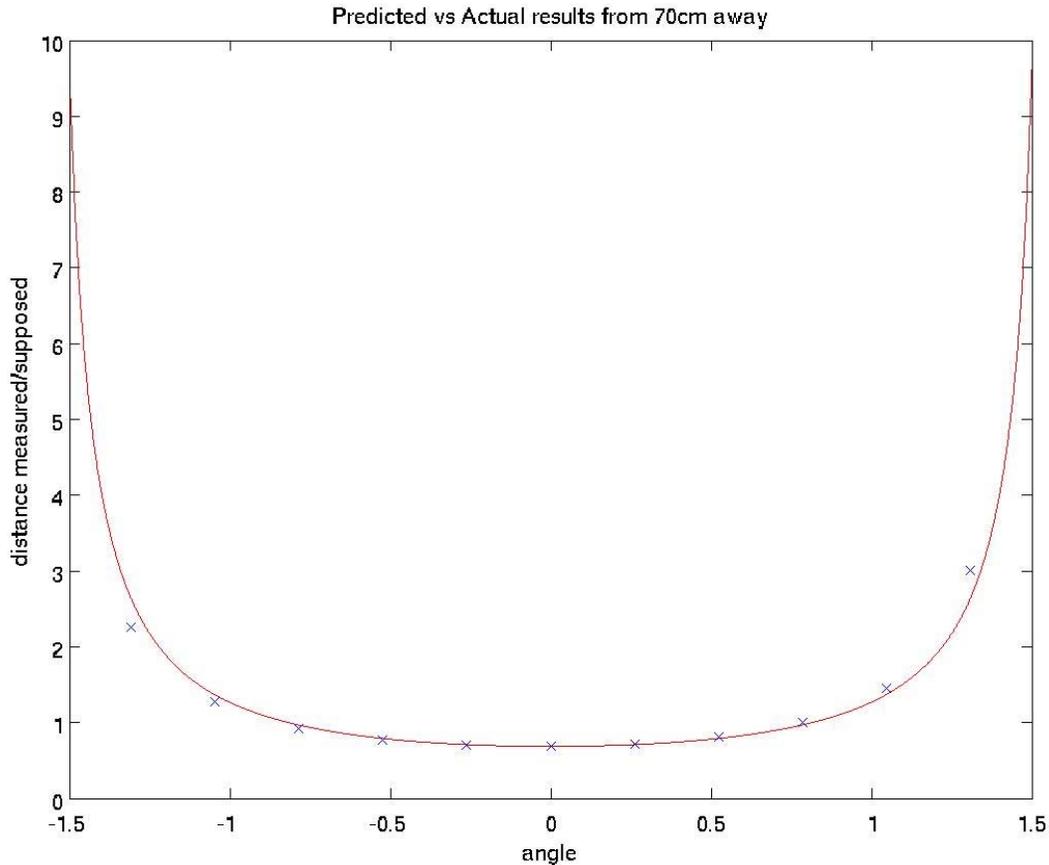


Figure 6: Distance measurements at angles

3.3. Effect of Smoke, Rain and Fog

Since this quadrotor is to be used for exploration in disaster relief situations, there is a possibility it would be needed in the presence of smoke, rain or fog. This causes trouble for the laser range finder as the particles in the air cause scattering of the laser beam. As a result, some of this scattered beam could return to produce a measurement much closer than the object is.

Most laser range finders use techniques to ensure that the measurement obtained is the actual distance to the object rather than the distance to the obstructing air particles. One method of

doing this is by measuring the time till the last pulse received[9]. By doing this, the laser scanner ensures that the distance measured is the furthest object detected.

3.4. Sensor Drift

Previous authors including Lee[10] have stated that drift in the measurement initially occurs when the laser range finder is turned on. After that, it settles down. Figure 7 shows the drift measured by Lee. Experiments we carried out were unable to categorically prove or disprove this with the Hokuyo scanner. The result can be seen in Figure 8. If there is any drift, the magnitude is very small and can be ignored.

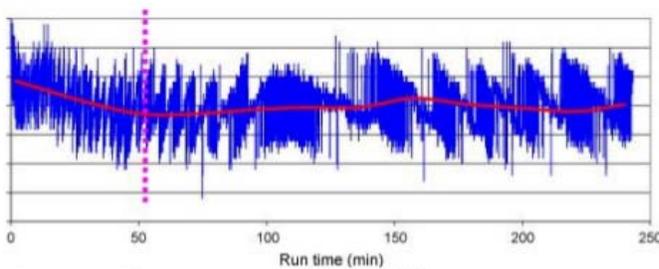


Figure 7a: Drift on power up as measured by Lee

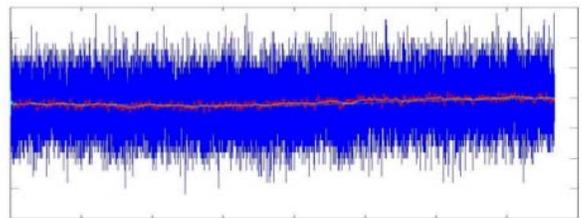


Figure 7b: Drift on power up as measured by Lee

4. MEASUREMENT CHARACTERISTICS INDOORS

4.1. Experimental Setup

The aim of this experiment is to find the spread of the data collected by the laser scanner and the Kinect at different distances from the object being measured.

The setup of the experiment with the laser range finder is shown in Figure 8a. The range finder is set up at a certain distance from the wall. A total of 1000 measurements are taken at each distance. The mean and standard deviation of those measurements are calculated. Using those results, we can plot the standard deviation of measurements vs the distance to the object. While the actual distance is not being measured in this experiment, we assume the actual distance is the mean of all the measurements. For the Kinect, we use a white sheet as the object to be viewed.

Since the accuracy of the Kinect is not as good as the accuracy of the laser scanner, it is necessary to use something to measure the actual distance from the white sheet. As can be seen from Figure 8b, measuring tapes are used to measure the actual distance from the object. We run two parallel measuring tapes to ensure that the Kinect is looking at an angle perpendicular to the white sheet.

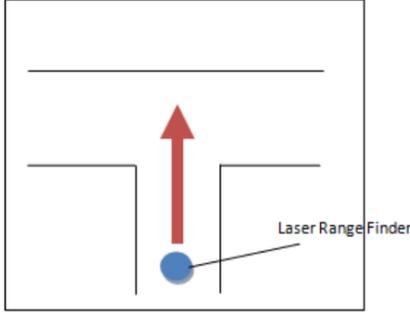


Figure 8a: Experimental setup with laser range finder

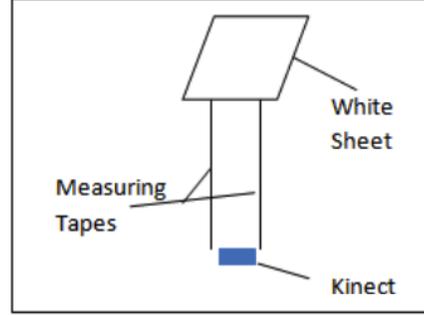


Figure 8b: Experiment setup with the Kinect

4.2. Standard Deviations

As objects get further away from the sensors, the standard deviations of the measurements increase. However, they do not increase in the same way for both sensors. The different modes of operation cause different types of increases in standard deviations.

When the experiment shown in Figure 8a was conducted with the laser range finder, the standard deviations increased linearly with distance from the object. The laser range finder uses the time of flight of the laser to measure the distance to the object. The distance measured is obtained by:

$$z = c \times \frac{t}{2}$$

The change of the spread of the measurements is caused by the slight variation of the speed of light. Since this is simply scaled by the time taken, the standard deviation increases linearly as the distance increases. This is seen from Figure 9.

The standard deviations for the Kinect, on the other hand, increase quadratically with distance from the object. This can be derived from the diagram of the Kinect in Figure 3. From Equation 3, we can write:

$$Z_k^{-1} = \frac{d}{fb} + Z_0^{-1}$$

However, for simplicity of mathematics, we would like to define disparity such that it is infinite when the distance is 0 and 0 when the distance is infinite. To do this we normalize:

$$d = md' + n$$

Therefore, we can write the following:

$$Z_k^{-1} = \frac{m}{fb} d' + \left(\frac{n}{fb} + Z_0^{-1} \right)$$

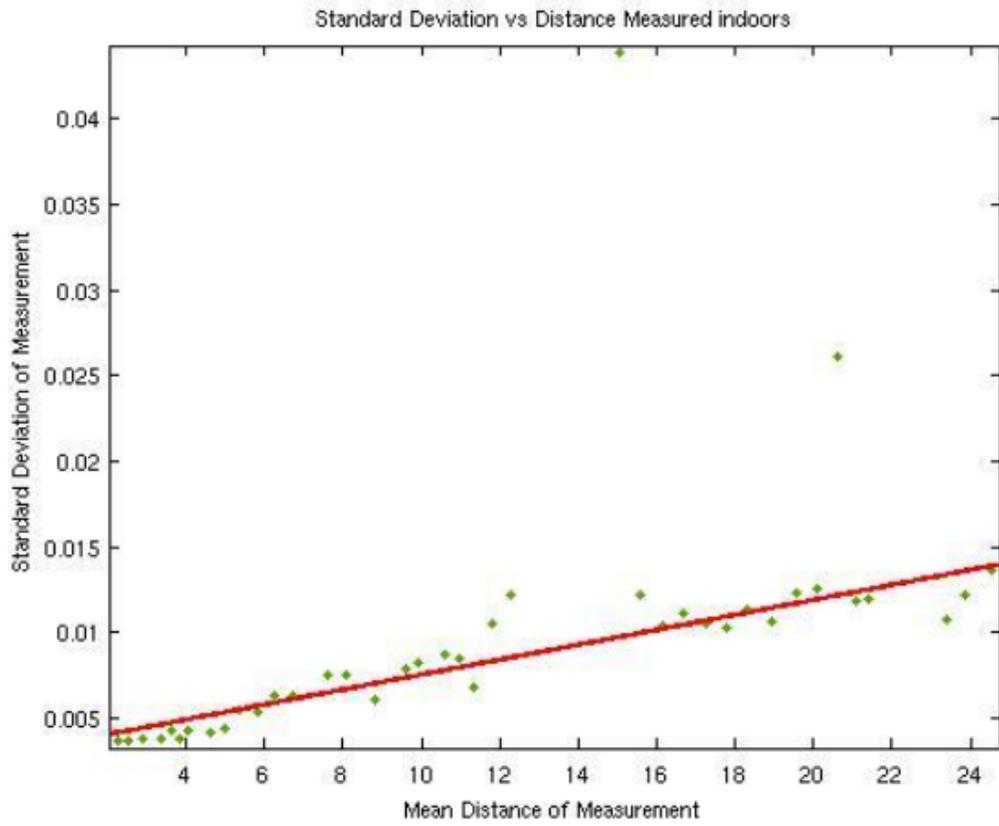


Figure 9: Standard Deviations of Laser Scan Measurements

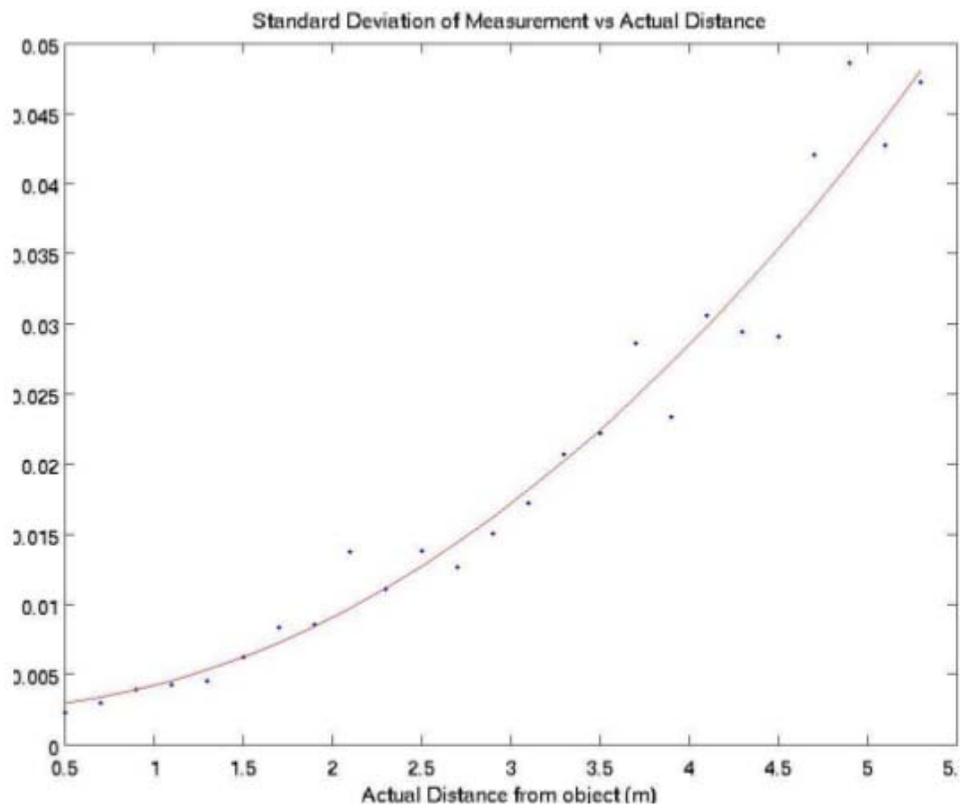


Figure 10: Standard deviation of Kinect measurements

From that equation we can derive the variance of the measurement:

$$\sigma_z^2 = \left(\frac{\partial Z}{\partial d'} \right)^2 \sigma_{d'}^2$$

Therefore,

$$\sigma_z = \left(\frac{m}{fb} \sigma_{d'} \right) Z_k^2$$

The quadratic relation between the standard deviation and the distance to an object can be seen from Figure 10.

4.3. Failed Measurements

There are times when a sensor will not sense objects in spite of their presence. This occurs in different situations with the two sensors.

The laser scanner does not seem to have any failed measurements in normal circumstances indoors with distances up to 25 meters. The only failed measurements are caused due to obstructions. Figure 11 shows the source of the failed measurements encountered. Since the laser does not travel as straight as it is theoretically supposed to, when something is in the way, it can block the return beam.

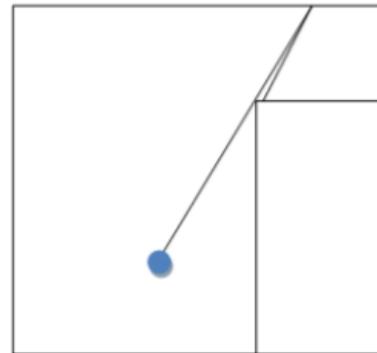


Figure 11: Object blocking the return beam of the laser scanner

The Kinect has different type of failed measurements. Since its measurements are based on the principle of disparity, the disparity must be measurable for the distance to be known.

When the object to be measured is too far, change in depth makes very little difference. Therefore, there is an upper limit to the distance measurable using the Kinect.

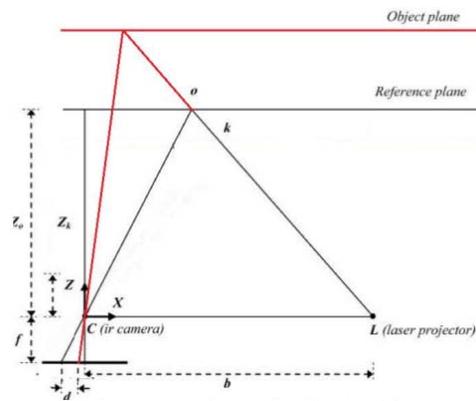


Figure 12: Object too far for Kinect measurements

Kinect measurements have a lower limit as well. When an object comes too close, the disparity will get too large to be measured as shown in Figure 12. Figure 13 shows two examples of how the object is seen when it is too close.

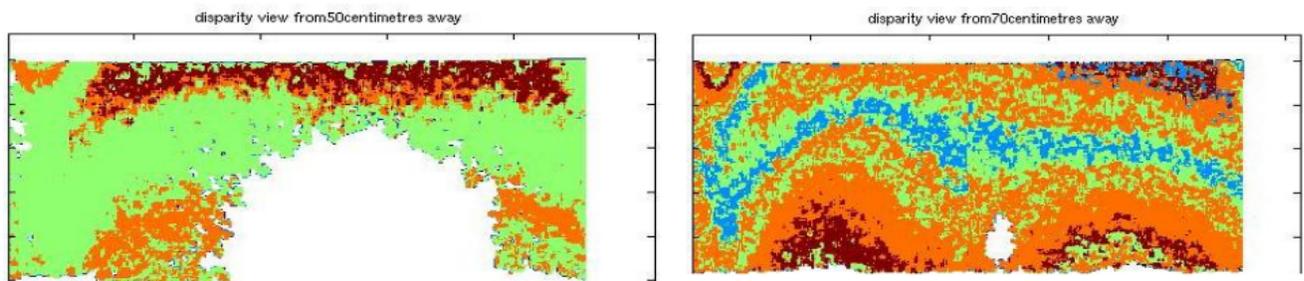


Figure 13: View of two objects 50cm and 70cm away with areas too close for the Kinect to see (white areas)

5. MEASUREMENT CHARACTERISTICS OUTDOORS

5.1. Standard Deviations

The same standard deviation experiment was performed outdoors with the laser scanner. At specific distances away, 1000 measurements were taken pointing towards a wall of the building. Due to the sunlight shining into the photo diode, the laser scanner can show erratic measurements.

As seen from the plot in Figure 14, up to 9-10 meters, the measurements from the laser scanner can be seen to be linear despite the effects of the sun. However, after that, the standard deviation increases dramatically.

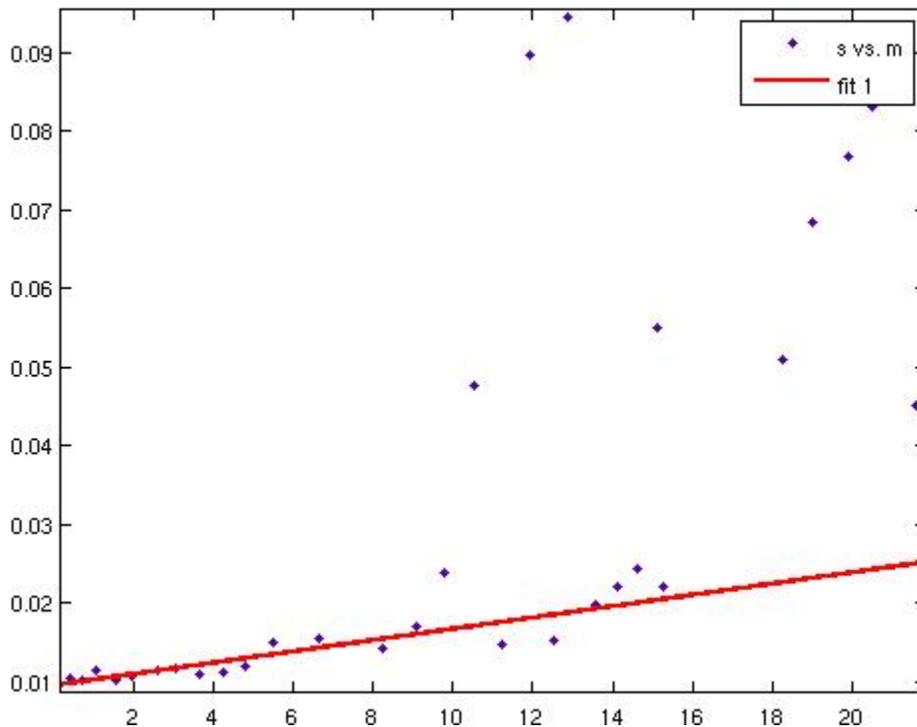


Figure 14: Standard deviations of measurements in the sun

5.2. Failed Measurements

Failed measurements can cause a severe problem when operating outdoors due to the effect of the sun on the sensors. The Kinect is extremely sensitive to sun rays. When the sun is present, all the distance values in the point cloud go to zero. This, coupled with the small range of the Kinect, makes it almost impossible to use to Kinect outdoors. Instead, the other sensors on the quadrotor must be relied on.

Outdoors, failed measurements are caused in the laser scanner due to the overpowering rays of the sun entering the photo diode. However, the laser scanner is not completely useless. Up to a distance of 10 meters, we have observed that the laser scanner has close to no failed

measurements. This is because the intensity of the reflection is strong enough to be detected by the diode. However, with larger distance, the intensity of the reflection is overpowered by the intensity of the sunlight.

With knowledge of these, the quadrotor can make better decisions based on the magnitude of the measurement received from the sensors.

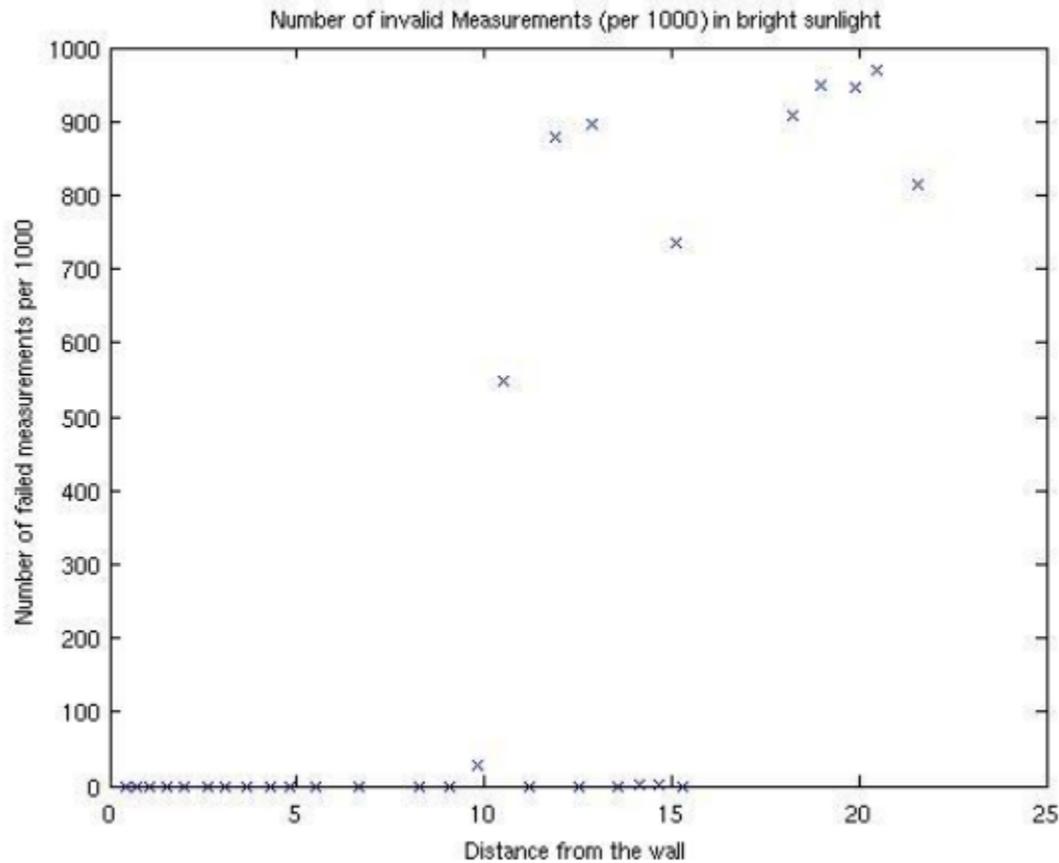


Figure 15: Number of failed measurements (per 1000) in sunny conditions

6. WINDOWS

Proper transitioning between indoors and outdoors is imperative for a quadrotor that is meant for exploration. Therefore, we must provide it with a way of recognizing closed and open windows. We conducted a series of experiments on windows to see how the sensors see them.

We performed our experiments on a double glazed glass panel that was part of a large window. The window separated a large, artificially lighted hall from a courtyard with little artificial lighting. The experiments aimed to find:

- The field of view of a laser scanner when looking at glass
- The effect of the surrounding light when viewing windows

- The difference between looking out and looking in

6.1. Experiment setup

The experiment was set up as shown in Figure 16. The vertex represents the position of the laser scanner, the red arrow shows the direction of the scan. The laser scanner takes a scan of 180 degrees in front of it. The smoothness of the glass limits the laser range finders field of view (see Section 3.2) . The red lines represent the field of view. In the experiment, we move the laser scanner to different distances from the glass and measure the field of view of the laser scanner.



Figure 16: Experimental Setup

6.2. Results

As mentioned before, the laser scanner sees the window perfectly within its line of sight. However, due to the smoothness of glass, at larger angles the reflection of the laser beam off the glass does not return to the photo diode in the laser scanner. As distance from the glass increases, the intensity of the laser beam reduces. That also reduces the field of view of the laser scanner. The experiment was performed from inside as well as from outside to see how the readings differ. The results are plotted in Figure 17. The field of view fits well as an exponential function of distance. Another significant finding is that the field of view from outside is significantly larger than the field of view from inside.

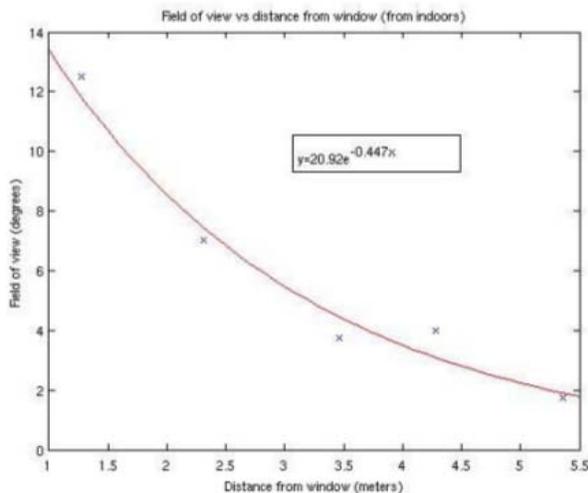


Figure 17a: Daytime field of view from inside

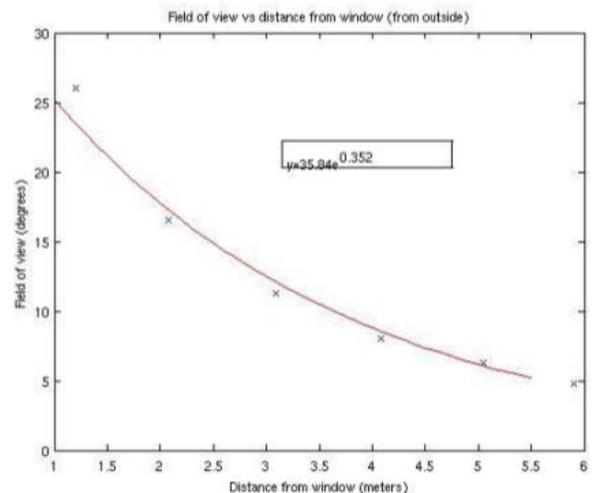


Figure 17b: Daytime field of view from outside

The difference observed between Figure 17 a and b can be attributed to the fact that most windows are tinted so that it is easier to see outside from inside than the other way around. When a window is double glazed, this effect could be created by making the outer glass slightly rougher causing more reflections in all directions. This roughness allows the laser scanner to see the glass better.

In order to test whether the difference in light causes any difference, we performed the same experiment at night, when the light difference between indoors and outdoors was opposite. The results obtained are shown in Figure 18. They were similar to the results obtained during the day, leading us to believe that differences in the lighting of the surrounding make very little difference to the distance measurements taken.

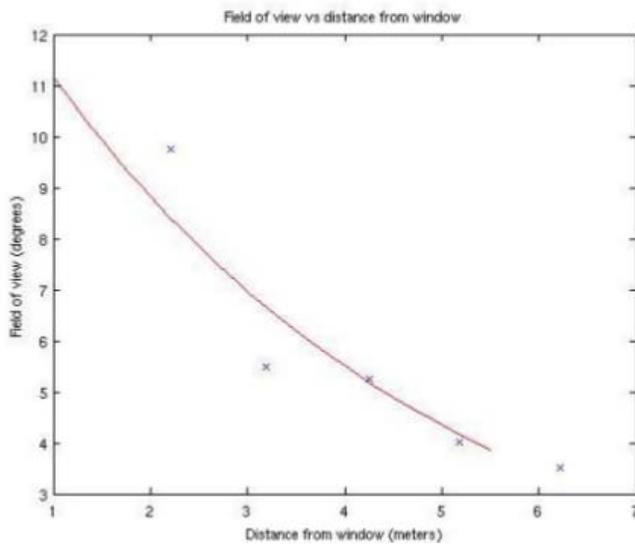


Figure 18a: Nighttime field of view from inside

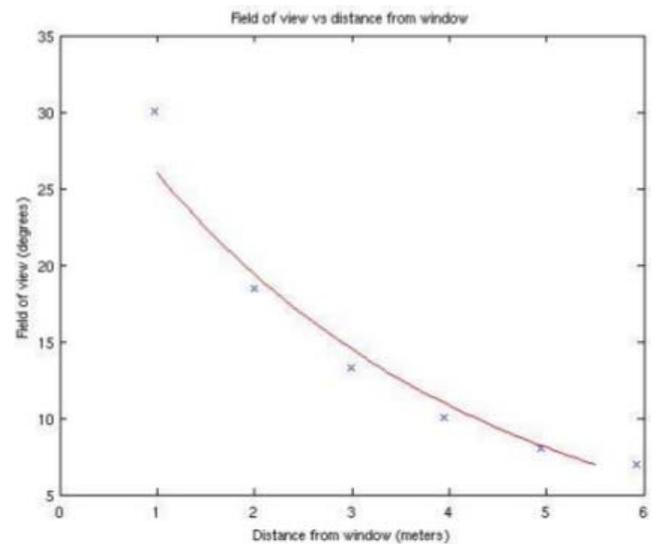


Figure 18b: Nighttime field of view from outside

If this information on windows is programmed into the robot, it would be able to detect windows much faster and more accurately.

7. USING SENSOR CHARACTERIZATION FOR MOTION ESTIMATION

The objective of characterizing the sensors is to enhance the accuracy of the performance of the quadrotor. In this case, the quadrotor is being used to map its surroundings, so characterization of the sensors aims to improve accuracy of the map generated.

Mapping and localization are equivalent problems. In order to be able to create a complete map of the surroundings, the quadrotor takes sensor data from multiple locations and puts the results together. If the translation between the consecutive locations is known, the translation to the origin will also be known. With this known, the distance measured by the sensors can be added to the map by applying the known translations to them.

We reconstructed an algorithm proposed by Olson[11] to use the laser scanner for motion estimation and tried to use the data from our characterization to further improve the algorithm.

Olson`s motion estimation algorithm consists of building a cost map of the probabilities of a measurement hitting objects. If no map is available, the previous scan is used as the cost map. The next scan is translated by all possible movements of the robot (x movements, y movements and theta rotations). The probabilities of each movement can be collected in a 3D movement table. This exhaustive table will have the probabilities of all movements. However, getting all this information is too computationally intensive. Olson suggested creating multi resolution cost tables. First, using the low resolution cost table (Figure 19a), we create a low resolution movement table. For the high probabilities in the low resolution movement table, we can calculate the high resolution movements.

Building on Olson`s work, when creating the cost table, we use our results from Sections 4 and 5. A cost map created using these results is shown in Figure 19b. Points which are further away from the laser scanner are larger than the points close to it. This is due to the larger standard deviations of these measurements.

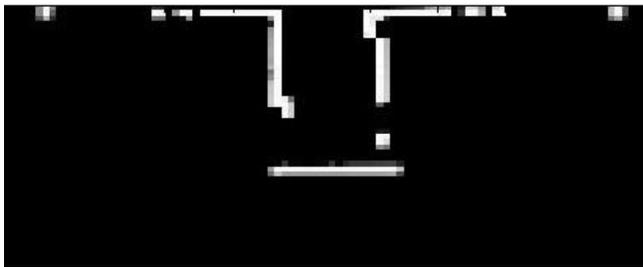


Figure 19a: Low resolution cost map

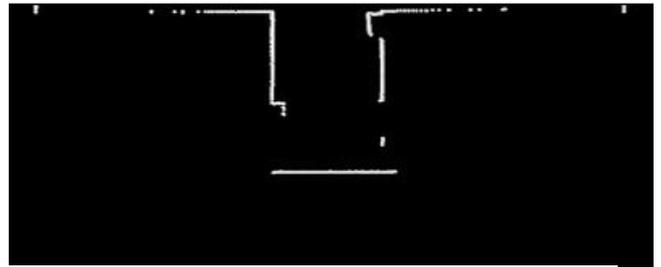


Figure 19b: High resolution cost map

The rest of the experiment with Olson`s algorithm is beyond the scope of this paper.

8. CONCLUSION

We have investigated the limits of the Hokuyo laser range finder and the Xbox Kinect in different indoor and outdoor environments.

With the data we have determined that indoors, in areas of average reflectance, the behavior of both sensors is predictable. They both follow models derived from their modes of operation. We specified models for our sensors so that the information the quadrotor has is as complete as the information provided by the sensors.

We also performed numerous experiments outdoors to find that there is only a limited area visible to the sensors in direct sunlight. This enables us to specify that the quadrotor must be selective in its use of sensors in these conditions. From the two sensors we found that the Kinect does not work at all in direct sunlight, while the Hokuyo laser range finder works within a range of 9-10 meters.

On characterizing the two sensors, we examined how characterization can come of use in the field of motion estimation. This use can be extended to other localization and mapping tasks that may be given to the quadrotor.

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