Tilt Measurement of Buildings Utilizing an Unmanned Aerial Vehicle

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Abstract

After an earthquake or other natural disaster, determining building stability and allowing entry into buildings is a key aspect of economic recovery. These assessments need to ensure safety, but economic recovery can be hindered if buildings are assessed incorrectly as unstable. An important factor of assessing building stability is determining building tilt. However, no single device functions exactly as a structural engineer would need for it to accurately assess the degree to which a building is leaning. The device described in this paper uses an absolute orientation sensor, ultrasonic sensor, and a camera, all connected to a Raspberry Pi computer, to determine the tilt of a building quickly and accurately.

1.0 Introduction

A disastrous earthquake has just occurred in a major city, and Urban Search and Rescue teams and structural engineers arrive on-site, ready to assess building safety. Inspected buildings will be tagged as red, yellow, or green, which roughly translate to dangerous, possibly dangerous, or safe, respectively (Bazzurro, 2006). Junior structural engineers who have only been in the field for a short time, tend to err on the side of caution, taking the conservative approach by labeling more buildings as red and yellow (Risha, 2021). Being able to utilize and access buildings is essential to rebuilding economies suffering the effects of a natural disaster, so taking a conservative approach to building assessment could prove detrimental to areas affected by natural disasters. Buildings tagged as red and yellow require a more in-depth assessment and take longer to be reopened if eventually found safe. This problem can be partially mitigated if a device is available to help junior engineers and even senior engineers make building condition assessments accurately and efficiently.

1.1 Background

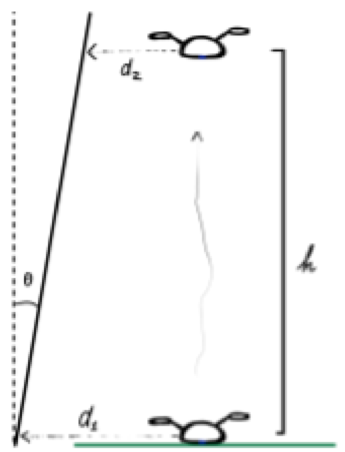

Figure 1. How to calculate tilt angle

The method to determine the tilt of a building that will be discussed in-depth in this paper involves calculating tilt by measuring the distance from the building at multiple heights (*Figure 1*) and using basic trigonometry to calculate building tilt. A distance measurement will need to be corrected for any motion of the sensor device, including drift, pitch (vertical rotation) and yaw (horizontal rotation). In this section, the methods to determine the distance between the device and the building as well as measurements needed for the correction will be explained.

The limit to how far a building should tilt without being dangerous depends on various factors, including the building's structure, heights, the purpose and ownership of the building, and the condition of the ground. The tilting of low-rise buildings such as civilian houses becomes a cause of concern when the tilt is greater than or at 1/100 (Charles, 2004). For example, for a 100 ft tall building, if the top of the building extends 1ft beyond the base, the tilt would be equal to this 1/100 ratio. In degrees, this is equivalent to 0.57°.

1.1.1 Devices

An ultrasonic sensor emits high-frequency sound waves in a straight line at a target, has an effective distance range of 2cm to 400cm, and can produce an accuracy of ±1 cm. A camera image can be used to determine the horizontal displacement of the device (section 1.1.2.2) as well as the height between the device and the base (section 1.1.2.3). The camera (Raspberry Pi Camera Module 2) specifications needed include:

Sensor area	3280 × 2464 px
Sensor image area	3.68 x 2.76 mm
Focal length	± 3.04 mm
Horizontal field of view	62.2°
Vertical field of view	48.8°

Table 1. Raspberry Pi Camera Module Specs

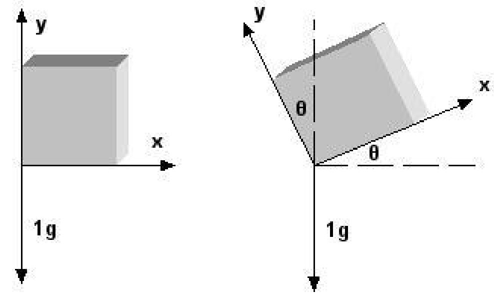

Figure 2. 2-axis accelerometer (Hobby, 2021)

To determine tilt from the measurements given by the two-axis accelerometer (*Figure 2),* the gravitational contribution to both the x-axis and y-axis can be used to calculate the angle of tilt using x/y = tan(θ).

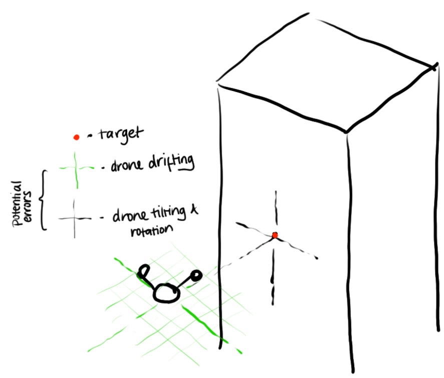

Figure 3. Potential measurement errors

1.1.2 Tilt and Absolute Position Measurements

This project is designed to be portable and flexible so that it can be utilized on any larger device (i.e. crane, drone, pole, etc.). To account for instability of the device during operation, finding the absolute position of the device itself is necessary, including drone drift forward/back (horizontal displacement), and the drone's tilting and rotation (yaw and pitch).

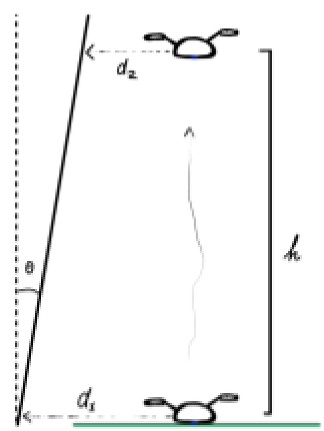

Figure 6. How to calculate tilt angle

A distance sensor such as an ultrasonic sensor can be used to calculate building tilt. Assuming that the distance sensor rises in a straight line, the distances acquired at various heights could be used to measure the angle of the building. The tilt angle can be calculated using the distance d_1 between the sensor and the building at the base, and the distance d_2 between the sensor and the building at height h, as the following equation states.

$$\theta = tan^{-1} \frac{(d_1 - d_2)}{h}$$

1.1.2.2 Height

The height of a camera can be determined by comparing the size of an image to the known size of the photographed object if the camera focal length and pixel size is known. Using the magnification equation, in which D_p is the diameter of a circle in pixels, D_o is the diameter of a circle measured in real life, f is the distance to the camera from the image sensor (focal length),and the H is the height between the camera and the image, the height can be found.

$$\frac{D_p}{D_a} = \frac{f}{H}$$ The Magnification Equation (*EQ 1*)

This method was selected over other altimetery techniques as there is no need to add an additional component that will not already be used.

1.1.2.3 Horizontal Shift

To account for horizontal displacement of the device as it takes measurements, the same camera images can be used. Using consecutive images an offset can be determined by measuring image shift and converting to actual camera drift x_d using the h height, x_p pixel size, and f focal length.

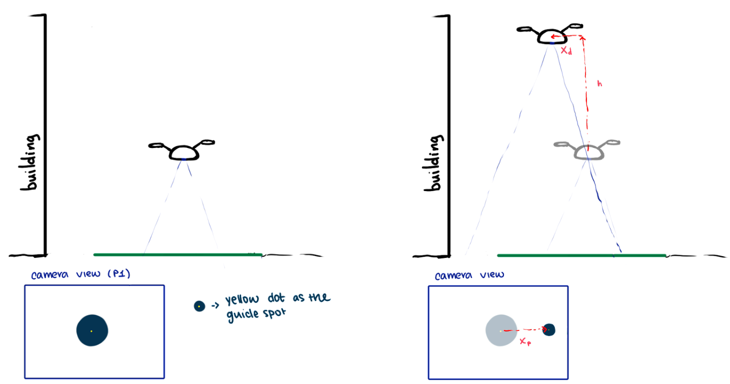

Figure 4. Horizontal Displacement

$$x_d = \frac{h \cdot x_p}{f}$$ (*EQ 2*)

1.1.2.4 Pitch and Yaw

A nine-degrees-of-freedom IMU fusion, BNO055 from Adafruit, can provide rotation angles which will be used to make corrections to building distance measurements provided by the ultrasonic sensor.

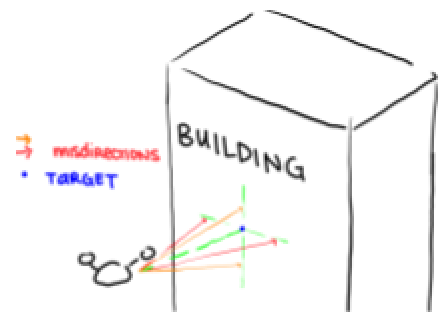

Figure 5. Potential Impacts of Pitch and Yaw Errors on Distance Measurements

1.2 Literature Review

Two existing building tilt devices have been reviewed for use with a structural engineering application. A South Korean project (W. A. Dai, 2015) developed a system that measured the tilt of old historical buildings and columns using a 3D Scandata technique. A second system that also utilized an accelerometer, tilt sensor, and rate gyro to determine accuracy in measuring tilt in several different testing beds was developed at UC Irvine (J. Leavitt, 2006).

1.2.1 Column Leaning with 3D Scan Data

Because traditional Korean wooden structures have changed over time, researchers have found a way to use 3D scan data to be able to measure the leaning of columns. Using the building Sungryeoljeon as the testing site for their device, researchers were able to accurately determine the leaning of all twelve columns. Specifically, the scientists used the Faro Focus 3D, a long-range scanner using phase shift methods (W. A. Dai, 2015). Three points of reference were set up around the building, after which the building was scanned and the data sent to a post-processing program which showed the leaning length of all three reference points. This method is similar to the one used in this project because both necessitate a reference point that would be determined with images.

1.2.2 Combined Angle Tilt System

The UC Irvine research team devised a method to measure inclination angles with low cost sensors (a low-bandwidth tilt sensor, rate gyro with inherent bias, and accelerometer). This method revealed that it was able to infer the correct tilt angle measurement from using all three sensors by canceling out the gyro bias effectively (J. Leavitt, 2006). A limitation on this device that is relevant for the current project is that it was tested on a flat surface with a zero base acceleration, making it unable to be used in an environment where the device would be moved around a lot.

1.3 Problem Statement

After a natural disaster, structural engineers need a way to efficiently and accurately assess the tilt of a building, which is a key indicator of stability. This project will develop a device utilizing ultrasonic sensors, IMU and cameras to measure the distance to a building at various heights, with the measured distances corrected for shift, pitch and yaw. The height and corrected distance data will be used to calculate building tilt and return the angle of tilt to the engineer. To simplify discussion, the device will be referred to as FASTR, or Fast Advanced Stability and Tilt Reconnaissance.

2.0 Methods

2.1 Device Design and Construction

FASTR is composed of multiple components as seen in the overall process diagram, including multiple sensors, software programs, cabling, hardware, and a portable battery. The overall flow diagram (*Figure 6*) shows both the physical processes and the software design for

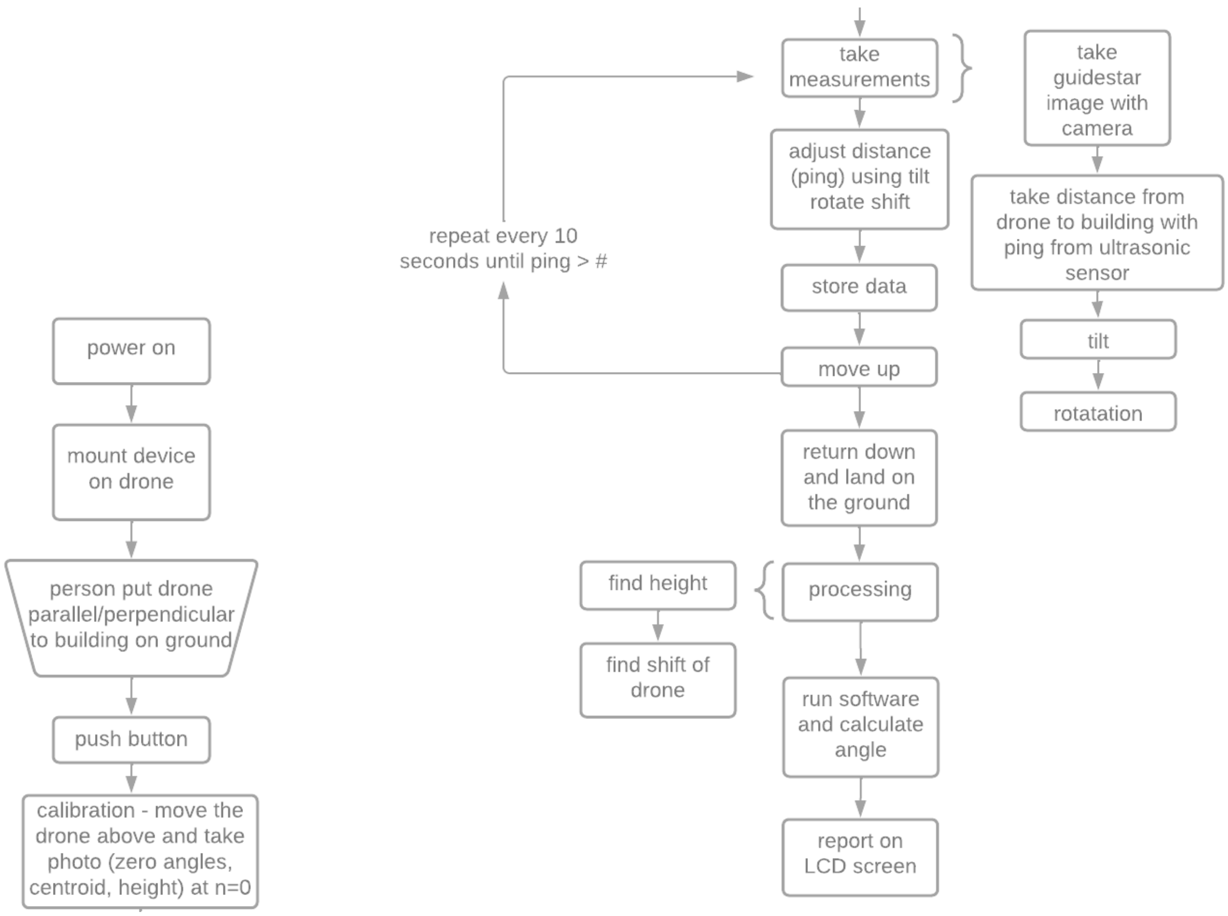

Figure 6. Overall Process Diagram

FASTR. A Raspberry Pi 4 Model B running Python will interface with an Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout, ultrasonic distance sensor HC-SR04, and the

Raspberry Pi Camera Module 2, and an LCD screen. The devices are housed in an enclosure (see *Figure 7*) to ensure sensor position stability.

2.1.2 Enclosure

A box-shaped enclosure, designed to allow mounting onto a larger device in the future, contains holes for the camera, ultrasonic sensor, and Raspberry Pi connection ports. The enclosure was modeled in Tinkercad and then 3D printed with PLA plastic. The camera window is located in the bottom of the enclosure so that a photo is able to be taken from a top view. The box is 5.9 inches by 6.5 inches by 2.9 inches.

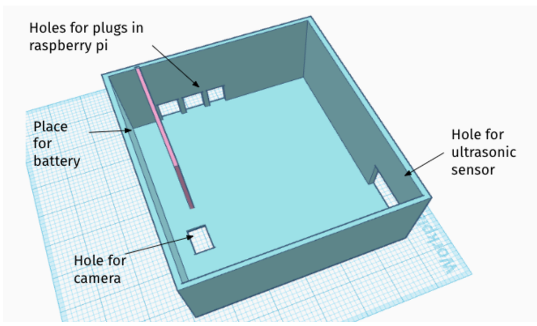

Figure 7. Image of enclosure

2.2 Measurements and Finding the Tilt Angle of Building

To ensure absolute accuracy of the device's position, camera and accelerometer data are acquired to determine the spatial orientation of the device. An accurate position of the device is necessary for an accurate building tilt angle output. Measurements that are needed are the height, horizontal position, as well as the device's angle in a 3-dimensional space. The height and horizontal position can be acquired from the image taken of the guidespot (as explained in 1.1.1.2). A good guidespot would be clearly marked and distinct from its background so as to allow minimal calculation errors in determining where it is and where the center, or centroid, is.

2.2.1 Measuring The Height

An image of a guidespot will be used for height and shift calculations. The height algorithm will select the largest and smallest "colored pixel" in both x and y coordinates. These pixel coordinates are used to calculate the diameter and center of the guidespot image. Diameter is used with EQ 1 to find height. Image center for two successive pictures is compared, with equation EQ 2 to find horizontal shift.

2.2.2 Measuring The Horizontal Displacement from the Building

Horizontal displacement is calculated using the specifications of the camera's sensor area, focal length, and its field of views (refer to 1.1.1.2). In order to acquire the difference in horizontal position of the drone, a pixel conversion, which is 891.3 pixels/mm, and the coordinates of the circle's center needs to be found by finding the average of the smallest and largest values in both the x and y lists. These coordinates can then be used to calculate the horizontal displacement using equation 2 in section 1.1.2.3.

As mentioned in 1.1.2.3, the horizontal displacement will be measured every two pictures after all photos are taken. The result will be an integer (negative or positive according to whether the device moved towards the building or further away) and is then added to the measured building distance at that particular height. It is necessary to determine whether movement towards the building will be in the x or y axis because the axis that moves to or from the building is the axis that matters.

2.2.3 Distance Adjustment From the Yaw and Pitch

In *Figure 8*, θ is the angle given by the accelerometer, x is the measured building distance and d is the corrected building distance. These variables are related through the cosine function.

$$d = \cos\theta \cdot x \qquad (EQ\ 3)$$

Equation 3 will be used to correct the raw distance that is

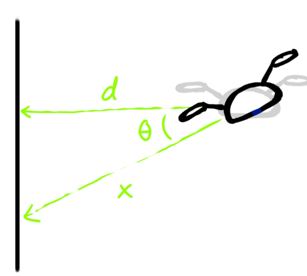

Figure 8. Adjusted distance from angle gained from accelerometer

output by the ultrasonic and convert it to an adjusted distance that is the true distance from the device to the building. The accelerometer device accuracy is ±3 degrees according to the datasheet. (Bosch, 2014)

2.2. Using Multiple Measurements to Determine Building Tilt

Once booted up, the device will ascend to some height above the ground so that the guidespot could still be pictured and used as the base for the rest of the calculations. As a whole, the code will first take the necessary measurements (image, angle, and raw distance) every 10 seconds as the device ascends parallel to the building. Above the top of the building, the pinged distance will record the sensor maximum, indicating there is no more building to measure, triggering the calculations and tilt reporting routines. Once the calculations have completed, the tilt angles will be averaged and displayed on an LCD screen.

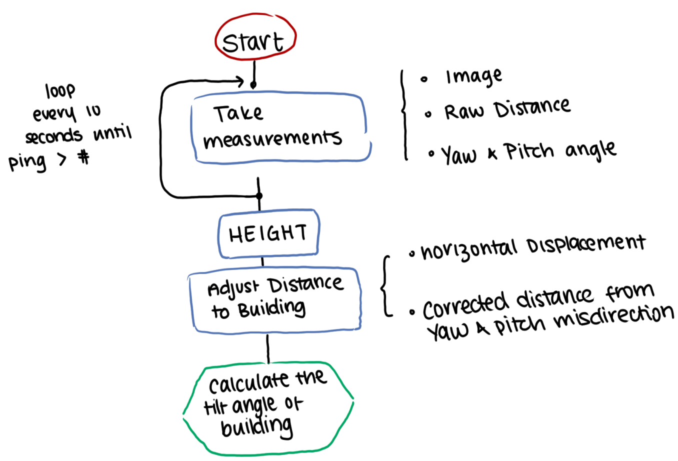

Figure 9. Overall Code Diagram

2.3 Component Validation

2.3.1 Horizontal Displacement Validation

The device is placed in front of a box and above a guidespot. The initial baseline distance to the box is verified by comparing the calculated distance to a manual measurement. The device is shifted in 1cm increments closer to the target box, and calculated distances are compared to the baseline distance.

2.3.2 Height Validation

A test bed with five known platform heights (10cm, 14.5cm, 20cm, 35cm, and 40cm) and a guidespot underneath is used. The camera is then placed on each platform and calculated heights are compared to known platform heights.

2.3.3 Pitch and Yaw Correction Validation

An initial baseline distance to the box is verified by comparing the calculated distance to a manual measurement. The device is placed a known distance away and manually tilted by known angles (the angle is calculated with inverse tangent). Calculated distances are recorded for comparison to the initial baseline distance.

2.4 Overall System Validation

After component testing is complete, a simulated building (large, flat board) will be set at a known tilt angle. The device will be initialized and lifted by hand to allow measurements across the height of the building. The calculated building tilt will be compared to the known tilt angle. Two tilt angles were tested, one being 2.2° and the other being 18.7°. For each manually measured angle, our device was used four times to see what the outputted angle would be.

3.0 Results

3.1 Component Validation Test Results

3.1.1 Height Validation Results

It was found in the testing stages that FASTR was able to correctly determine height with a ±0.42cm accuracy.

Height Measured With Ruler	**Height Calculated**
10cm	9.8cm
14.5cm	13cm
20cm	20.5cm
35cm	34.6cm
40cm	40.4cm

3.1.2 Pitch and Yaw Correction Validation Results

True distance and adjusted distances matched within a standard deviation of ±0.49 for the yaw validation and ±0.23cm for the pitch validation.

Yaw Correction:

Raw Distance (from Ultrasonic)	**Yaw Offset**	**Adjusted Distance**	**True Distance**
9.3	18.6°	8.8 cm	8 cm
10.1 cm	18.1°	9.6 cm	9 cm
18.8 cm	15°	18 cm	18.4 cm
13.6 cm	12.6°	13.2 cm	13.4 cm

Pitch Correction:

Raw Distance (from Ultrasonic)	Pitch Offset	Adjusted Distance	True Distance
15.3 cm	17.8°	15 cm	14.8 cm
16.8 cm	25.5°	14.9 cm	15 cm
40.8 cm	10.4°	39.9 cm	39.4 cm
31.5 cm	16.4°	29.9 cm	30.4 cm

3.1.3 Horizontal Shift Validation Results

As the device is shifted 1 cm forwards and backwards, the average of the shift calculated by the device is 0.86 cm, which makes for a ±0.29cm standard deviation.

Calculated Output
1.00 cm
0.51 cm
0.77 cm
1.19 cm

3.1.4 Overall Testing Validation Results

Tilt of Simulated Building	Mean Tilt Measured	Uncertainty
2.2°	7.5°	11.3°
18.7°	23.8°	20.2°

The overall angle testing results show that our angle uncertainty was extremely high. In our first testing group with a measured angle of 2.2°, we had an overall uncertainty of 11.3°. In our second testing group with a measured angle of 18.7°, we got an overall uncertainty of 20.2°.

4.0 Discussion

Individual Component	Experimental Measurement Precision
Height	± 0.42 cm
Horizontal Shift	± 0.29 cm
Pitch	± 0.2 cm
Yaw	± 0.5 cm
Theoretical Worst Case Building Angle Uncertainty	± 1.7°

Having developed a device (FASTR) to measure the tilt of a building, preliminary results verify that the uncertainty in height is ±0.42cm, the average uncertainty in adjusted distances is ±0.365cm, while the uncertainty in horizontal shift is ±0.29cm. Using these uncertainties, the worst case tilt error would have a theoretical uncertainty of ±1.7°.

The threshold for the worst case tilt error for a 1/100 tilted building would need to have a ±0.57° uncertainty. The theoretical uncertainty is still higher than the threshold uncertainty. More testings and modifications on sensors and codes are needed to lessen the uncertainties of each individual component.

However, the full device validation proved to have an uncertainty of ±20.2° and ±11.3° on two tests, which are exceedingly high compared to the theoretical ±1.7° error, and are even higher compared to the worst case tilt error for a 1/100 tilted building. Further testing needs to be conducted, as well as finding sensors with more accurate measurements.

Individual component testing suggests high precision building tilt measurements are possible. Preliminary full device validation shows that an additional source of device uncertainty exists and needs to be understood.

5.0 Conclusion

After a natural disaster, engineers on-site need an efficient way to determine building tilt so that buildings can be assessed more accurately. The rapid assessment of buildings allows damaged economies to recover faster and return to normal in a more timely manner. The goal of the device that was developed was to take measurements and calculate building tilt, returning the output to the engineer via an LCD screen. Component testing shows an uncertainty of ±1.7° uncertainty in tilted angle in the case of a 1/100 tilted building. However, the overall device testing shows an uncertainty of ±20.2° and ±11.3°. Results show a need to perform further testing and debugging of the main code.

5.1 Further Exploration

Further testing and observation is still needed to be conducted in order to decrease the uncertainty. Though the theoretical worst case scenario based on component testing is low, it is still not low enough to be effective in real life scenarios yet.

The causes of a low uncertainty also need to be identified, as to whether the problem lies in the overall integration, or if it is due to using less than accurate sensors. As of now, it has been observed that the cause mainly lies in the interference of shadows and external factors which disturbed the height calculations. FASTR currently observes a black guidespot. However, shadows and lighting effects will potentially disrupt image clarity and associated calculations. Changing the color to a less common, easily identifiable color should be explored.

As the project progresses into field testing, the size of the guidespot will have to increase, and the height that the device traverses through will increase. However, with the increase of the height, the more uncertainty there is in the overall device. At some point, there will be a limit that the camera won't be able to clearly discern the pixels of the guidespot image. This will greatly decrease functionality of the overall device. Other than modifying the guidespot to be bigger, other solutions are needed.

A 4000mAh battery is available for use in field testing. However, total power requirements for the Raspberry Pi and sensors have not been determined so time of use limitations for FASTR are currently unknown. In addition, a field testable prototype will first need to be transitioned from prototyped breadboard construction to soldered connections.

Finally, FASTR has only been used in a lab testing environment. There are several obstacles that a field test will likely reveal, including that of bushes blocking the base of buildings, building decorations that could interfere with the measurements and unique outdoor lighting conditions affecting measurements.

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Additional Consultants: Bruce Waggoner, Janah Risha, Randii Wessen, Steven Cronkhite

7.0 References

Adafruit Industries. (n.d.). *Adafruit 9-DOF absolute orientation IMU Fusion Breakout - BNO055*. Adafruit. Retrieved December 7, 2021, from https://www.adafruit.com/product/2472.

A. Venkatanarayanan. (2014). *Capacitive accelerometer*. Capacitive Accelerometer - an overview | ScienceDirect Topics. Retrieved January 9, 2022, from https://www.sciencedirect.com/topics/engineering/capacitive-accelerometer

Bazzurro, P., Cornell, A., Menun, C., & Luco, N. (2006, September). *Peer reports 2005/09 and*

2006/05 receive SEAONC Award of excellence. PEER Reports 2005/09 and 2006/05 Receive SEAONC Award of Excellence | Pacific Earthquake Engineering Research Center. Retrieved April 3, 2022, from https://peer.berkeley.edu/peer-reports-200509-and-200605-receive-seaonc-award-excellence

Bosch (2014). BNO055 Intelligent 9-axis absolute orientation sensor (1.2) Retrieved from https://cdn-shop.adafruit.com/datasheets/BST_BNO055_DS000_12.pdf

Charles, J. A., & Skinner, H. D. (2004). Settlement and tilt of low-rise buildings. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, *157*(2), 65–75. https://doi.org/10.1680/geng.2004.157.2.65

Dimension Engineering. (n.d.). *A Beginner's Guide to Accelerometers*. A beginner's guide to accelerometers. Retrieved December 18, 2021, from https://www.dimensionengineering.com/info/accelerometers

Hobby Electronics. (2021). *Accelerometers*. Accelerometers. Retrieved December 18, 2021, from https://www.hobbytronics.co.uk/accelerometer-info

Hughes, M. (2018). *Precise incline measurement: A high-stability 3-axis digital accelerometer from STMicroelectronics - News*. All About Circuits. Retrieved December 18, 2021, from https://www.allaboutcircuits.com/news/high-stability-low-noise-3-axis-digital-accelerometer-STMicroelectronics/

J. Leavitt, A. Sideris and J. E. Bobrow, "High bandwidth tilt measurement using low-cost sensors," in IEEE/ASME Transactions on Mechatronics, vol. 11, no. 3, pp. 320-327, June 2006, doi: 10.1109/TMECH.2006.875571.

Krishnan, N., Rosebrock, A., Fan, Jean-Marie, Singh, KhanhPhamDinh, Lu, Vinod, Aaron, Cuong, Powers, David, Anis, Egemen, M., Cassigoli, A., Carlos, Florian, Behrens, H.-M., Sudharsan, … OBrien, B. (2021, April 17). *OpenCV object tracking*. PyImageSearch. Retrieved December 10, 2021, from https://www.pyimagesearch.com/2018/07/30/opencv-object-tracking/.

W. A. Dai and H. W. Yang, (2015), A survey of column-leaning in Korean traditional wooden architecture structures using 3D scandata with a focus on the columns of the Sungryeoljeon in Namhansanseong, *Digital Heritage*, pp. 145-148, doi: 10.1109/DigitalHeritage.2015.7419473.

Risha, J. (2022, October 4). Personal Interview.

Techopedia. (2013, October 14). *What is piezoelectric accelerometer? - definition from Techopedia*. Techopedia.com. Retrieved January 9, 2022, from https://www.techopedia.com/definition/24743/piezoelectric-accelerometer