

Experimental Validation of Roll Angle Estimates Using Atmospheric Temperature Sensors

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Abstract: Accurately estimating the position and orientation is critical for the control systems of both airborne and ground-based unmanned vehicles. In many cases, GPS-derived data provides a suitable absolute measurement. Unfortunately, many unmanned vehicles may have to operate in GPS-denied environments, thus a suitable method for obtaining an absolute attitude measurement is highly desired. Thermal emissivity sensors have been experimentally shown to successfully estimate pose of airborne vehicles at high altitude or during continuously rolling maneuvers. Previous work has shown through simulation that the roll angle can be estimated with the vehicle orientation static using three or four thermal emissivity sensor arrays. The closed form estimation method previously presented for three and four sensor arrays is expanded to a six-sensor array. An array of eight sensors is developed to allow for simultaneous experimental data collection for all three arrays. The data is collected in a realistic and non-ideal environment and then processed with the proposed estimation algorithm for each of the three arrays. The results demonstrate that three-sensor arrays do allow for estimation of roll angle, with improved error bounds for increasing number of sensors in the array. Thus, low altitude absolute roll estimation is possible with a thermal emissivity sensor array and may be suitable for certain applications.

Keywords: Pose Estimation, Unmanned Aerial Vehicle, Gps-Denied, Thermopile

1. Introduction

Estimating attitude is critical to an effective control strategy for all vehicles. Maintaining level flight and controlling rolling maneuvers of aerial vehicles has been addressed for many classifications of aircraft from high-orbit spacecraft, to small unmanned aerial vehicles (UAV), and smart-projectiles. Many of the solutions previously used, though not all, have relied on the integration of Global Positioning System (GPS) estimates of position to augment inertial measurements of the motion of the aerial vehicle. Other works have addressed estimation of attitude through direct measurement of the environment. Britt et al. used LIDAR measurements of the earth plane in front of an unmanned ground vehicle (UGV) to estimate attitude [1, 2]. Dusha et al. used horizon detection through implementation

of an optical-flow algorithm and a vision system [3]. The latter group of solutions is desirable in cases where reception of GPS signals is not possible whether due to adversarial or environmental causes. However, estimating attitude in these environments is not without additional challenges. The work detailed here aims to extend the previous methods that were appropriate in high-earth orbit and further their use in low-altitude applications.

Thermopile sensors are used to measure thermal energy within a field-of-view (FOV) and convert it to an electrical signal. The National Aeronautics and Space Administration (NASA) introduced the first use of thermopile measurements to determine spacecraft attitude [4, 5]. Estimation accuracy in those works depended on clear line of sight to the earth horizon. The method is valid and still in use for small Cube-Sat satellites, and has been proposed for use in aircraft to be flown on Mars [6, 7]. VanRensburg concluded that solar

interference amounted to less than 1.5% error in each measurement resulting in a quantifiable and typically acceptable amount of error when the sun is present in the FOV [8].

Previously, thermopile sensor measurements have been used for low-altitude aircraft. McBride used horizon detection with thermopile sensors to update the attitude estimate for a small model-aircraft [9]. That work used a predefined algorithm for roll estimation and as such did not provide details regarding how the estimates were calculated. The most prevalent method is used by a number of groups including Monash University and The Paparazzi Project started at École Nationale de L'aviation Civile (ENAC) [10, 11]. Using this method, stabilization about a single axis is possible with only two thermopile sensors to measure atmospheric radiance. The two sensors are mounted in a model airplane orthogonal to the axis being stabilized. Additionally, the sensors are mounted to take measurements separated by 180°. This configuration allows for the aircraft to be stabilized by driving the differential signal between the two sensors to zero. While this strategy results in stable flight it is not possible to discern between the upright and inverted orientations. Additionally, it is not possible to estimate the angle relating the body axis to the reference plane provided by the horizon. These works typically use two additional sensors to make an estimate of the body angle. The two additional sensors are used to determine which sensor is pointed at the earth and which is pointed at the sky. Ground calibration is performed to find a reasonable value for the amplitude of the assumed sinusoidal sensor output prior to launch. The maximum value of the voltage differential is then monitored during flight to refine the estimate of the maximum value. This maximum value is then assumed to be the amplitude of the sensor output as the aircraft is rotated around the body axis. This approach results in little computation to calculate the estimates though no details regarding estimate accuracy were provided. Also, the use of four sensors to estimate the angle of a single axis does not represent the minimal number of measurements necessary.

Rogers et al. applied horizon detection to estimate the roll angle of a smart mortar round [12,13]. That work assumed a continuously rolling movement of the projectile. The continuous roll allows thermopile sensors mounted in line with the lateral axis to sample the (assumed) sinusoidal radiance [14]. This data was then used as a measurement update in a Kalman filter to identify the roll rate and roll angle of the projectile. Given the assumption that the projectile is continuously rolling it is not possible to extend this method to estimate pitch angle. Ultimately, that work concluded that 3 to 4 sensors were required for adequate estimates of attitude. Given the specific application that work was successful however not appropriate for extension to aircraft maintaining level flight.

Broderick and Wilson studied the minimum number of sensors necessary to estimate roll angle in a static orientation [15]. That work presented closed-form solutions for three and four sensor arrays and considered the effect of altering the

FOV and number of sensors on estimate accuracy. The only source of error present in that work was the discrepancy between the physics-based model and a sinusoidal assumption. Further error may be present when the aircraft is operated at low-altitude and without a clear horizon.

This work presents experimental data in support of the work by Broderick et al. [15]. The operation of thermopiles is reviewed and the method of estimation is restated for the three and four thermopile sensor arrays. Additionally, the closed-form solution for the six-sensor array is developed and presented here. Data collection is then described and an evaluation of the underlying sinusoidal assumption is discussed. Estimates are presented for a complete rotation of the vehicle for the three, four, and six-sensor arrays and compared to theoretical results.

2. Background

A thermopile measures thermal emissivity within some FOV specified by the manufacturer. The summation of energy within the FOV is converted to either an analog or digital signal. When mounted on an airborne vehicle such as a UAV the atmospheric thermal radiation measured varies depending on how much of the FOV is occupied by open sky and how much is occupied by the earth. The angle between the bore sight of the sensor and the plane defined by the horizon is defined as γ as depicted in Figure 1

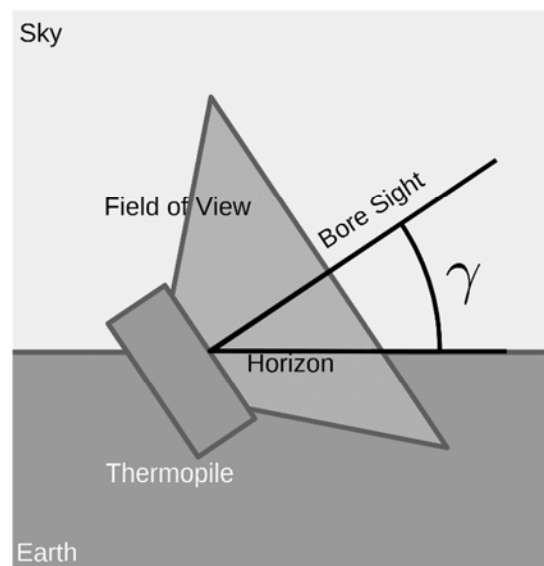


Figure 1. A single sensor and its position relative to the horizon.

Rogers et al. developed and validated a sensor model that was approximated by Broderick et al. [12, 15]. The work detailed in this paper uses the same sinusoidal approximation in the form:

$$T_x = -A \sin(\gamma) + T_{\text{OFF}} \quad (1)$$

where γ is the angle previously discussed and labeled in Figure 1, A is amplitude of the sine over a full rotation of the sensor in a plane perpendicular to the horizon, and T_{OFF} represents the

offset temperature of the sine as it is not expected to vary around 0 °C. All three parameters of the approximate model must be estimated though only γ is of interest for this work.

Broderick *et al.* investigated the number of sensors necessary to make estimates of attitude and the error introduced by the sinusoidal assumption [15]. The physics-based model and approximate model are shown in Figure 2 using a 35° FOV. While this is not the optimal FOV, it represents the available hardware at the time of data collection presented below.

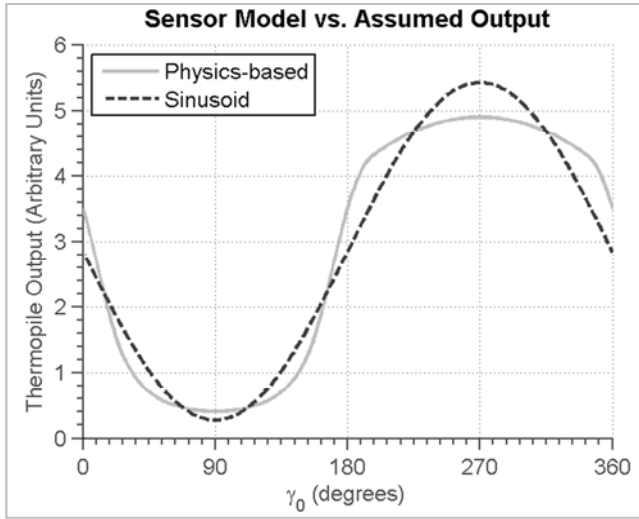


Figure 2. Comparison of physics-based and approximate sensor models, 35° FOV.

The discrepancy between the two models introduces error in the estimates detailed below [15]. Modeling error is only one source of error and other practical sources may further degrade estimate accuracy.

Previous work discussed the accuracy of estimates generated by various quantities of thermopiles. In each sensor array the sensors were evenly distributed around the axis. Figure 3 shows the sensor arrays used with three, four, and six thermopiles.

The three-sensor array was identified as the minimal number of sensors necessary for roll angle estimation. The previously published closed-form method of estimation for three sensors is included here for completeness and clarity. The amplitude is estimated for the three temperatures T_1 , T_2 , and T_3 using:

$$A(T_1, T_2, T_3) = -\frac{2U}{3} \quad (2)$$

where $U(T_1, T_2, T_3)$ is defined as:

$$U(T_1, T_2, T_3) = \sqrt{T_1^2 - T_1T_2 - T_1T_3 + T_2^2 - T_2T_3 + T_3^2} \quad (3)$$

For brevity, the function notation for U is dropped for the roll angle solution shown here:

$$\phi(T_1, T_2, T_3) = -2 \arctan\left(\frac{\sqrt{3}(T_2 - 2T_1 + T_3 + 2U)}{3(T_2 - T_3)}\right) \quad (4)$$

The offset temperature is simply the average of the

temperature measurements

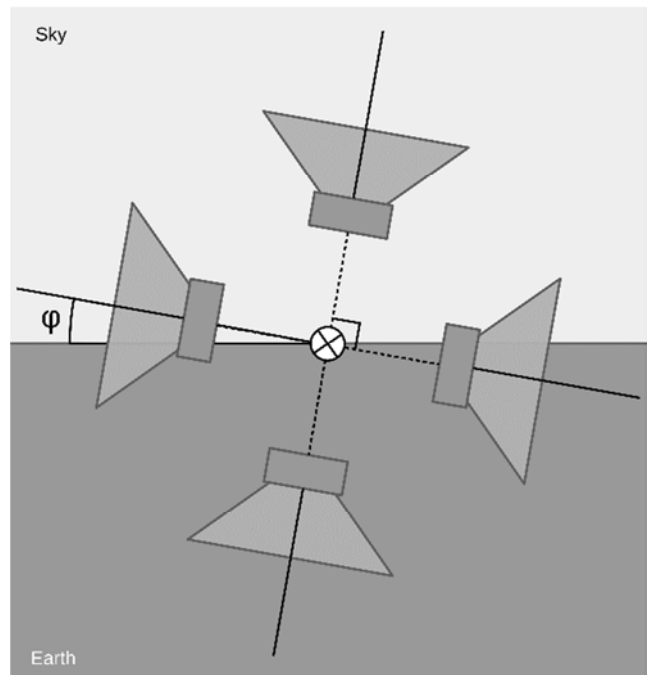
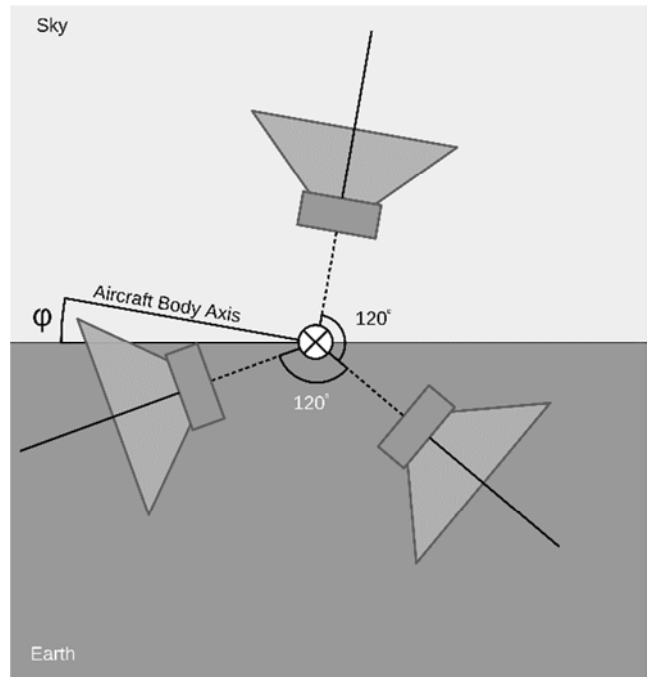
$$T_{\text{OFF}}(T_1, T_2, T_3) = \frac{T_1 + T_2 + T_3}{3} \quad (5)$$

A similar closed-form solution is presented here for the four-sensor array. The amplitude over a rotation is:

$$A(T_1, T_2, T_3, T_4) = -\frac{U}{2} \quad (6)$$

where $U(T_1, T_2, T_3, T_4)$ is defined as:

$$U(T_1, T_2, T_3, T_4) = \sqrt{T_1^2 - 2T_1T_3 + T_2^2 - 2T_2T_4 + T_3^2 + T_4^2} \quad (7)$$



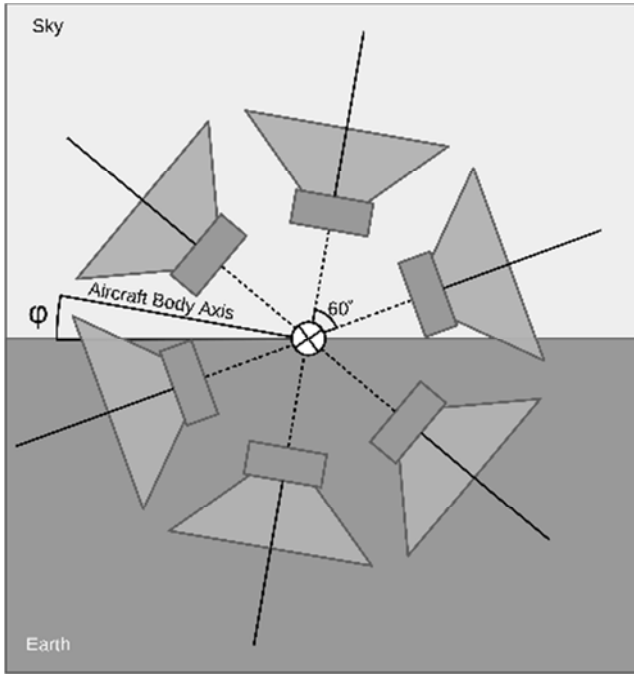


Figure 3. Evenly spaced thermopiles of three, four, and six-sensor arrays.

and ϕ is estimate with:

$$\phi(T_1, T_2, T_3, T_4) = 2 \arctan \left(\frac{T_4 - T_2 + U}{T_1 - T_3} \right) \quad (8)$$

Again, the temperature offset is simply the average of measured temperatures:

$$T_{\text{OFF}}(T_1, T_2, T_3, T_4) = \frac{T_1 + T_2 + T_3 + T_4}{4} \quad (9)$$

Previous work omitted solutions for sensor arrays larger than four given the length of the solutions. The closed-form solution for the six-sensor array was developed in the manner discussed by Broderick et al. and is presented here [15]:

$$A(T_1, T_2, T_3, T_4, T_5, T_6) = \frac{U}{3} \quad (10)$$

where $U(T_1, T_2, T_3, T_4, T_5, T_6)$ is

$$U(T_1, T_2, T_3, T_4, T_5, T_6) = \sqrt{\begin{aligned} &T_1^2 + T_1 T_2 - T_1 T_3 - 2T_1 T_4 - T_1 T_5 + T_1 T_6 \\ &+ T_2^2 + T_2 T_3 - T_2 T_4 - 2T_2 T_5 - T_2 T_6 \\ &+ T_3^2 + T_3 T_4 - T_3 T_5 - 2T_3 T_6 \\ &+ T_4^2 + T_4 T_5 - T_4 T_6 \\ &+ T_5^2 + T_5 T_6 \\ &+ T_6^2 \end{aligned}} \quad (11)$$

roll angle is estimate with:

$$\phi(T_1, T_2, T_3, T_4, T_5, T_6) = -2 \arctan \left(\frac{\sqrt{3}(T_2 + T_3 - T_5 - T_6) + 2U}{2T_1 + T_2 - T_3 - 2T_4 - T_5 + T_6} \right) \quad (12)$$

and the temperature offset is calculated as:

$$T_{\text{OFF}}(T_1, T_2, T_3, T_4, T_5, T_6) = \frac{T_1 + T_2 + T_3 + T_4 + T_5 + T_6}{6} \quad (13)$$

The estimates presented in the subsequent sections were generated using (4), (8), and (12) as those expressions represent the estimate of vehicle roll angle, ϕ .

3. Data Collection

Validation of the estimation methods described in the previous section was performed using recorded data that was then post-processed. Thermopile sensors arranged on a wheel recorded thermal emissivity synchronously. The arrangement shown in Figure 4 allowed for generation of a single dataset recorded with invariant environmental conditions.

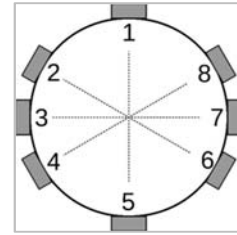


Figure 4. Thermopile arrangement during data collection.

The sensors depicted in Figure 4 are mounted at the angles listed in Table 1 mounted with 0° as the vertical position facing up.

Table 1. Sensor mounting angles during data collection.

Sensor	Angle from Vertical
Thermopile #1	0°
Thermopile #2	60°
Thermopile #3	90°
Thermopile #4	120°
Thermopile #5	180°
Thermopile #6	240°
Thermopile #7	270°
Thermopile #8	300°

Post processing of the data separated the sensors shown in Figure 4 into groups that correspond to the three configurations described previously. Table 2 lists the sensor groups comprising the arrays.

Table 2. Thermopiles assigned to sensor arrays of varying size.

Sensor	Angle from Vertical
Three-sensor array	1, 4, 6
Four-sensor array	1, 3, 5, 7
Six-sensor array	1, 2, 4, 5, 6, 8

Each sensor shown in Figure 4 is a Melexis Technologies MLX90614ESF with a 35° FOV. The sensors communicated with an Atmel Atmega328p over an I2C bus at 400 kHz. The microcontroller recorded values for every 1.8° of rotation and stored the values in memory. After the wheel completed a single rotation, the microcontroller transmitted the values over an HC-06 Bluetooth module and stored the values in a comma-separated values file prior to processing. The microcontroller controlled rotation of the sensors with a geared 667 oz-in NEMA 17 stepper motor. The gearbox specification stated a backlash error of 1.5° introducing an

additional source of error not previously considered. The maximum roll rate of the sensor array was $22.5^\circ/\text{s}$. The I2C communication was the limiting factor for the roll rate during data collection.

The sensor array was mounted on a 6-meter long aluminum pole with a 50 mm diameter. The pole was placed in the center of a field 100 meters from the nearest obstruction, a row of deciduous trees native to the area. This position was not ideal and does not match the assumption made by the physics-based model used in previous work that the sensor was at a high-altitude free from obstructions. However, the position of the sensor array was typical of the intended application, eg~ low-altitude flight of UAVs in obstructed environments. Therefore, the data presented in the next section may serve as a baseline for estimate accuracy in such an environment.

4. Results

Figure 5 shows a comparison of the physics-based model, the sinusoidal assumed model, and recorded data from a single thermopile over a single rotation of the sensor array.

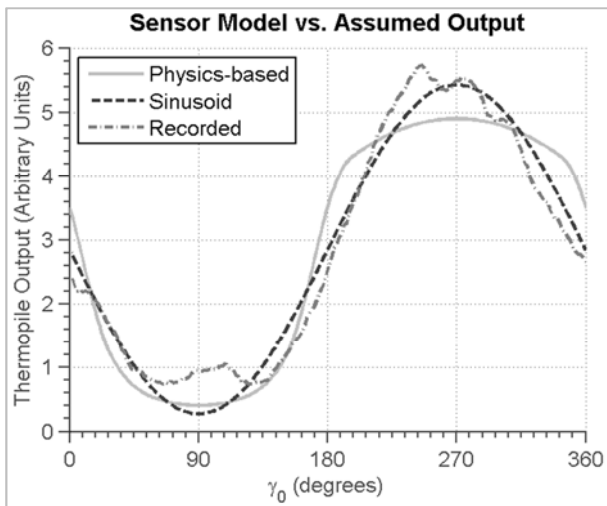


Figure 5. Comparison of physics-based model, recorded data, and the assumed sinusoid.

While neither the physics-based model nor the recorded data matches the assumed sinusoid, all three plots are similar in shape. Of the two, the data matches the assumed sinusoid more closely with an RMS error of 0.3431° while the model matches the sinusoid with an RMS error of 0.3920° .

Estimates generated by (4), (8), and (12) using the recorded data exceed the anticipated error due to the assumed sinusoidal model of sensor output. The three, four, and six-sensor arrays resulted in a maximum roll angle error of 34.28° , 12.13° , and 11.82° respectively. This additional error may be caused by any number of environmental factors. However, these factors will be present in the anticipated environment of operation and therefore the values more accurately represent the anticipated error.

Figures 6, 7, and 8 show the estimates plotted against the

angle indicated by the step count of the motor. The same figures also show the error over a single rotation matching the bounds identified above.

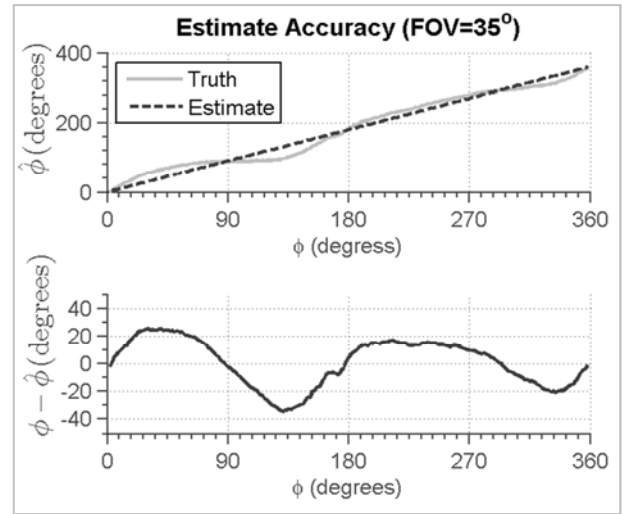


Figure 6. Three-sensor array estimates and error.

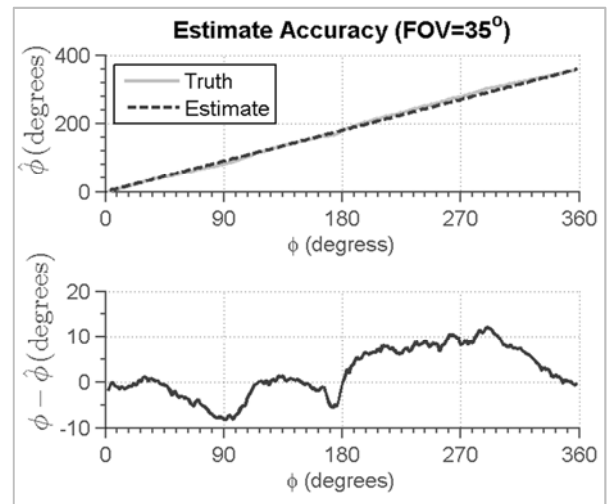


Figure 7. Four-sensor array estimates and error.

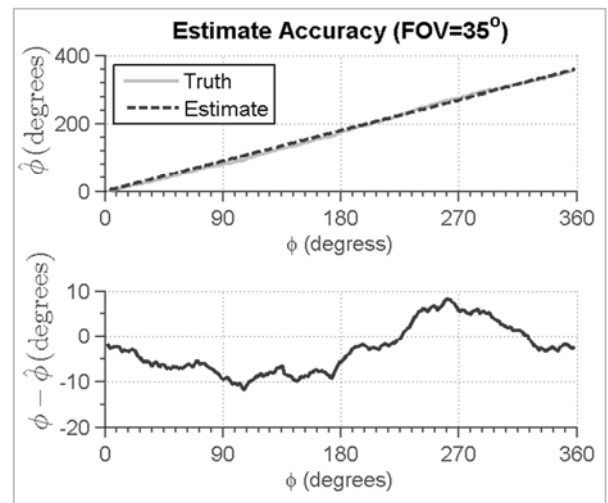


Figure 8. Six-sensor array estimates and error.

Figure 9 also shows the error bounds over a varying-sized array from three sensors to eight. The three error bounds identified from recorded data are included as scatter points in that figure.

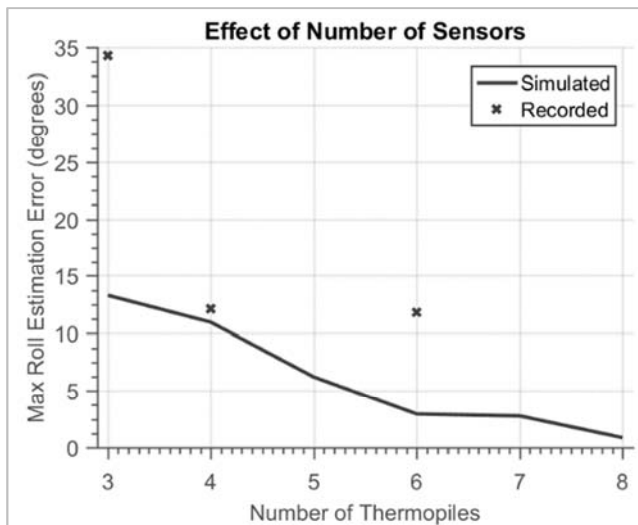


Figure 9. Simulated vs recorded error.

5. Conclusion

Pose estimates in GPS-denied environments are critical to opening up new areas of operation for UAVs and UGVs. While previous work focused on high-altitude operation or rolling maneuvers, this work endeavors to address roll angle estimation in low altitude and static orientations.

Prior work developed and presented closed-form solutions for estimates with three and four thermopile sensors. This work extends the closed-form solutions to include a six-sensor array. The previous work relied solely on simulated data under ideal conditions: high-altitude with no obstructions. The results presented here represent recorded data under realistic operating conditions.

In all three cases examined here, the recorded data error bounds were greater than those of the simulated data. This result was anticipated given the assumptions made during simulation were not valid during data collection. The estimates and error bounds presented here represent a clearer expectation for roll angle estimates using the methods developed in previous work and furthered here. Ultimately, the end-application will determine the required accuracy of such estimates. Future work may further refine the estimates in such environments through other methods such as sensor fusion.

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