

Roll Angle Estimation Using Thermopiles for a Flight Controlled Mortar

by Michael Don, David Grzybowski, and Richard Christian IV

ARL-RP-380

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A reprint from the 2011 Aeroballistic Range Association Meeting, pp. 1–15, 18–23 September 2011.

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Although high cost guided missiles are a mature technology, low cost precision munitions is a new field with many technological challenges. One of these challenges is to find inexpensive sensors to replace expensive high-precision sensors that exist in traditional smart weapons. Thermopiles are low cost sensors that convert thermal energy into electrical energy. By using thermopiles to sense the difference in thermal energy between the ground and sky, the roll angle of a projectile can be determined. In July of 2011, the Army Research Labs conducted a flight test of an 81-mm Flight Controlled Mortar (FCMortar) equipped with four thermopile sensors. Roll angle was accurately estimated by processing the thermopile data with a Recursive Least Squares (RLS) filter implemented on a field programmable gate array (FPGA). These results demonstrate the feasibility of using thermopiles on precision munitions for real-time roll angle estimation.				
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Roll Angle Estimation using Thermopiles for a Flight Controlled Mortar

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Summary— Although high cost guided missiles are a mature technology, low cost precision munitions is a new field with many technological challenges. One of these challenges is to find inexpensive sensors to replace expensive high-precision sensors that exist in traditional smart weapons. Thermopiles are low cost sensors that convert thermal energy into electrical energy. By using thermopiles to sense the difference in thermal energy between the ground and sky, the roll angle of a projectile can be determined. In July of 2011, the Army Research Labs conducted a flight test of an 81-mm Flight Controlled Mortar (FCMortar) equipped with four thermopile sensors. Roll angle was accurately estimated by processing the thermopile data with a Recursive Least Squares (RLS) filter implemented on a field programmable gate array (FPGA). These results demonstrate the feasibility of using thermopiles on precision munitions for real-time roll angle estimation.

INTRODUCTION

The US Army Research Laboratory in conjunction with the Naval Surface Warfare Center (NSWC) is developing a Flight Controlled Mortar (FCMortar). FCMortar is comprised of a guidance and control system that screws into the fuze thread of an 81-mm mortar body and a super-caliber fin set that provides aerodynamic stability (Figure 1). One of the essential requirements of FCMortar is to provide affordable precision. This creates a challenge to find inexpensive sensors to replace expensive high-precision sensors that exist in traditional smart weapons. One of the promising novel sensors that ARL is researching are thermopiles. ARL has successfully integrated thermopiles into two flight tests at Yuma Proving Ground (YPG). The first firing event (FE1) was conducted on May of 2010 using two thermopile per round spaced 180 degrees apart. The second (FE2) was completed during July of 2011 featuring four thermopiles per round spaced 90 degrees apart. These flight tests show that roll angle can be accurately determined using thermopiles.

ARL efforts in integrating thermopiles into its sensor suite can be divided into two main areas. The first encompasses the hardware design, test, and calibration. The second entails the data processing to determine roll angle. First a brief introduction of thermopiles will be given. Next the hardware selection and design will be explained followed by a description of the thermopile assembly test and calibration. Finally an algorithm employing a recursive least squares (RLS) filter will be described as well as its implemented on a field programmable gate array (FPGA). Sample results of FE2 will be presented demonstrating the feasibility of using thermopiles on precision munitions for real-time roll angle estimation.



Figure 1. FCMortar Model

THERMOPILE OVERVIEW

A thermopile is a sensor that converts thermal energy into electrical energy. The output of the sensor is a voltage proportional to the amount of infrared (IR) energy received from radiation within its field of view (FOV). The thermopile can be used in a wide range of applications such as bio chemical, medical, automotive, obstacle detection & avoidance, robotics, satellites, unmanned aerial vehicles (UAVs), and horizon determination.

ARL has used thermopiles to detect the roll angle of spinning munitions. Since the ground emits more IR energy than the sky, a spinning thermopile that alternates between viewing the ground and sky will produce a sinusoidal output similar to that shown in Figure 2.

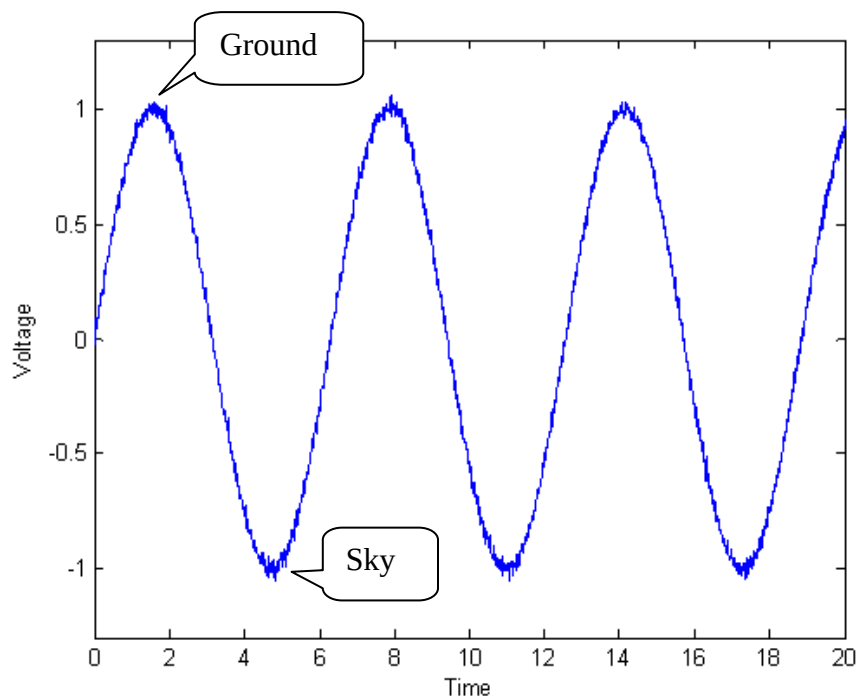


Figure 2. Output of a Spinning Thermopile.

HARDWARE DESIGN

Considerable effort was required to integrate a thermopile onto a projectile. The first step was to choose a suitable commercial off-the-shelf (COTS) thermopile. Several criteria were of interest:

- Size: Small size was required to be less susceptible to shock as well as to conserve limited area resources.
- Temperature Range: A large temperature range was desirable to be able to meet the needs of varied environments.
- Response Time: Faster response time would allow for better signal transmission.
- Field of View: A larger field of view was desirable for more robust roll angle estimation.

Initially the Melaxis MLX 90247 was chosen for evaluation. This was later replaced with the Heiman J11 F5.5 which had more desirable characteristics as detailed in Table 1 below. A number of potential COTS thermopiles have not been evaluated yet and the search is ongoing.

	Melaxis MLX 90247 [2]	Heiman J11 F5.5 [1]
Field of View	88 degrees	120 degrees
Time Constant	30 ms	6 ms
Size	9 mm diameter	4.7 mm
Temperature Range	-40 to 85 Degrees C	-20 to 120 Degrees C

Table 1. Thermopile Property Comparison

The thermopile sensor output is a small voltage usually measured in micro-volts which must be amplified before it is used. A four layer printed circuit board (PCB) was designed with a low noise amplifier that has programmable gain and offset. The calibration process was automated using a LabVIEW controlled data acquisition system (DAQ) to program the gain and offset. After programming, the thermopile assemblies were carefully constructed. Figure 3 shows the thermopile soldered onto the PCB, with attached leads and a copper backplane. The assembly was then encased in an aluminum housing, resulting in the finished assemblies in Figure 4.

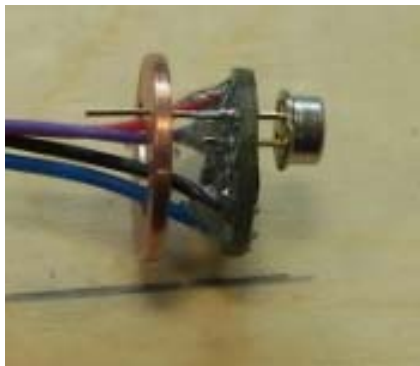


Figure 3. Thermopile with Conditioning Board, Wire Leads, and Copper Backplane

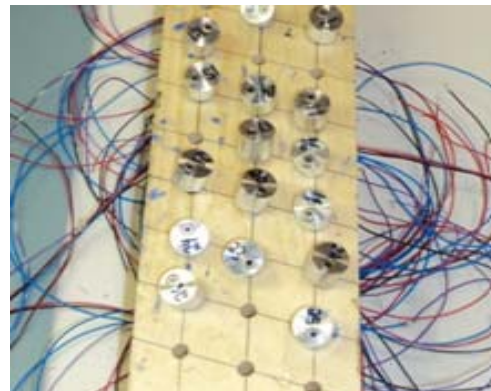


Figure 4. Completed Thermopile Assemblies

TEST AND CALABRATION

After the thermopiles units were assembled, the units were evaluated, shocked, and then re-evaluated in order to determine if the thermopile units would survive the high G forces that the thermopile would experience on a mortar. The evaluation employed a blackbody radiator to radiate the thermopile and an oscilloscope to measure output voltage. The units then were subjected to a 12000 G shock test in ARL's high G facility. The units were re-evaluated and the results are documented in the tables below. Although a voltage shift was noticeable after shock, the data shows that the thermopile assemblies were still fully functional.

	Evaluation before Shock (V)	Re-evaluation after Shock (V)
-10 Deg. C	2.52	2.55
25 Deg. C	2.67	2.68
80 Deg. C	3.40	3.10

Figure 5. Unit 1 Shock Results

	Evaluation before Shock (V)	Re-evaluation after Shock (V)
-10 Deg. C	2.22	2.22
25 Deg. C	2.42	3.42
80 Deg. C	2.94	2.91

Figure 6. Unit 2 Shock Results

	Evaluation before Shock (V)	Re-evaluation after Shock (V)
-10 Deg. C	2.28	2.18
25 Deg. C	2.41	2.39
80 Deg. C	2.82	2.88

Figure 7. Unit 3 Shock Results

FE1 employed two thermopiles on each round spaced 180 degrees apart. A sample of the thermopile output is shown in Figure 8 with a close-up shown in Figure 9. A large bias shift can be seen in Figure 8 beginning at launch at 10 seconds. This caused the thermopile response to clip at the beginning of flight and data to be lost. In order to solve this problem for FE2, the gain of the amplifier was decreased and the thermopile's thermister output was monitored in order to collect data on the body temperature. FE2 was equipped with four thermopiles evenly spaced around the mortar. Figure 10 shows an example thermopile and thermister response from the second flight test. Even with diminishing the gain, the thermopile output was still clipped. Although the thermistor output somewhat mimics the bias of the thermopile, the minimum of the thermistor output is around 30 seconds compared to the thermopile minimum which occurs around 20 seconds. This suggests that there are other factors than body temperate that effect bias shift. Further laboratory experiments are needed to understand and predict this bias shift phenomenon.

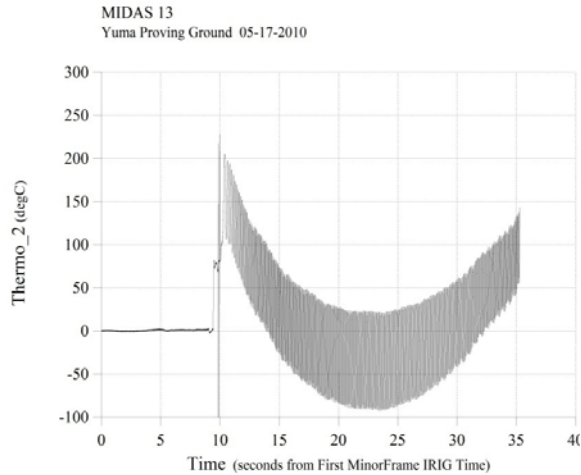


Figure 8. Thermopile Response from FE1

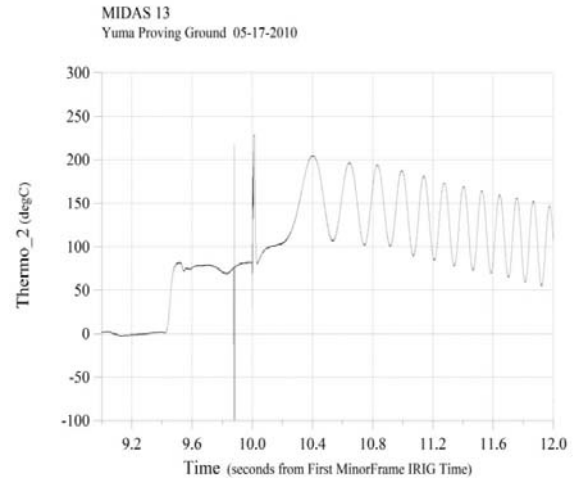


Figure 9. Thermopile Response Close-up.

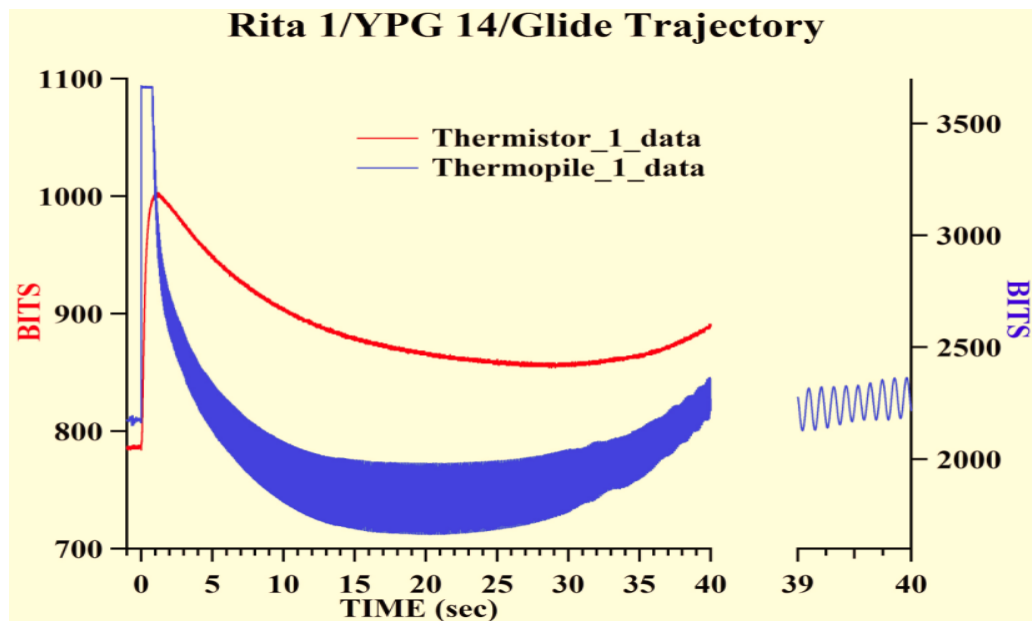


Figure 10. Example Thermopile Response from FE2

ROLL ANGLE ESTIMATION ALGORITHM

Rogers [3] suggested a recursive least squares (RLS) filter to estimate roll angle on a spinning projectile. This algorithm will be reviewed first and then ARL's modifications and FPGA implementation will be presented. The RLS algorithm described here has three main steps: Predictor, Corrector, and Amplitude update. The reference frame use in the following discussion is shown in Figure 11.

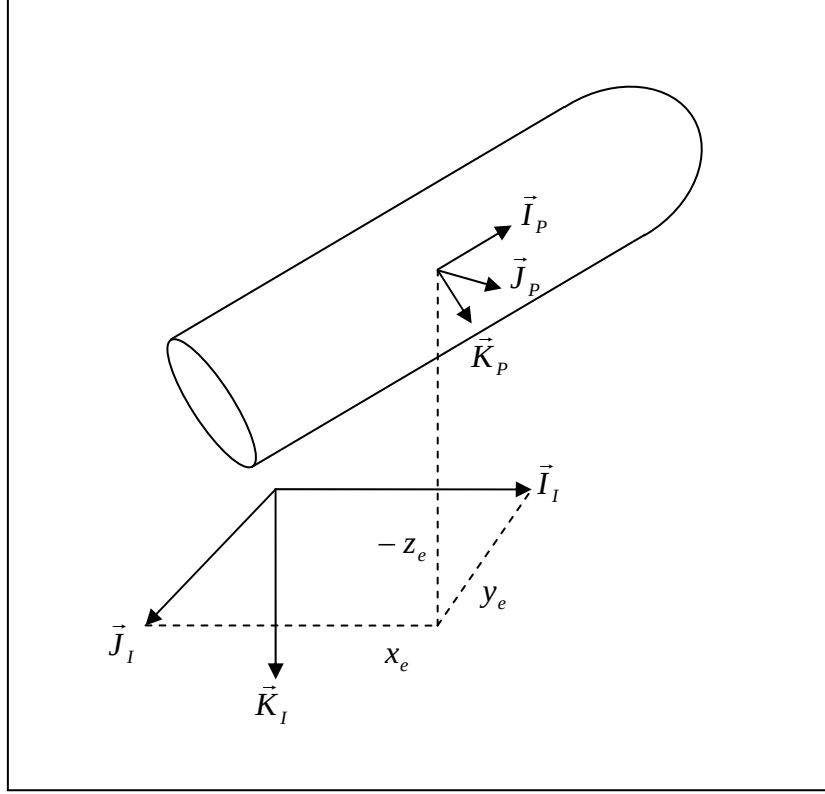


Figure 11. Projectile Reference Frame

The predictor step predicts the next roll angle estimate ($\hat{\phi}_T^P$) given the previous estimate ($\hat{\phi}_{T-1}$) by assuming the projectile rolls at rate p_0 as shown in Equation 1. p_0 does not have to be very accurate, and can even be a constant, since the corrector step will minimize any error.

$$\hat{\phi}_T^P = \hat{\phi}_{T-1} + t_s p_0$$

Equation 1

The corrector step requires a relationship between the sensor measurement and the roll angle to be defined. Although the actual relationship is more complex, a sine wave is used as a close approximation that minimizes complexity as shown in Figure 12.

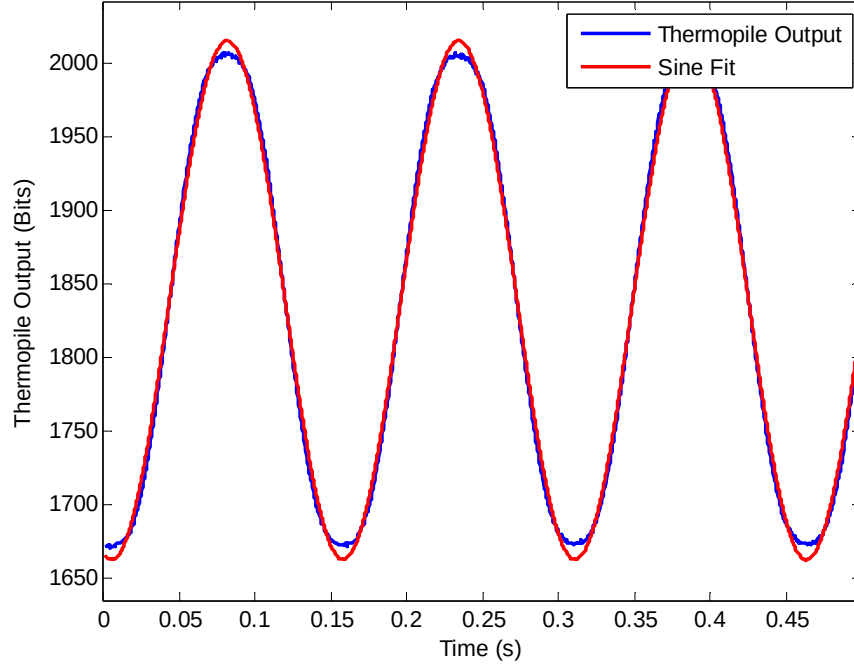


Figure 12. Comparison of thermopile output to sine wave.

Equation 2 shows the sine wave definition of the n th thermopile measurement (v_n^*) with amplitude A_n , roll angle ϕ , and offset from $\vec{J}_B$, δ_n . Here it is assumed that the thermopile bias has been removed.

$$v_n^* = A_n \sin(\phi + \delta_n)$$

Equation 2

The predicted roll angle and n thermopile measurements are then used to calculate the linearized output matrix C :

$$C = \begin{bmatrix} \frac{\partial v_1^*}{\partial \phi} & \frac{\partial v_2^*}{\partial \phi} & \dots & \frac{\partial v_n^*}{\partial \phi} \end{bmatrix} = \begin{bmatrix} A_1 \cos(\hat{\phi}_T^P + \delta_1) & \dots & A_n \cos(\hat{\phi}_T^P + \delta_n) \end{bmatrix}$$

Equation 3

This matrix and a user defined $n \times n$ diagonal matrix R are used to compute the RLS estimation gain K :

$$K = \left(\mathbf{1} - C(R + C^T C)^{-1} C^T \right) C R^{-1}$$

Equation 4

The roll rate estimate ($\hat{\phi}_T$) can now be corrected using K and difference between the measured sensor output (v_n^*) and the predicted sensor output v_n^P calculated in Equation 6.

$$\hat{\phi}_T = \hat{\phi}_T^P + K \begin{Bmatrix} v_1^* - v_1^P \\ \vdots \\ v_n^* - v_n^P \end{Bmatrix}$$

Equation 5

$$v_n^P = \hat{A}_n \sin(\hat{\phi}_T^P + \delta_n)$$

Equation 6

This process is then repeated for the next time step using the roll estimate calculated in Equation 5 as the previous roll estimate back in Equation 1. As the algorithm iterates, the maximums and minimums of the thermopile outputs are used to update the sine amplitudes used in Equation 2 and Equation 6.

This algorithm depends on the output voltage changing with the spin of the projectile. Figure 13 shows a view of the top of a mortar traveling horizontal to the ground, with two thermopiles marked with red on either side of the round 180 degrees apart. Since the temperature of the sky and ground are different, as long as the horizon is within the FOV of the thermopile, the output voltage will change as the round rotates and the ratio of sky to ground within the FOV changes. However, if the thermopile is pointing up or down and only has the sky or ground in its FOV, there will be little change as the round rotates. This is a significant problem with spacing the thermopiles 180 degrees apart as was done in FE1. If two thermopiles were spaced 90 degrees apart, then the horizon would always be within view of one of the thermopile. FE2 used four thermopiles evenly spaced around the mortar to achieve even better performance (Figure 14). This is also the reason why a larger field of view leads to more precise roll angle estimation. The larger the field of view, the more time the horizon is within the field of view, resulting in a better signal to determine roll angle.

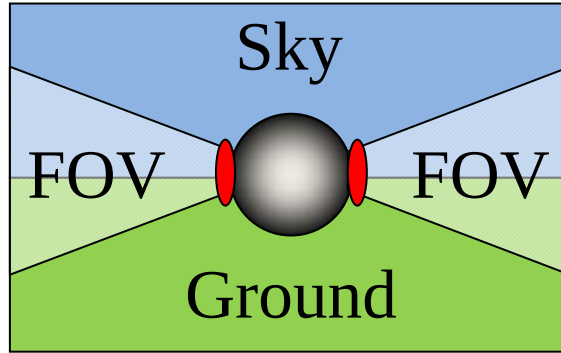


Figure 13. View of Top of Mortar Horizontal to the Ground

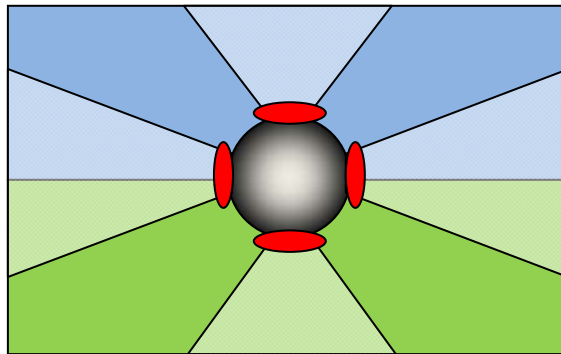


Figure 14. View of Top of FE2 Mortar

FPGA Implementation

Several changes to the RLS filter had to be made to implement the algorithm on an FPGA. The matrix inversion in Equation 4 is a computationally intensive operation. By changing the filter into a sequential implementation, the matrix inversion can be eliminated [4]. This is accomplished by looping through the following equations for $i = 1$ to n , with $\hat{\phi}_0$ initialized to $\hat{\phi}_T^P$, and the resulting $\hat{\phi}_T$ given by $\hat{\phi}_n$.

$$C_i = A_i \cos(\hat{\phi}_{i-1} + \delta_i)$$

Equation 7

$$K_i = C_i (R + C_i^2)^{-1}$$

Equation 8

$$\hat{\phi}_i = \hat{\phi}_{i-1} + K_i (v_i^* - v_i^P)$$

Equation 9

Calculations on the FPGA will be carried out in fixed point arithmetic. In order to keep the bit length of the numbers to a minimum, the range of calculated values should also be kept to a minimum. It is therefore more advantageous to normalize the thermopile output than to keep track of its amplitude. Once the thermopile output is normalized, the amplitude can be removed from all of RLS equations. Since the amplitude is already being kept track of, it is also easy to remove any DC bias in the signal. A simple peak search routine is executed in order to find the current maximum and minimum values of the thermopile waveform. The amplitude and bias values are updated whenever a new peak is found.

A model based design approach was used to implement the RLS filter. Using Xilinx's System generator, the entire design was implemented at a relatively high level within Malab's Simulink. This allowed VHDL code to be automatically generated and synthesized from the Simulink diagram which could be run in a Hardware-in-the-loop environment using Simulink's for test vector generation and data visualization.

Figure 15 shows the top level of the Simulink block diagram. The system clock is set to 5 Mhz. The Xilinx block can take a number of clock cycles to complete an operation, therefore the algorithm's clock rate is set relatively fast at 2.5MHz. Each loop in the sequential RLS filter is given 100 clocks to complete. With four thermopiles, four loops are needed for each output measurement. This gives a total filter rate of 6.25 KHz. Briefly stepping through the blocks, the thermopile data enters the system through the from workspace blocks on the lower lefthand side of the diagram. The gateway in blocks transfer the data to the Xilinx domain, sampled at 6.25 KHz. The data is upsampled to 2.5 MHz, and then passed through the rescale blocks which find the signals minimums and maximums, computes the amplitude, normalized the signal, and removes any DC bias. The signal enter Mux, controlled by counter, where they are sequentially multiplexed into predictor, which implements the predictor and corrector steps of the algorithm. The roll angle is then unwrapped in the mcode block to keep the values within the fixed bit length. It is enters Down Sample1 to be downsampled by 100 and then feed into Mux9 which effectively downsamples it by 4 giving an output sampling rate of 6.35 KHz.

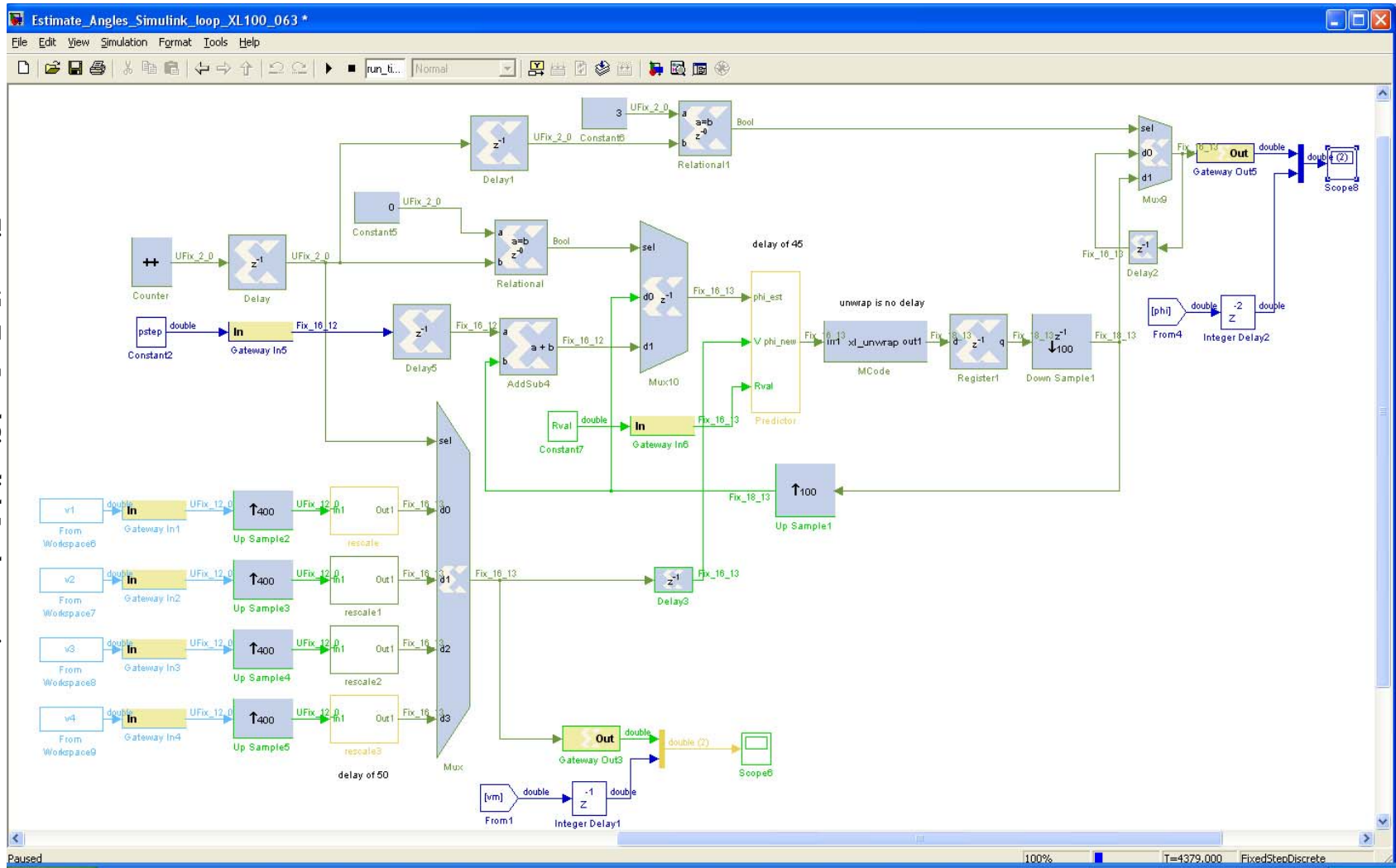


Figure 15. Top Level Simulink Implementation

The FPGA implementation was validated in a HIL environment on a Xilinx development board using simulated input data. Figure 16 shows how the fixed point FPGA algorithm converges to the floating point simulated solution. Figure 17 shows the results of using the filter on simulated input of 4 thermopiles 90 degrees apart.

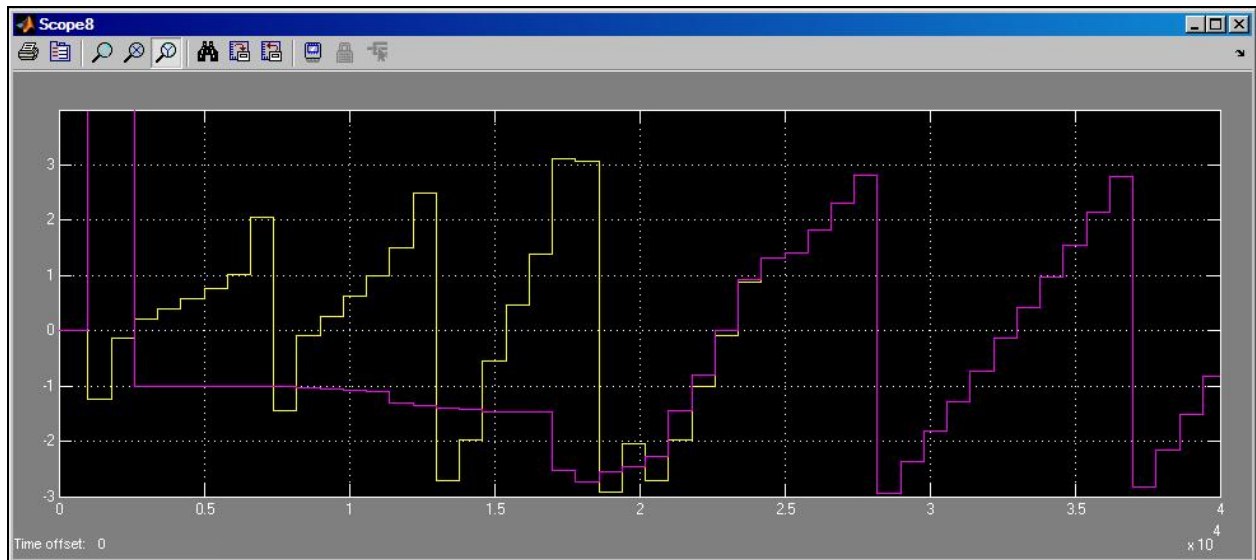


Figure 16. Comparison of FPGA Output to Matlab Simulation

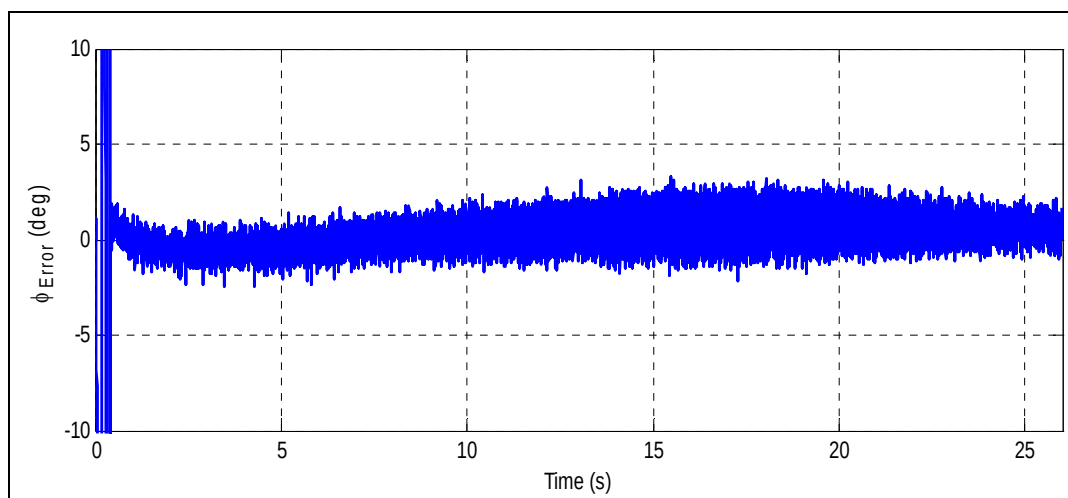


Figure 17. Simulation Roll Angle Error

One factor that was neglected in simulation was the time constant of the thermopile. Modeled as a first order system, the time constant acts like an RC low pass filter that creates a frequency dependent phase shift in the thermopile data, distorting the real frequency measurement. Figure 18 shows the phase difference between the roll angle calculated from thermopile data and the roll angle calculated from solar sensors from the second flight test. The magnitude starting at 235 degrees is a consequence of sensor location and fixed time delays and is inconsequential. What is of consequence is the 30 degree phase drift over the course of the 30 second flight.

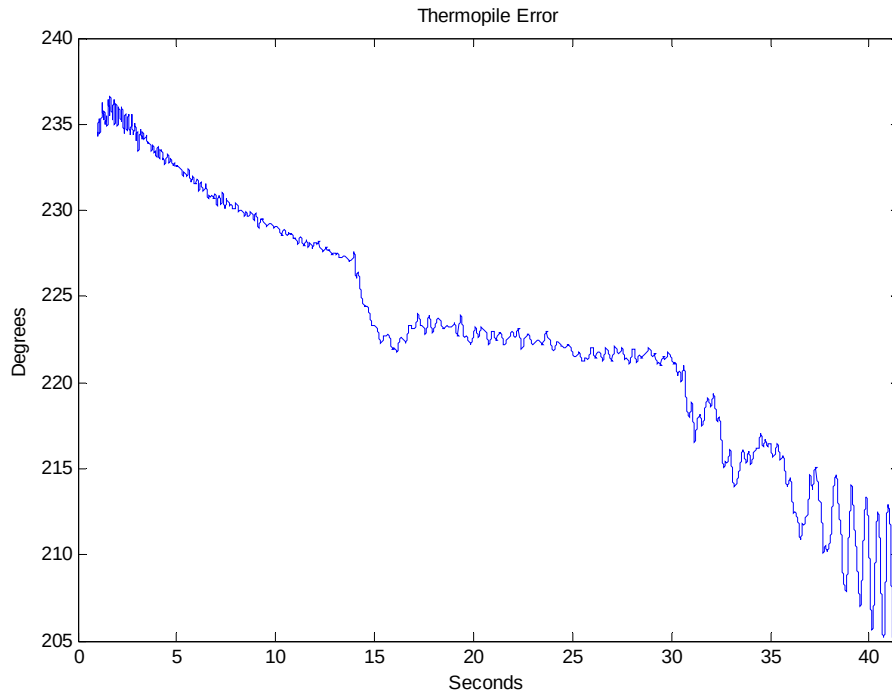


Figure 18. Thermopile Error Due to Time Constant.

In order to remove the effects of the time constant, a technique that is used in zero-phase filters was employed. Zero-phase filters achieve zero phase shift because after the data is filtered, it is reversed and run through the filter a second time before being restored to the original sequence [5]. Any phase shift that occurred from the first pass through the filter is thereby canceled out during the second filter pass. One detail that needs to be considered is that the thermopile acts as an analog filter, whereas the non-causal filtering required to remove any phase shift must be a digital filter. As long as the sampling frequency is high enough, the phase response of the digital filter will match the analog well as shown in Figure 19. Using this technique, the data was first reversed and passed through a first order low pass digital filter. The order was then restored before executing the roll angle estimation algorithm giving the results in Figure 20. Although there is still a phase drift towards the end of the flight, this is probably due to errors in the roll angle generated from the solar sensors. Solar sensors easily give a reliable roll angle when the projectile is aligned to the direction of travel. If this is not the case the roll angle will be inaccurate. In the latter half of this flight test the projectile was maneuvering which could lead to misalignment between the projectile and its path of travel leading an inaccurate solar roll angle.

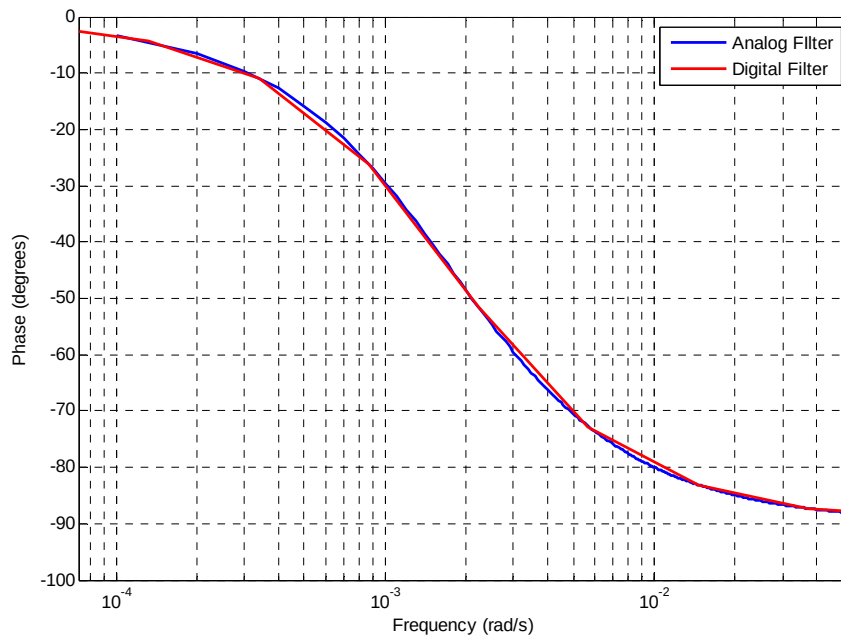


Figure 19. Analog vs. Digital Phase Response

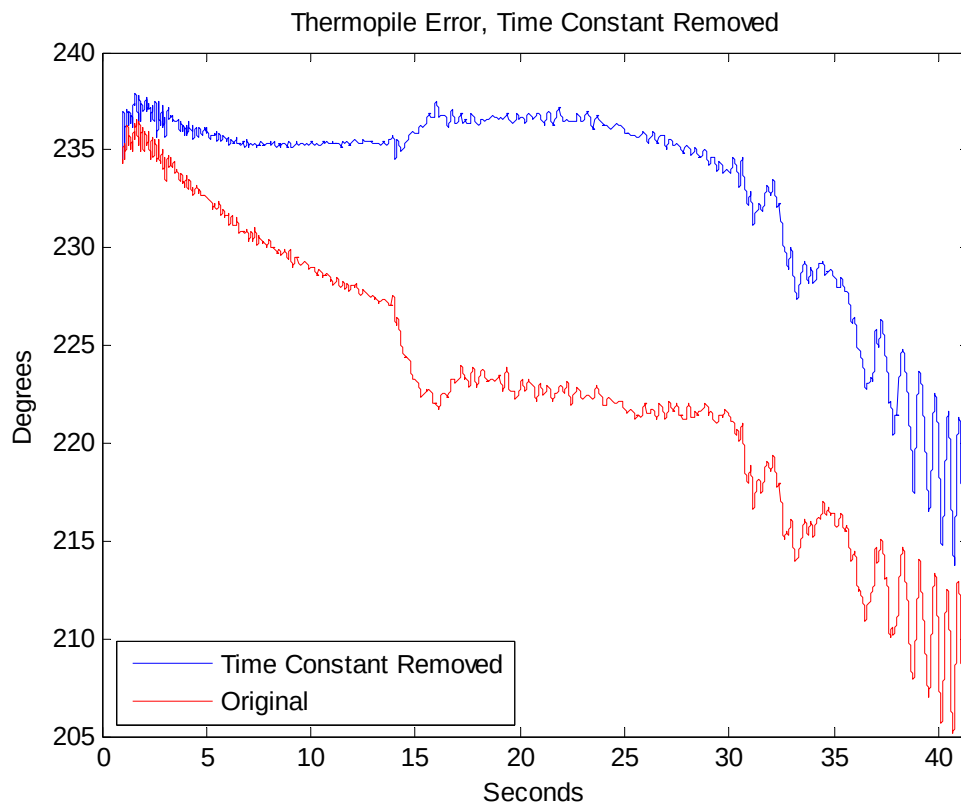


Figure 20. Thermopile Error, Time Constant Removed.

CONCLUSION

Thermopiles are a promising sensor to accurately estimate roll angle. More work is required to understand and mitigate large DC bias shifts in the thermopile output during launch. Real time compensation for the thermopile time constant must also be explored. ARL has made significant advancements in developing gun-hardened thermopile units to integrate into guided munitions as well as the supporting test and celebration procedures. Implementation of a roll angle estimation algorithm on an FPGA enables on board real time processing to support guidance and navigation.

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