Milestone Report 2

# Autonomous Thermal Camera EE449

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**Executive Summary**

The purpose of this milestone was to understand the systems modeling parameters. This includes the parameters, equations, inputs, outputs and internal states along with any observable and/or observable models. Due to delays in finding the adequate material to protect the thermal camera all goals were reached except for a comprehensive system simulation.

## List of Symbols

- Motor winding resistance $R_m$ (Ohms)
- Motor winding inductance $L_a$ (H)
- Torque constant $K_T$ (N-m/A)
- Motor constant $K_v$ (V-sec/rad)
- Back-emf voltage e(t)
- Nonlinear friction $B_m$ (N-m)
- torque delivered by the motor T(t) (N-m)
- Armature voltage $V_a$(t) (V)
- A disturbance torque $T_L$(t) (N-m)
- motor drive inertia $J_m$ (kg-m2)
- Change in current di(t)/dt
- Initial Angular Acceleration Theta-double-dot(0+)

## Mechanical Modeling

The mechanical part of our system consists of the plant(Thermal Box) and the motor that will be used to rotate the box. As can be seen in the figure below, aside from using gears instead of pulleys, our system can be represented as a rotational force governed by Km the motor constant and a bearing damper B connected to a load with a load inertia JL. When input voltage Vi increases and feeds through the Motor resistance R the DC motor rotates with a motor rotor inertia Jm[1].

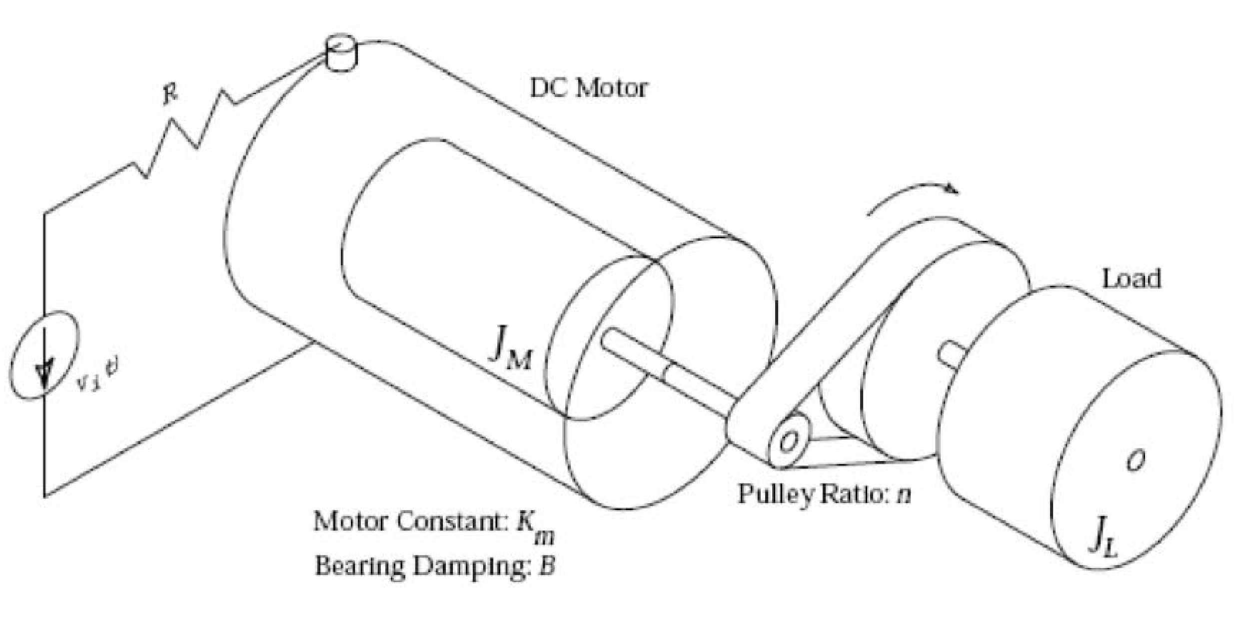


Figure 1: Graphical Dynamic System[1]

This system can then be evaluated graphically using the cyclical graphical approach as shown in the figure below.

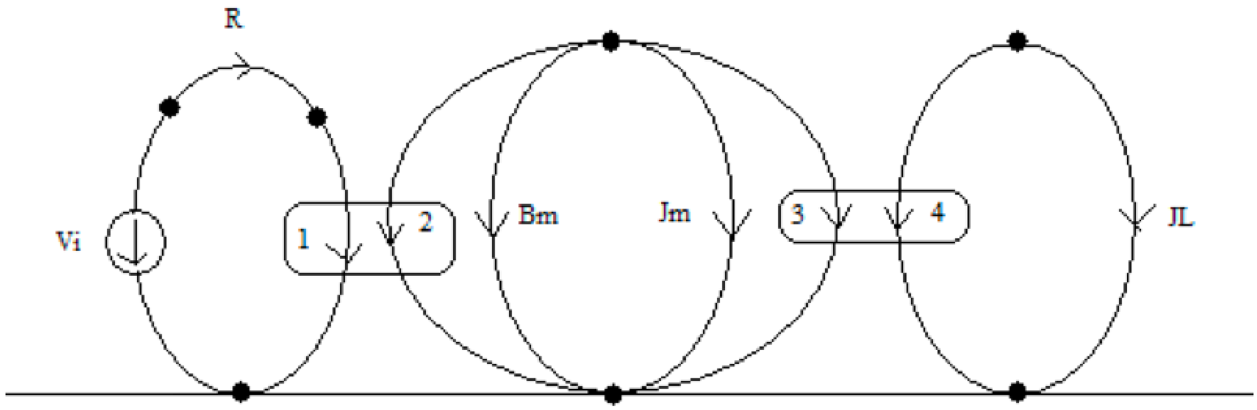


Figure 2: Electrical to Mechanical Cyclical Dynamics Graph[1]

The cyclical graphical approach allows us to ignore motor winding inductance and characterize the transition from electrical energy to mechanical motion using a graphical approach instead of a mathematical one by assuming that any change from mechanical to electrical can be represented as links. This method directly gives the equation below.

$$\frac{d\Omega_m}{dt} = \frac{-n\ \left(k_m{}^2 + B_m R\right)}{R(J_L + n^- J_m)}\Omega_m(t) + \frac{n^- k_m}{R(J_L + n^- J_m)} V_i(t)$$

Figure 3: Electrical to Mechanical System Equation[1]

From this equation we can see that the change in motor resistance is determined by a change in resistance and the Voltage that enters the system. Canceling and Solving for the motor resistance gives us the equation below.

$$\Omega_m = \frac{d\theta_m}{dt}$$

Figure 4: Motor Resistance[1]

Were the integral of the motor angle derived from the original equation is:

$$\theta_m(t)\left(s^2 + \frac{n^2\left(k_m{}^2 + B_m R\right)}{R(J_L + n^2 J_m)} s\right) = \frac{n^2 k_m}{R(J_L + n^2 J_m)} V_i(t)$$

Figure 5: Motor Angle [1]

Taking our equation for the motor angle over the input voltage then gives us our transfer

$$G(s) = \frac{\theta_m(t)}{V_i(t)} = \frac{\left(\frac{n\ k_m}{R(J_L + n^2 J_m)}\right)}{\left(s^2 + \frac{n\ \left(k_m{}^2 + B_m R\right)}{R(J_L + n^2 J_m)} s\right)}$$

function as shown below.

Figure 6: Final Transfer Function [1]

## *Controller Logic and Modeling*

### *Controller Requirements*

For the purpose of recording footage of wildfires, the customer indicated that accuracy and speed were not considerations for them. Along those lines, the requirements for the controlled system are as follows:

1. The plant must be able to detect and track a hot spot of the fire with an error of 45˚.
2. The settling time must be less than 20 seconds.
3. The controller should remain stable in a noisy environment.

### Overview

In order to isolate complexity to one particular subsystem, the controller logic of the fire tracking system is comprised of two parts: position control and heat tracking. The position controller is comprised of a simple proportional controller. This controller takes an angular position as its command signal and using a quadrature encoder, is able to track any angle with negligible [specify/prove] steady state error.

The second stage of the controller acts as an outer loop on the position loop. In order to detect the presence and direction of the fire, thermopiles (also known as Pyrolytic Infrared or PIR sensors) are used in a radiating configuration to detect heat in all directions.

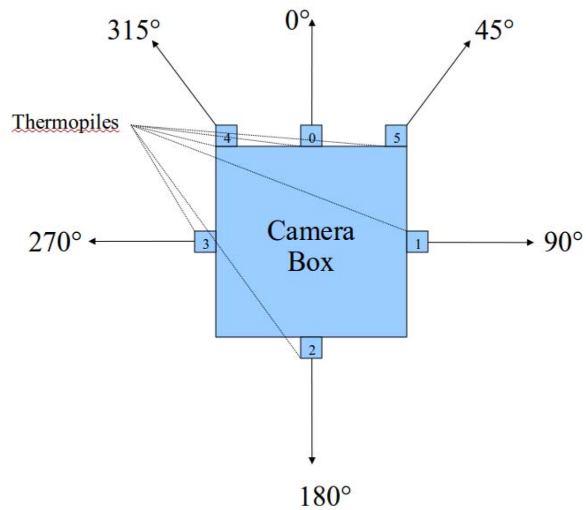


Figure 7: Description of Sensor Layout

Since the values gleaned from the six PIR sensors above do not immediately give an accurate direction of the fire, a controller must be used that can move them around to more accurately determine the direction of the fire.  To accomplish this, the following logic is implemented in software.

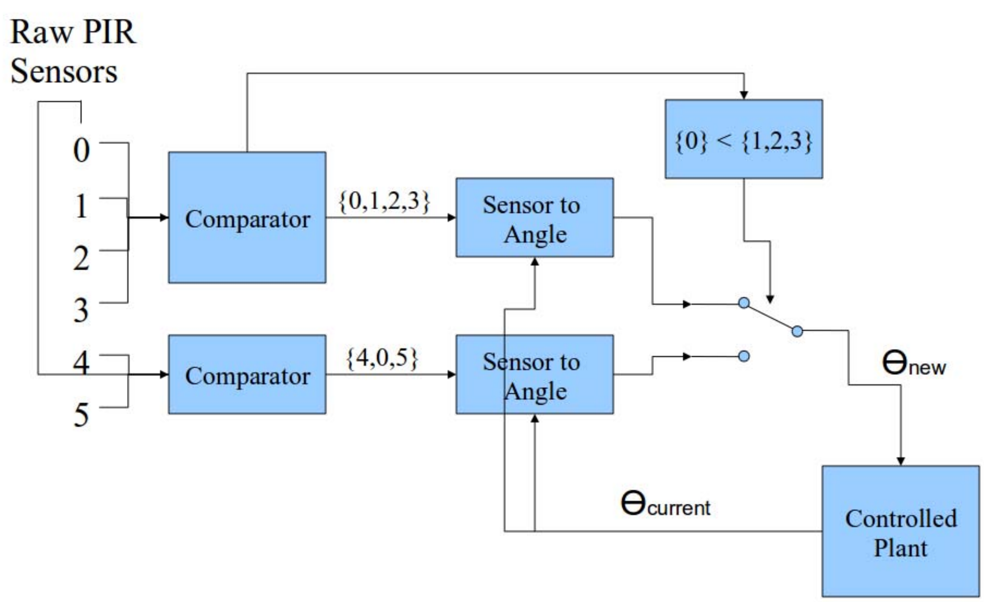

Figure 8: Block diagram of the fire tracking logic

The functionality can be explained as such:

Discovery State: If either sensor 1,2, or 3 has a higher voltage (higher incident heat) than sensor 0, then rotate to that position. This causes the controller to seek its position to either 90, 180 or -90 degrees depending on which sensor reads the highest intensity.

Trim State: If none of the sensors 1,2, or 3 have a higher value than sensor 0, then compare the value of sensor 0 with sensors 4 and 5. If either 4 or 5 have a higher value, then track by increments of 5% in the direction of the higher temperature.

Do Nothing: If sensor 0 has the highest value, then no action will be taken as that sensor is looking at the highest perceived temperature. Even if there is a section of fire that may be hotter, the camera is recording a substantial section of the flame and is subsequently satisfying the requirements of our customer.

## Modeling

For the purpose of this report, it was indicated that proof that the controller will satisfy the requirements of being able to target and watch fire in a stable and timely manner was required. To this effect, a Simulink model was created to emulate the controlled system in as realistic circumstances as was feasible to create within the available expertise and time constraints.

### *Thermopile Model*

While very little information is available about the precise characteristics of most thermopiles as manufacturers generally leave the calibration and characterization of such components to the customer [3][4], based on experience with similar photoelectric components [5] it might be expected that a PIR sensor will express a roughly Gaussian behavior regarding angle of incidence. By this logic, a purely angle based model for the PIR sensor was constructed. The equation for this model, where u is the number of degrees that the camera faces away from the heat source is:

$$y = e^{\left(\frac{5u^2}{2 \cdot 180}\right)} \qquad [6]$$

$$-180 < u < 180$$

### *Controlled Plant Model*

Since the plant has not been constructed yet, the characteristics have not yet been determined. That said, the basic characteristic curve of a motor can be modeled using the physics derived in EE/AA 448 for the DC motor lab. [2] This consists of the following Simulink model:

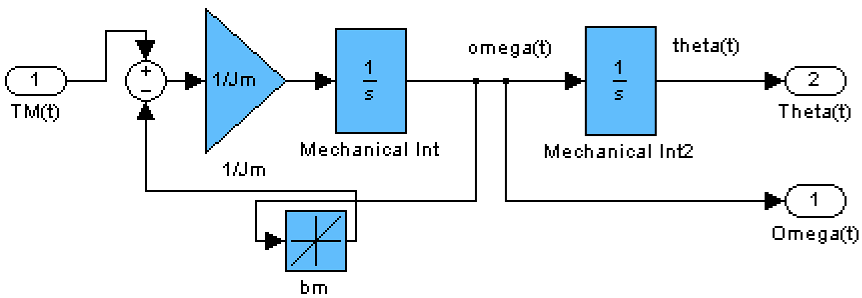


Figure 9: Simulink model describing the behavior of a motor

Where Jm is the mass of the angular load, bm is the damping behavior of the bearings and TM(t) represents the torque applied by the motor.

In this configuration, a Jm and bm were chosen as .2 and 1 respectively to obtain a reasonable closed loop response. A value of 1 was chosen for the closed loop gain.

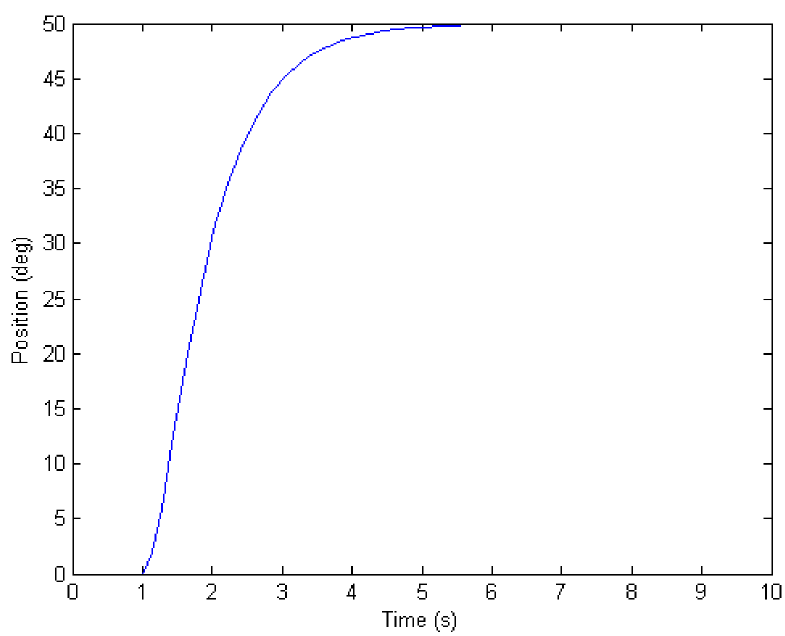


Figure 10: A simulated step response for an arbitrary motor system similar to the expected response of the plant

It should be noted that the parameters chosen were done so as to produce a step response similar to the worst case expected response from our box-motor device. By choosing a worst case plant, the outer loop's robustness can be better tested.

### *Fire Tracking Model*

The logic that used for the purpose of fire tracking is the same as presented in the controller Overview. In order to be modeled, this was created in Simulink and linked up with the aforementioned simulated components.

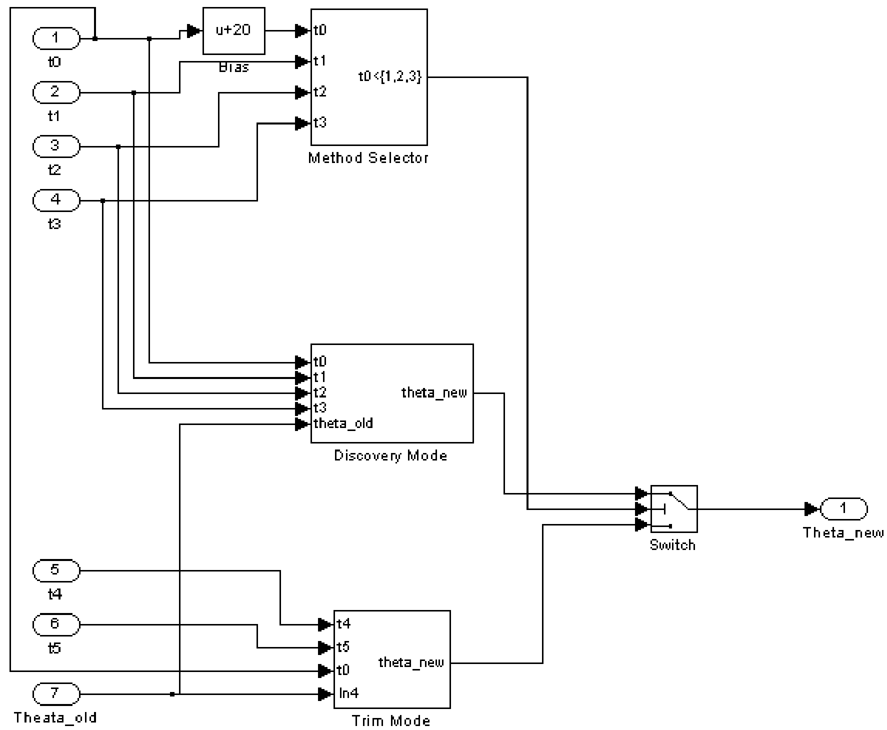


Figure 11: The overview view of the Sensor to Angle module showing both modes of control

The individual Sensor to Angle modules are also shown.

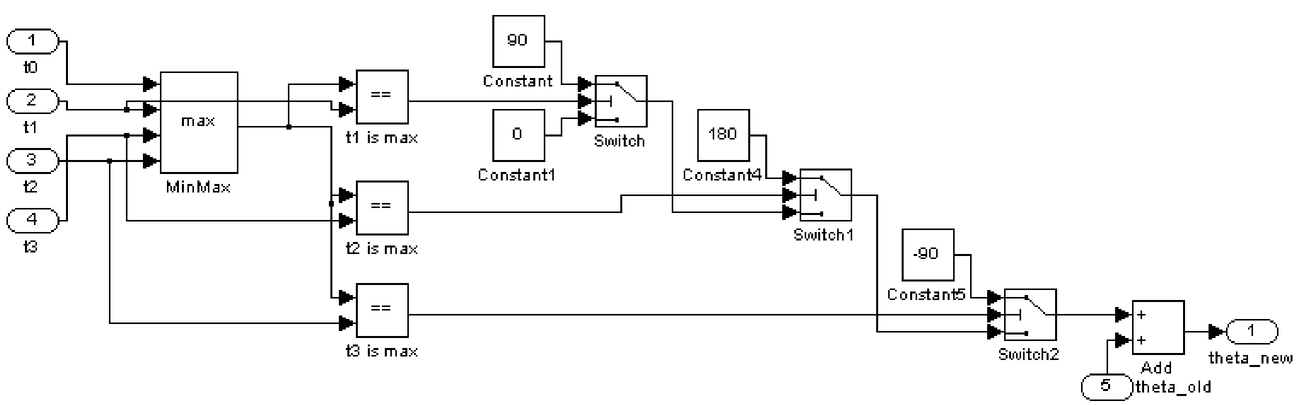


Figure 12: The discovery mode module

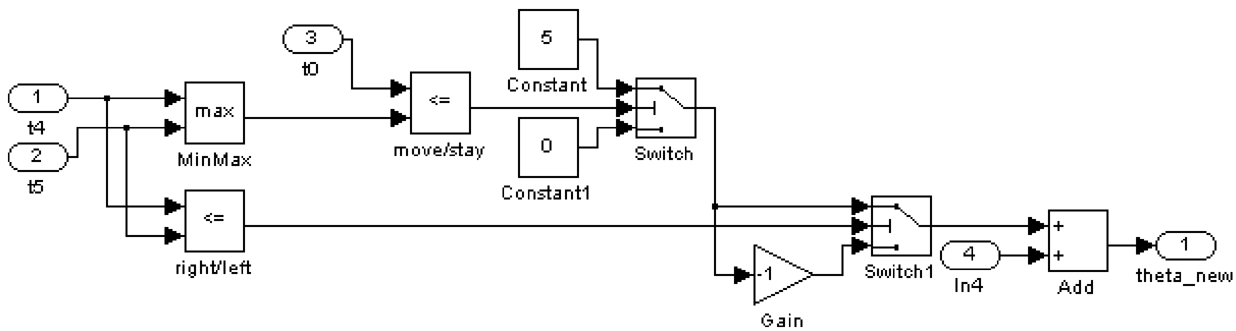


Figure 13: The trimming mode module

**Model Analysis**

For the purpose of empirically testing this model, a series of step responses and noise signals were introduced into the simulated value representing the direction the heat of the fire originated from. From these responses, it was determined that for all angles, the controller was able to track and settle well within 4 seconds to a steady state error of less than 20˚.

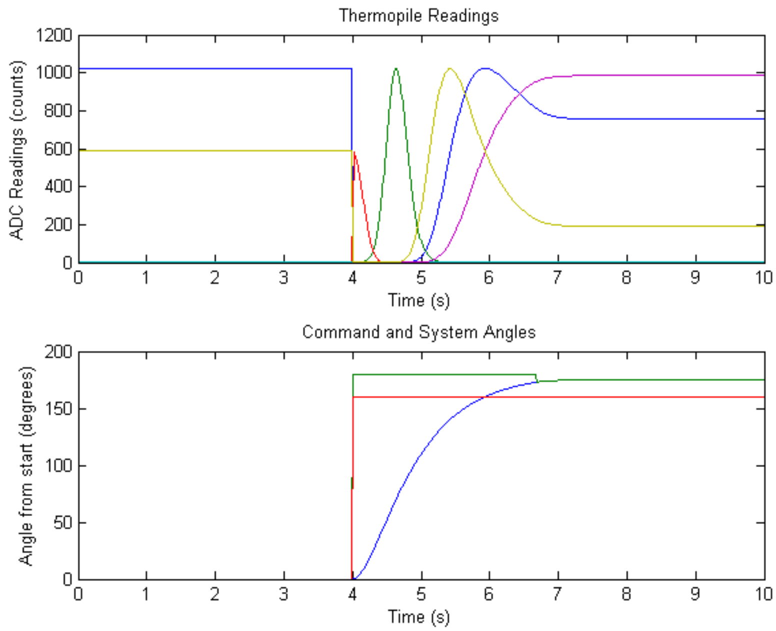


Figure 14: Testing multiple step responses showed the system always turned towards the fire

When introducing noise into the fire position, the thermopile measurements seemed to generally amplify that noise. Even with +/- 20˚ of noise, the controller exhibited a stable behavior and was not perturbed.

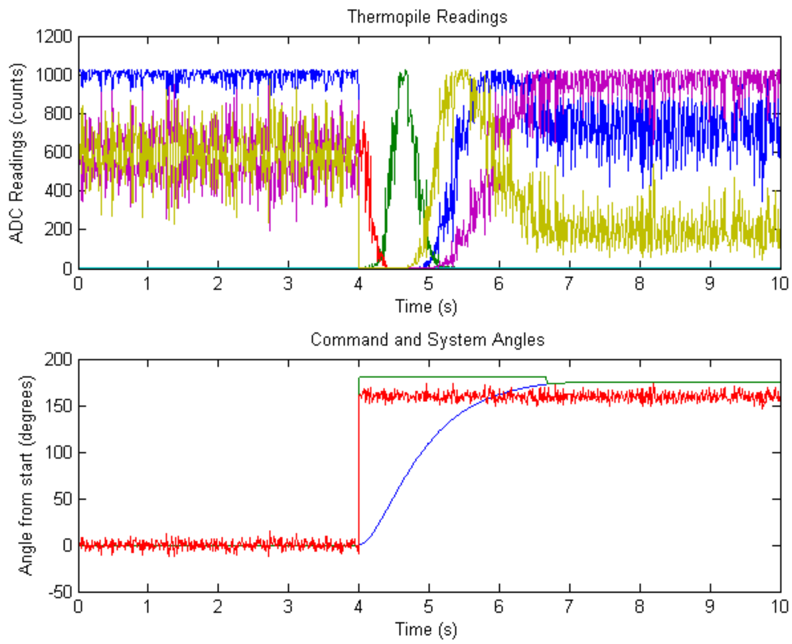


Figure 15: Even with large amounts of noise, the controller remained stable

## *General Remarks*

In terms of the usability of this project's plant, there exist two components. For the physical motor-box assembly, the plant is both observable and controllable due to the quadrature encoder and the well understood behavior of a DC Motor driven system. The second component, the wildfire, can be considered as part of the plant and subsequently presents some problems. The wildfire itself is definitely not controllable and for some purposes, it is not even observable. For our purposes of tracking the flame, some inferences must be made when the sensors available only show a fraction of the entire state of the fire. In order to work with this constraint, the above controller design was implemented.

Even with the potential incongruencies between our model and the real world, the ultimate controller parameters will come down to adjusting the gain on the proportional controller and the thresholds on the fire tracking controller. These modifications are so one-dimensional that our team could potentially tweak the parameters by hand using test stimuli. Since the engineering tolerances on the controller systems are so low as per our customer's requirements, even a poor model is sufficient. (Note: We do not consider the controller characterization to be "poor," this statement was to point out the constraints.)

[1] Dr. Per Rienhall. System Dynamic Analysis and Design Mechanical Engineering, http://faculty.washington.edu/reinhall/ME374/labs/Lab%201%20Spring10.pdf

[2] Dr. Uy-Loi Ly. Course Resources for EE448, https://courses.washington.edu/aa448/labprojects.htm

[3] PIR Sensor CO., LTD. Pyroelectric Infrared Radial Sensor, http://www.futurlec.com/PIR_Sensors.shtml

[4] Melexis. Thermopile Infrared Sensor Datasheet for MLX90247, http://media.digikey.com/pdf/Data%20Sheets/Melexis%20PDFs/MLX90247.pdf

[5] Vishay Semiconductors, Datasheet for Silicon PIN Photodiode BPV10NF, http://www.vishay.com/docs/81503/bp10nf.pdf

[6] Carl Friedrich Gauss, Disquisitiones Arithmeticae, 1798