Satellite Attitude Control System

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***Abstract*—This paper discusses the design of a satellite attitude control system. An attitude control system utilizes commands provided by a controller to the thrusters (i.e., actuators) to correctly position a satellite (i.e., the plant) to operate any instruments or tools that require specific positioning. The satellite attitude control system has been implemented in discrete time (z-domain) as opposed to continuous time (s-domain). Discrete controllers have been popular in industry for many reasons including ease of modifications (software versus hardware), low cost, and their low susceptibility to noise, environment, and aging [iv]. Knowing the system's open-loop response is important when designing a controller for a closed-loop system. The system is inherently open-loop unstable as any input or disturbance will cause the satellite to continuously spin without a means of stopping as the satellite is assumed to be in space (i.e., a nearly frictionless environment). Therefore, a tuned closed-loop control system, using a Proportional-Integral-Derivative (PID) controller, is required to position the satellite correctly and remain stable. This paper provides the block diagram of the open-loop and closed-loop systems, the transient response of the system, the effect of disturbance on the system, a description of the tuning for the discrete PID controller, and a state-space representation of the attitude control system. This paper also provides a sensitivity study of system response due to sampling frequency (Fs) and the PID parameters.**

I. Introduction

By traveling at velocities high enough to counteract the gravitational force exerted by the Earth, satellites are able to remain in orbit around the Earth. The attitude control system used within this paper focuses on controlling the orientation of the satellite in space via thrusters receiving commands from a discrete controller [1]. This allows for position changes to the satellite to ensure that the gravitational force of the earth will not cause the satellite to go unstable and leave Earth's orbit.

This report looks at the development of a discrete control system that orients a satellite in space via thrusters. The satellite and environment consist of assumptions that enable the focus to stay on the controls aspect rather than diverging into the engineering and physics of satellite design..

Open-loop and closed-loop models of the system were created using Matlab and Simulink. Each model consists of the satellite (i.e., plant), a discrete controller, a disturbance introduced into the system, a sampler, a thruster gain (i.e., actuator), and a zero-order hold (ZOH). The closed-loop system utilizes feedback, which is modeled as a sensor gain (Hk).

II. Background

The word satellite has many definitions. It can be a moon or a planet or a machine found in space that orbits a mass. The

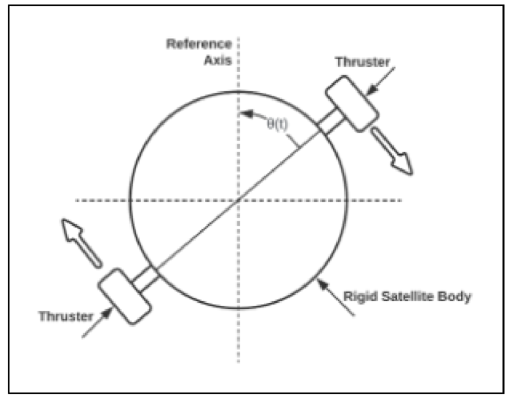


Fig. 1. Satellite

mass can be a star or a planet. In the case discussed within this paper, the satellite is a machine that will be orbiting the earth with a goal of remaining in orbit, which requires varying positional adjustments via the thrusters [i]. Attitude control is one of the fundamental challenges with satellite and spacecraft control. The two parts of the problem include detection of rotation, and torque correction of the rotation.

Rotational detection can be covered through the use of internal or external methods to the satellite itself. Internally, a gyroscope can be used to detect subtle changes in rotation due to its sensitivity. Externally, there are position sensors that can take images of different astronomical bodies to determine changes in rotation (e.g., looking at the horizon of the earth) [ii].

There are several different options or technologies that can be used to implement torque correction. Thrusters are generally the most common solution, where a system consumes fuel to produce the forces necessary to generate torque on the rigid body [iii]. General spin stabilization, through the use of fins or other aerodynamic implementations, can be used while the body is operating within an atmosphere. Momentum wheels can provide precise control, and do not need fuel to operate - only requiring electricity to power the rotors. Additionally, there are methods that utilize the magnetic field from the earth as well as the gravitational forces to orient a satellite.

This project discusses the design of a discrete attitude control system that uses thrusters to achieve the corrective forces necessary to orient the satellite on its axis and remain in orbit.

To accomplish this, it is assumed that the satellite is a rigid spherical body, with thrusters positioned 180° from one another. These thrusters are capable of providing forces in two directions tangent to the body of the satellite itself.

Assumptions include:

- Rigid satellite body and of uniform density
  - This allows for simplified calculations
- Operating in a frictionless environment
  - There will be no force acting on the satellite when the system is in motion
- The satellite is constrained on a two-dimensional (2D) axis
- Thruster impact on the system will be modeled as a constant gain (K)

III. OVERVIEW

The satellite will be of spherical shape orbiting the earth. As it rotates around the earth the orientation of the satellite will need to be adjusted to remain in orbit. This will be achieved by using the two thrusters found on each side of the satellite.

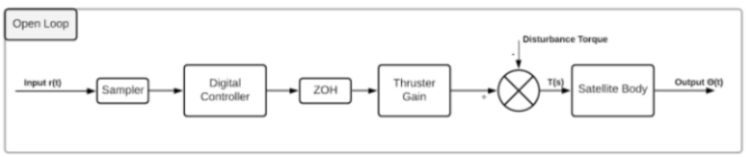


Fig. 2. Open Loop

The open-loop system block diagram is shown (Fig.2). The input r(t) will be an analog voltage that will be translated through our controls, to an output of theta. This input voltage will range from 0-5 volts corresponding to a desired angle. The input goes into a sampler that transforms the continuous input into discrete time, which is the input to the digital controller. The digital controller is a PID controller tuned to ensure the system remains stable for a bounded input. The output of the controller feeds into a ZOH and is scaled by the thruster gain. The thruster gain output is a torque that is applied to the system to reach the desired angle, referred to as theta. A disturbance torque is also acting on the satellite. The thrust gain torque and the disturbance torque together, make up the total torque applied to the satellite, which feed into the plant transfer function providing the actual angle of the satellite.

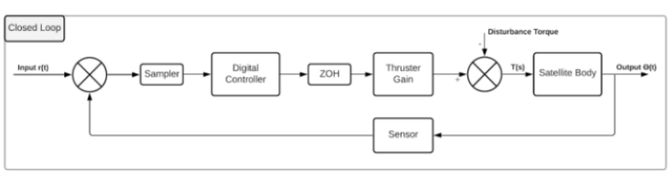


Fig. 3. Closed Loop

The figure above (Fig.3) shows the block diagram for the closed-loop system. The two models (open-loop and closed-loop) are identical with the exception of the sensor found in the feedback path of the closed-loop system. Here the sensor will take in the output signal theta which is fed back into the summation block with the input where the error signal is derived.

IV. SYSTEM DESIGN CHARACTERISTICS

In order to fully understand the design of the system, critical design information/characteristics are listed below:

1) Moment of inertia

   The moment of inertia used here is represented by the variable "J". The value of the moment of inertia will be

   $$J = 0.1kg * m^2$$

   This will give us an output that is equatable while still allowing the focus to be on the control of the system.

2) Input

   As previously discussed, the input to our system, represented by r(t), will be an analog voltage signal. This signal will range from -5 V to +5 V. This voltage will be fed into our controls which will be translated into the requested output theta.

3) Sensor gain

   The sensor gain (Hk) will be set at 0.02. The sensor gain will translate the output theta into an analog voltage that will compare to the input voltage range of +/- 5V.

4) Thruster gain

   The thruster gain will be set at a constant 2 and be represented by (K).

5) Disturbance torque

   The disturbance (D) will be a torque value that will be randomized using Matlab.

6) Sampling period

   The sampling period will be at a constant of 0.01 sec. This gives us a sampling frequency

   $$f = \frac{1}{0.1} = 100Hz$$

V. IMPLEMENTATION OF MATLAB AND SIMULINK

Using Matlab and Simulink we were able to create our open loop and closed loop control systems. Each variant results in different output for the satellite body. The open loop model (Fig.4) is designed to be manipulated using MATLAB scripts for ease of analysis. Inputs are set as constants that can then be updated in the active workspace.

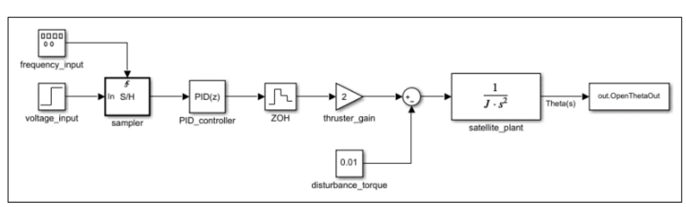


Fig. 4. Open loop model

Set up in a similar way, the closed loop model (Fig.5) adds the feedback loop using sensor gain along with additional disturbance controls for more analysis.

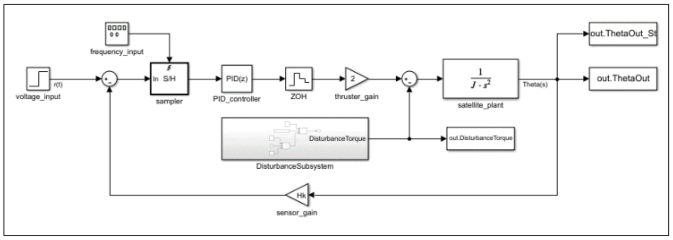


Fig. 5. Closed loop model

VI. RESULTS

A. Transient Response

The open-loop transient response for the attitude control system is entirely dependent on the input. This is because the output of the system grows in a non-linear manner and a larger magnitude input causes the angle to increase in a more rapid manner. The figure below (Fig.6) shows the open-loop system created in MATLAB/Simulink with a constant disturbance torque of 0.01 Nm.

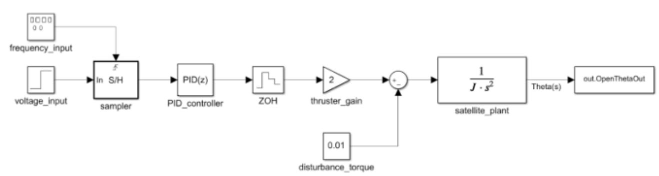


Fig. 6. Open loop Simulink model

Any non-zero input will result in the system becoming unstable as time approaches infinity. The results are as shown below (Fig.7) in the plot, which varies input.

In order to reliably control a satellite's attitude, a closed-loop control system is required, which can be implemented digitally or analogously. Digital control systems are preferred for many reasons including low cost, software modifications (as opposed to hardware), and decreased susceptibility to environmental aspects. The figure below (Fig.8) shows the implementation of the digital closed-loop attitude control system in MATLAB/Simulink.

The digital control system utilizes sensor feedback represented as a gain block referred to as Hk. The summation block takes the input and subtracts the feedback to achieve an error signal for the digital controller to minimize. The sampler digitizes the continuous time input by taking samples at the sampling rate, Ts, which then feeds into the digital controller. The output of the digital controller is fed into a ZOH block to create a continuous time signal that gets summed with a disturbance provided to the plant. Depending on the voltage

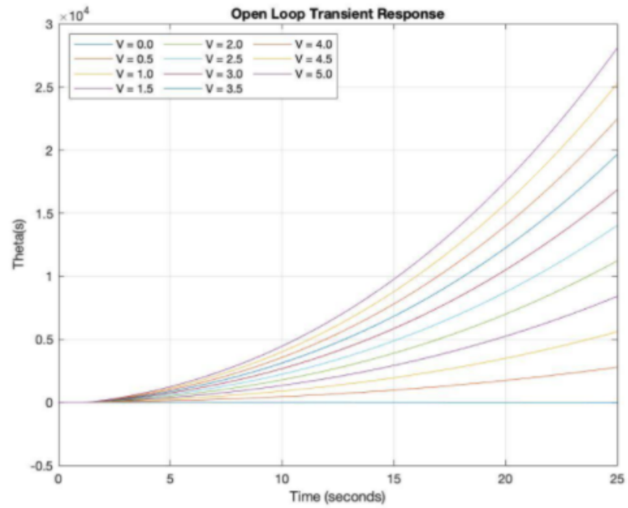


Fig. 7. Open loop Transient Response

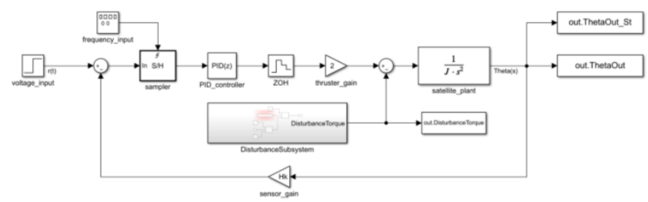


Fig. 8. Closed loop Simulink model

input, which correlates to a desired angle (theta), the closed-loop system reaches a steady-state value in a quick manner and is stable.

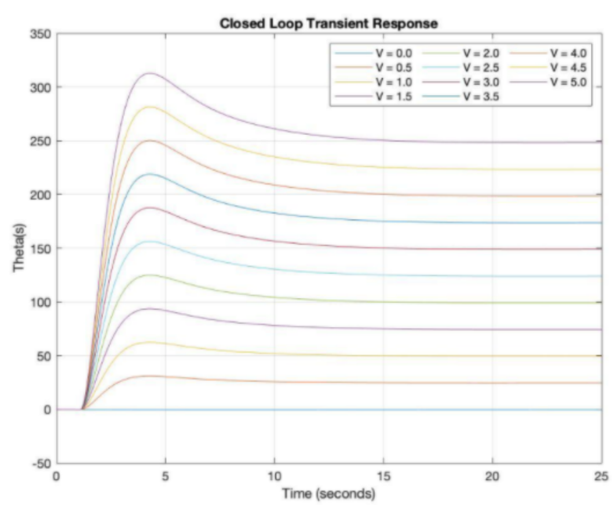
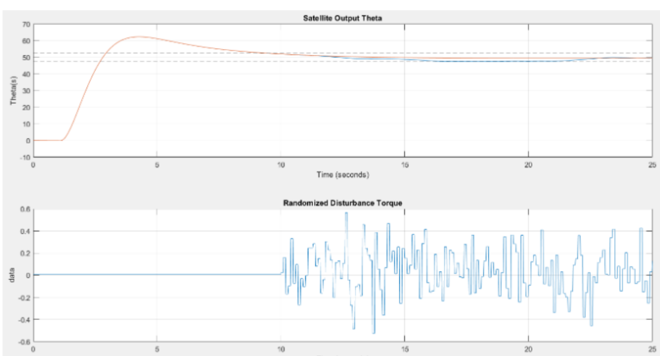


Fig. 9. Closed loop Transient Response

B. Effect of Disturbance and Controller's Impact on Disturbance

The open-loop system step response approaches infinity as time approaches infinity (i.e., the open-loop system is not stable). As a result, any disturbance will result in the system approaching infinity at a quicker rate. Although disturbance doesn't highly impact the open-loop system step response, it does significantly impact the closed-loop system response as the closed-loop system, with a well-tuned PID controller, is stable. The closed-loop system response is heavily dependent on the magnitude of the disturbance. The disturbance impacts the settling time of the output (i.e., the time it takes for the output to remain within +/- 2% of the steady-state value). The steady-state "band" is depicted in the figures below as the dashed blue line in the top subplot. The figure below shows the closed-loop system step response. After 10 seconds, a randomized disturbance is added to show the impact to the system and controller. Each figure modifies the mean of the randomly generated function with a variance of 25% of the mean (e.g., mean of 0.05 results in a variance of 0.0125). The first subplot of the following figures show the system step response with no introduced disturbance (orange line) and the step response with the disturbance added after 10 seconds (blue line). The second subplot shows the disturbance that is being applied to the system.

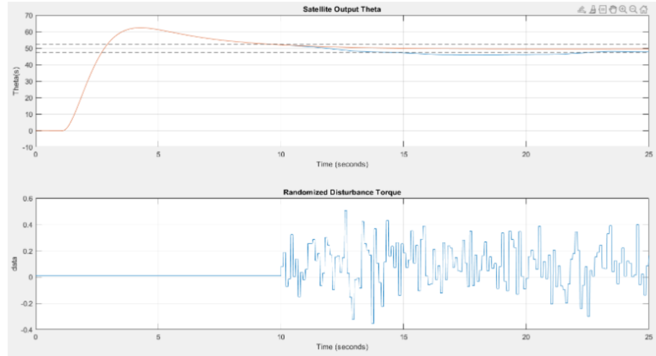


(Mean 0.05 Nm)

Fig. 10. Disturbance mean 0.5 Nm

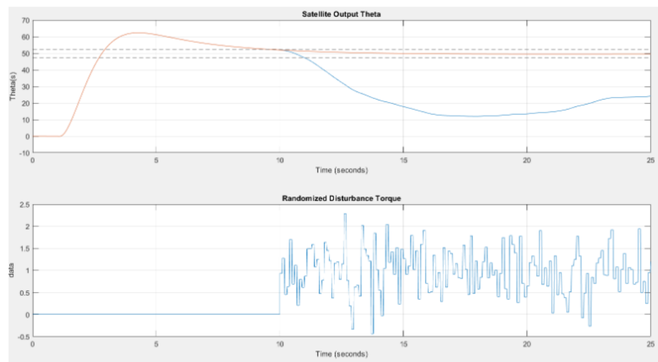
A slight disturbance (i.e., a disturbance with a mean of 0.05 Nm) shows that the system remains well-controlled and within the steady-state band. A more severe disturbance (mean of 0.1 Nm) (Fig.11) results in the output leaving the steady-state band and increasing the settling time of the system. However, the controller still handles the disturbance well and is nearly back at the steady-state value after 15 seconds.

An exaggerated disturbance is provided in the plot below (Fig.12) which is ten times greater than the magnitude of the disturbance in the previous plot. It is clear that the controller cannot handle such a massive disturbance well and the steady-state value starts to deviate largely from the expected value of 50 degrees.



(mean 0.1 Nm)

Fig. 11. Disturbance mean 0.1 Nm



(Mean of 1.0 Nm)

Fig. 12. Disturbance mean 1 Nm

C. State Space Analysis

Conducting state space analysis on the closed loop system is a useful practice to collect and characterize general information. Commonly adapted to time series, this method is more critical in the application for Multiple Input Multiple Output (MIMO) systems but is applicable to Single Input Single Output (SISO) systems as well [d]. The satellite model used for analysis is currently developed as a SISO system.

Calculated using inverse z-transform tables, the transfer function of the closed loop system can be defined and written in MATLAB by the following code:

```
% using J=1, T=0.01
numerator = [0.0001,0.0001];
denominator = [2,-4,2];
sys = tf(numerator,denominator);
```

Fig. 13.

Where the output transfer function is:

Translation of this into a state space system yields the following matrix representation.

```
0.0001 s + 0.0001
-----------------
 2 s^2 - 4 s + 2
```

Fig. 14.

Given:

$$x(k+1) = Ax(k) + Bu(k)$$

$$y(k) = Cx(k)$$

The MATLAB ‘ss’ function determines the state space matrices to be:

```
A =
        x1   x2
   x1    2   -1
   x2    1    0

B =
              u1
   x1   0.007813
   x2          0

C =
           x1        x2
   y1  0.0064    0.0064
```

Fig. 15.

Stability analysis of the state space equations can be completed. This includes the calculation of the closed-loop poles, along with building the root locus.

Poles for the system are determined as 1+j0.01and 1-0.01j. Since the real part of the pole is positive, the closed loop system is said to be unstable. This analysis does not factor in the PID controller for the system.

Plotting the root locus (Fig.16) confirms the placement of the poles and zeros of the system, and highlights that stability is possible. Further attempts to introduce stability to the system is analyzed in the section on PID tuning - where a PID controller introduces terms to achieve system stability.

D. Sampling Frequency Impact on Response

The introduction of a sampler to the control model allows for use of digital controls techniques on the control signal, as opposed to standard analog methods. The design and implementation of the sampler itself can have a significant impact on the output signal. Aliasing, and other issues will become apparent when the sampling frequency is not set correctly. Analysis was completed by sweeping through several frequencies and inspecting the resulting step response.

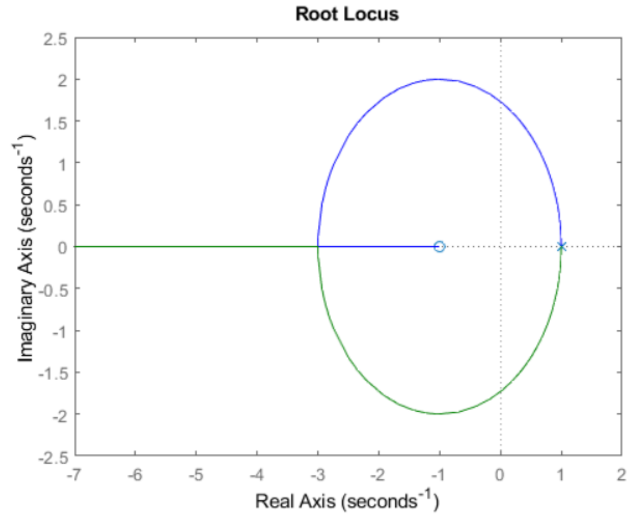


Fig. 16. Root Locus

For the closed loop system defined, the calculated bandwidth was found to be 0.011 given the base sampling frequency and standard step response. This was determined using the MATLAB ‘powerbw(..)’ function. From this, the nyquist sampling rate was calculated to be 45 Hz. The analysis completed below (Fig. 17) shows sampling completed below and above the nyquist rate, looking to highlight the impact and importance of selecting a high enough sampling rate to avoid adverse sampling effects [c].

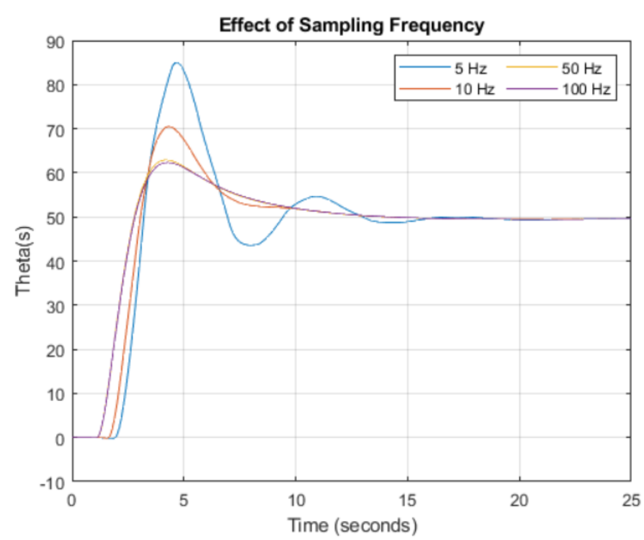


Fig. 17.

At a sampling rate of 5 Hz there were several noticeable impacts on the control response. Rise time was decreased, there was significant overshoot, the settling time was increased, and overall the system appeared to be more underdamped than we would have expected. Sampling rate of 5 Hz is well below the nyquist rate, indicating that there is some amount of aliasing or data loss that is occurring.

The 10 Hz sampling rate is still below the nyquist rate, and was seen to exhibit similar effects on the step response to the 5 Hz rate. Most prominently, there was a significant increase to overshoot. The other impacts are much less significant when compared to the standard step response.

Moving to 50 Hz and 100 Hz, past the nyquist rate, the expected step response can be seen with minimal difference or advantage to further increasing the sampling rate. After exceeding the nyquist rate for the system (45 Hz) there were no longer signs of aliasing.

E. PID Tuning

A three-term PID controller was chosen to be used as part of the closed loop model. This choice introduces three different parameters that were controlled to adjust the desired output response. For this model and the design parameters it was desirable to have an underdamped response, where overshoot is fine as long as the model can reach the requested rotational angle in a reasonable amount of time. Depending on the function of the satellite, this may or may not hold true for a real-world application.

$$K_p + \frac{K_i}{s} + K_d * s$$

With a three-term PID controller there are several options for tuning that can involve complex analysis of the system to achieve the desired response. Methods such as the Tyreus - Luyben (T-L)Technique or Modified Ziegler-Nichols(M Z-N) Technique have been proven and tested extensively [a]. MATLAB Simulink offers tuning capability built in, following a manual tuning method where the user is responsible for determining the output response that is desired and the tool back-calculates the PID terms required.

Modifying each term of the PID controller has various impacts on the characteristic of the control step response. This can be seen in the system rise time, settling time, overshoot, steady state error, and stability. Impact of these modifications is summarized in table xx shown below [b]. The following analysis confirms the information in this table.

Change & Term	Rise Time	Settling Time	Overshoot	Stability
Increasing Proportional	Decrease	Increase	Small Increase	Degrade
Increasing Integral	Small Decrease	Increase	Increase	Degrade
Increasing Derivative	Small Decrease	Decrease	Decrease	Improve

Table xx: Impact of increasing PID terms on specific output

Fig. 18.

1) Proportional Impact: The baseline proportional term of 0.56 was used to generate the step response for all other analysis. To view the impact of the proportional term, it was stepped from 0.0 (inactive) to 1.0 by 0.1 increments. Rise time decreases with each increment, and overshoot of the baseline value increases. Settling time and stability were more difficult to discern, but this has been attributed to how the integral and derivative terms were left at the baseline values - likely overpowering the proportional term for those characteristics.

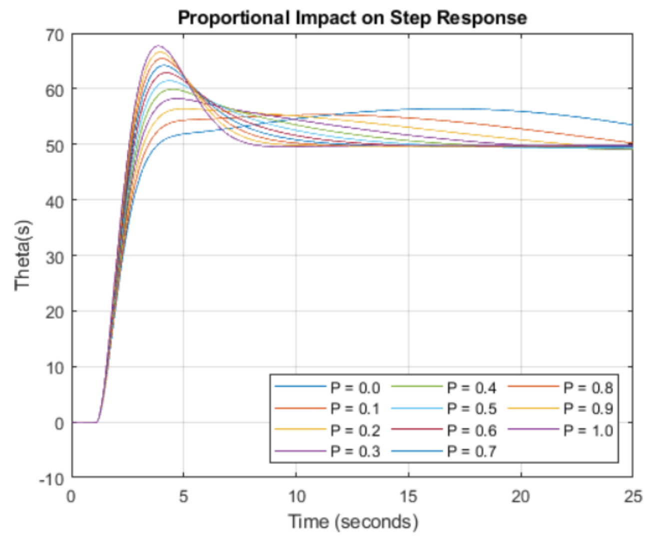


Fig. 19.

2) Integral Impact: The baseline integral term of 0.03 was used to generate the step response for all other analysis. A similar increment was used for integral impact analysis. The resulting graph highlights the degrading stability of the control system with increasing proportional terms, with minimal impact to the other characteristics. For the most controllable response, it was desired to decrease the integral term to be as close to 0.0 as possible.

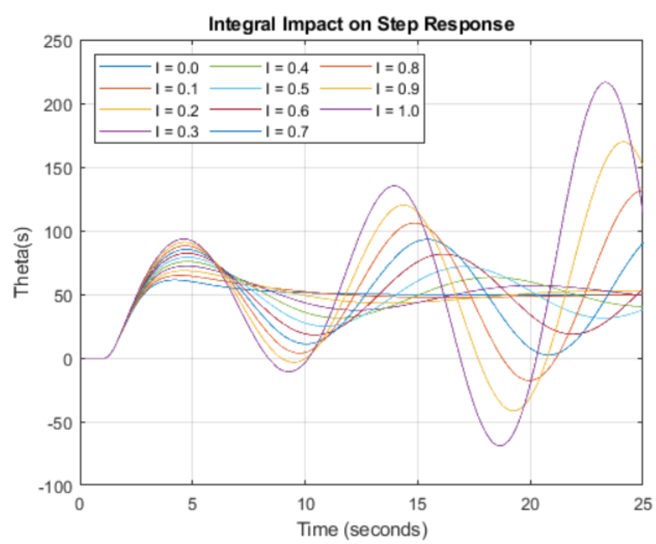


Fig. 20.

3) Derivative Impact: The baseline derivative term of 2.14 was used to generate the step response for all other analysis. The derivative term has the most significant impact on the response, generally improving stability and decreasing overshoot, settling time and rise time. As such it is desirable to have a larger derivative term as part of the control system.

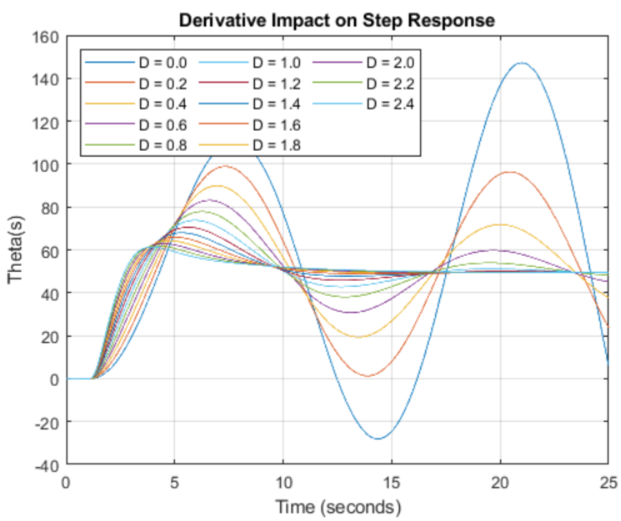


Fig. 21.

VII. LESSONS LEARNED

Both the open loop and closed loop control systems that were derived are not stable unless a digital controller is included and tuned.

Disturbance rejection is limited by controller tuning and thruster gain. Stronger thrusters responding to a more aggressive control signal would theoretically be capable of rejecting higher levels of disturbance - remaining within 5

When designing a digital control system the sampling frequency is a piece where optimization can be found. Calculating and meeting the Nyquist rate for sampling is all that is necessary to avoid aliasing and other issues with data sampling. Boosting the sampling rate past this point does not provide any significant benefit.

VIII. CONCLUSION

Attitude control systems represent a unique controls problem that compliments digital control design and analysis. This design project has only scratched the surface when it comes to the complexity of attitude control in satellite or spacecraft. The first piece of added complexity would be to introduce a third dimension, quickly followed by calculations of a dynamic moment of inertia and more advanced methods of torque application.

This project has developed a model that can be used to simulate satellite attitude control in an ideal environment. With a strong understanding of the basic operation of this system, it is possible to add elements of increasing complexity as desired.

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