Precision Stabilization Simulation of a Ball Joint Gimbaled Mirror Using Advanced MATLAB® Techniques

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Abstract

With the increasing use of smart weapons and sensors, there is a need to consider potential areas of improvement that could positively affect large numbers of systems with common concepts and approaches. One area that lends itself to this desire is the improvement of high precision high bandwidth antenna and mirror steering systems that can be utilized across a broad range of sensor systems. Pointing and tracking motions of typical antenna/mirror systems have been accomplished using gimbaled control systems in one or more axes. While these systems generally exhibit high dynamic range, and excellent accuracy and precision, they suffer from the common problems of weight and power requirements, and mechanical envelope constraints. This paper presents techniques and results for the simulation of stabilization characteristics of a joint gimbaled mirror using advanced MATLAB tools and packages.

1. Introduction

Our goal in this work is to create a complete and accurate simulation model of a ball-joint-gimbaled mirror system and all electronic control systems used to position the mirror, using MATLAB's Simulink. The Simulink model must provide an accurate representation of the mechanical system's dynamics, and include all possible ranges of motion and potential error in the mechanical system's operation. The model must also provide equally accurate representations of the electrical systems, especially the control systems, and allow for the simulation of potential errors in the design. Here we first describe the total system being modeled in Simulink. We will then describe the process through which has been followed.

The ball-joint-gimbaled mirror system is used to provide precise line of sight stabilization for the seeker (mirror). The mirror is attached to four Kevlar lines that are then connected to respective precision servo controlled capstans. These capstans may wind or unwind to change the length of each Kevlar line to position the mirror appropriately. The ball is mounted to a support structure, made up of a fixed body. To maintain stability and position of the seeker, the Kevlar lines must be kept in constant tension [1]. The figure below depicts the ball joint gimbaled system, which we seek to model.

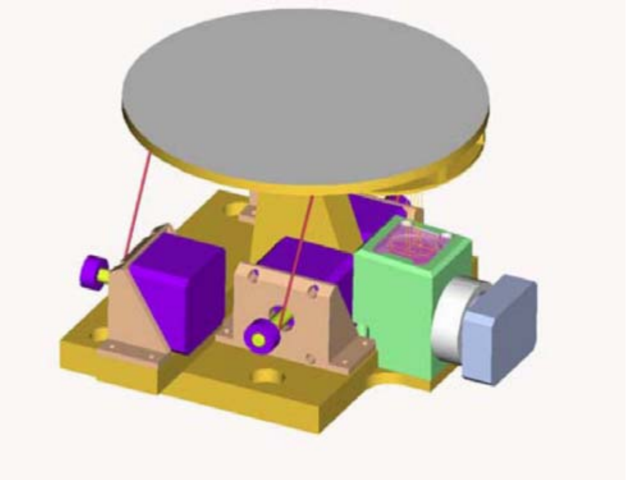

Figure 1. Joint Gimbaled System

2. Control System and Model Description

The figure below depicts the block diagram for the design of the control system that is modeled. The block diagram includes the information added by the use of an electro-optical sensor. The new sensor data provided, results in another feedback loop being used in the control systems to improve accuracy of the positioning of the seeker. This new feedback loop is the addition to the system that is investigated in our Simulink model.

The Simulink model is being used to determine the capabilities of the control system and the positioning accuracy of the mirror. To begin determining the response of the control system, we are first build models of the physical systems, starting with the mirror attached to the ball joint gimbal.

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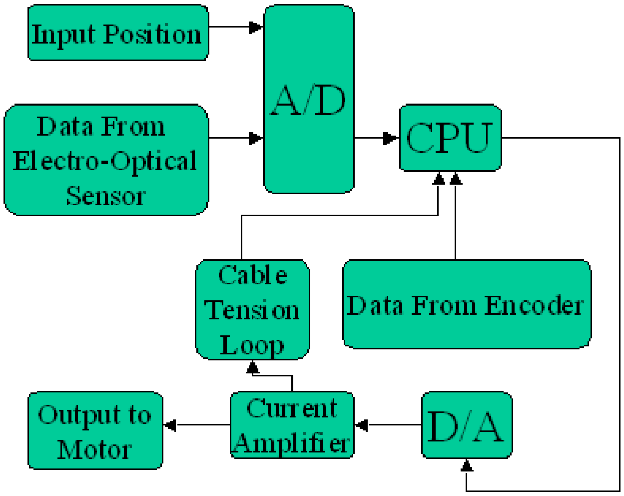

Figure 2. Block Diagram of Control Systems and Motor Control

The ball-joint gimbal mirror Simulink model has been divided into four main systems, the digital signal processing, servo-capstan operation, the Kevlar rope behavior, and mirror's physical behavior. The digital signal processing model calculates the final length of the Kevlar ropes for a given desired mirror orientation. The Simulink blocks used in this system can be seen in the figure below.

The calculation to determine the final length of the Kevlar ropes is done by first converting the angles that have been entered as the input to a direction cosine matrix. The angles entered must be given in radians for the direction cosine matrix to be properly calculated. The direction cosine matrix provides a complete mathematical description of the mirror's orientation. The direction cosine matrix is then operated on to determine the location of the holes in the mirror to which the Kevlar ropes are attached. The current coordinates of the hole in the mirror's new orientation is determined by multiplying the direction cosine matrix with a diagonal matrix containing the initial coordinates of the hole. This process is summarized by the equations below where the first matrix is the direction cosine matrix, and the second is a diagonal matrix of the holes' initial coordinates.

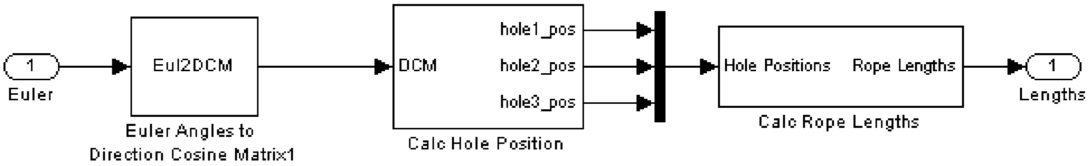

Figure 3. Simulink System Used to Calculate Final Rope Length

To determine the final coordinates of the hole in the mirror each row must be summed, producing the X, Y, and Z coordinates in the first, second and third rows respectively. The initial positions of the holes are determined from a Pro/Engineer model of the ball-joint gimbal mirror at 0 degrees azimuth and 0 degrees elevation. The coordinates where the rope meets the capstan, also determined from the Pro/Engineer model of the ball-joint gimbal mirror, is then subtracted from the coordinates calculated previously. The magnitude of this vector is then calculated to produce the distance between the two points, giving us our final rope length. To avoid initialization of the rope lengths, which may be seen as a large disturbance by the system, the initial length of the rope is subtracted from the commanded position, yielding the change in rope length from the initial position as the command received by the control system.

To determine the lengths of the ropes from the optical encoders in the capstans we use the measure of the angle provided and multiply it by the radius of the capstan. This yields the length of rope that has been wound, or in the case of a negative angle, unwound, from the capstan. There is also no initialization added to the optical encoder, resulting in the output being the change in rope length from the initial position's appropriate rope lengths.

$$\begin{bmatrix} \hat{u}_x & \hat{v}_x & \hat{w}_x \\ \hat{u}_y & \hat{v}_y & \hat{w}_y \\ \hat{u}_z & \hat{v}_z & \hat{w}_z \end{bmatrix} \times \begin{bmatrix} X_i & 0 & 0 \\ 0 & Y_i & 0 \\ 0 & 0 & Z_i \end{bmatrix} = \begin{bmatrix} X_{xx} & X_{xy} & X_{xz} \\ Y_{yx} & Y_{yy} & X_{yz} \\ Z_{zx} & Z_{zy} & Z_{zz} \end{bmatrix} \tag{1}$$

The information from the optical controller is dealt with in the same fashion as the input command. The angles measured by the sensor are first converted to a direction cosine matrix, and then through the calculations previously mentioned the lengths of the ropes are calculated and sent to the control system, which can be seen in Figure 4.

The resulting signal from the control system is sent to the servomotor-capstan system. The servomotor accepts the signal and uses a lookup table to determine the position the command given by the digital signal processing system, corresponds to. The position is then used to supply the electrical model of the servomotor with a voltage proportional to the difference in current position and commanded position. The Simulink blocks used to create the model of the servomotor can be seen in Figure 5. The model of the servomotor assumes that the servo is powered by a 5-volt source whose polarity may be reversed to spin the servomotor in the opposite direction.

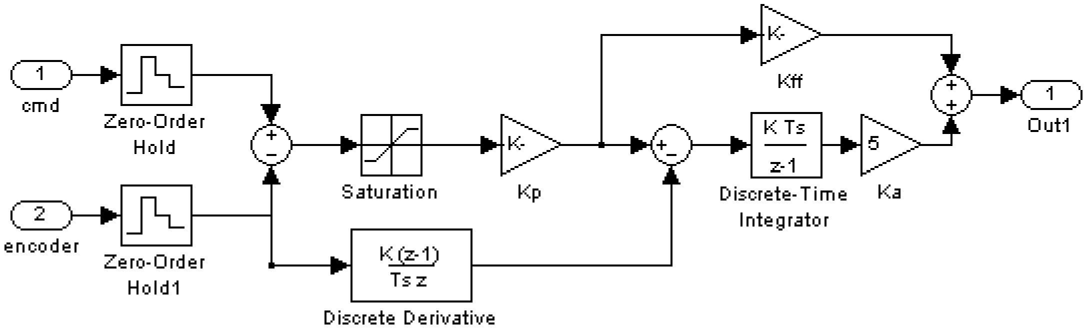

Figure 4. Simulink Model of Control System

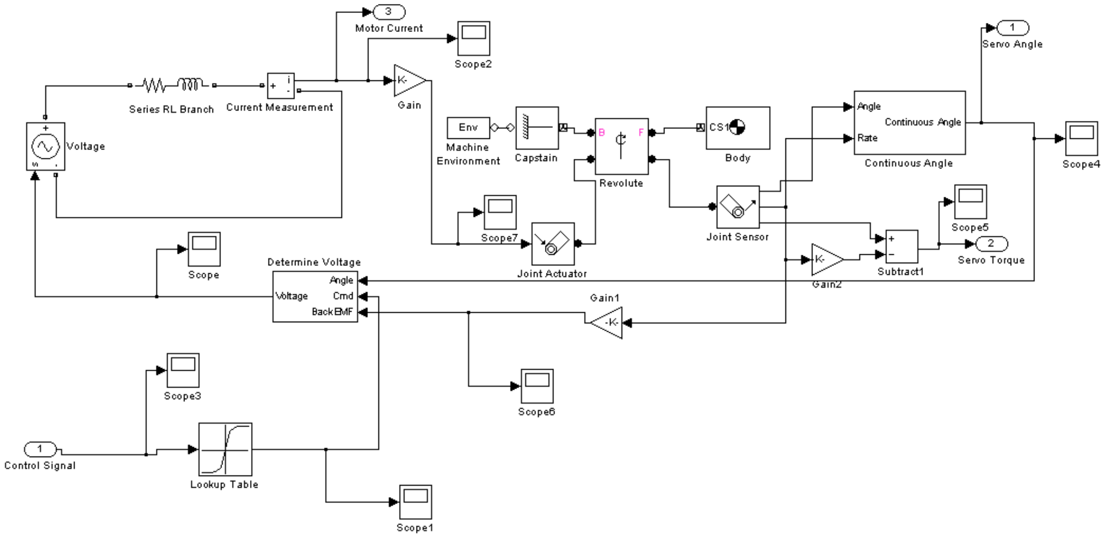

Figure 5. Simulink Model of a Servo Motor

The mechanical components of the servomotor are modeled as a rotating mass with a torque proportional to the current through the electrical model. The angles of the servomotor, as well as the current through the electrical model, are sent to analog to digital converters, and the torque is sent to the Kevlar rope system of the model.

The torque of the capstan is converted to a force vector applied to the mirror. The force vector is calculated by determining the unit vector, which points from the capstan to the hole on the mirror to which the rope is attached. The magnitude of the torque is then multiplied through the unit vector, resulting in the appropriate force vector, which is then passed to the mechanical model of the mirror. The calculation of the force vector can be seen in Figure 6. The calculation of the force vector in Figure 6 assumes that there is no change in the length of the rope while under tension and that the line never becomes slack.

The three force vectors calculated through this fashion are applied to the mechanical model of the mirror, which can be seen in Figure 7. The model applies the forces at the appropriate point on the mirror, which is mounted on a spherical joint. The mirror is modeled as a body placed on top of a spherical joint that is connected to an object fixed in space.

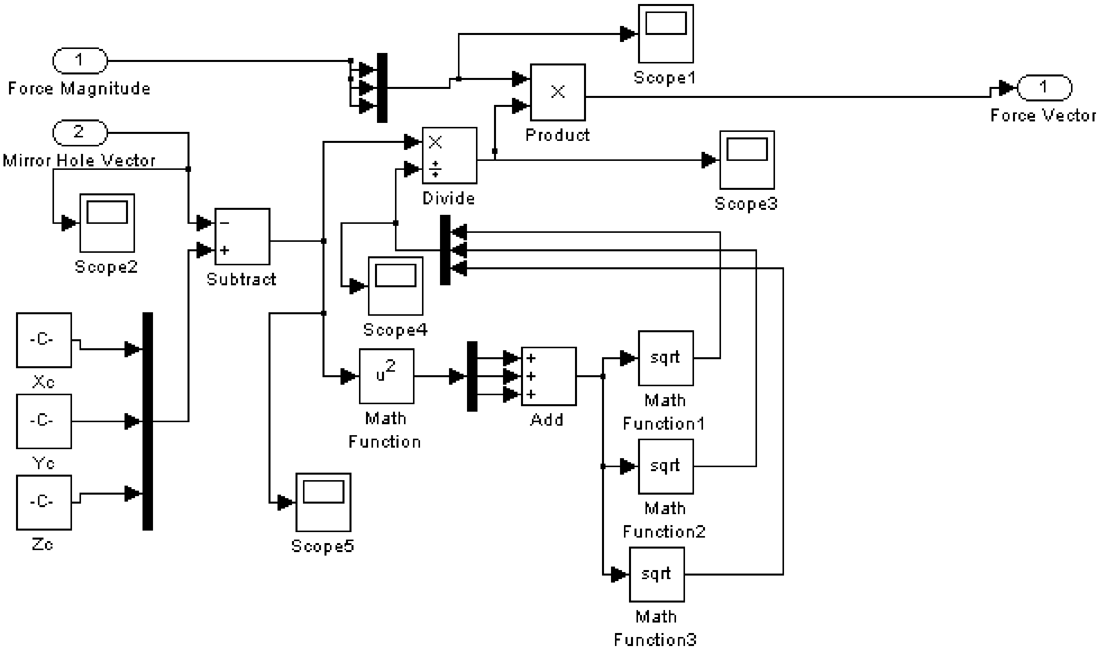

Figure 6. Conversion of Capstan Torque to Force Vector

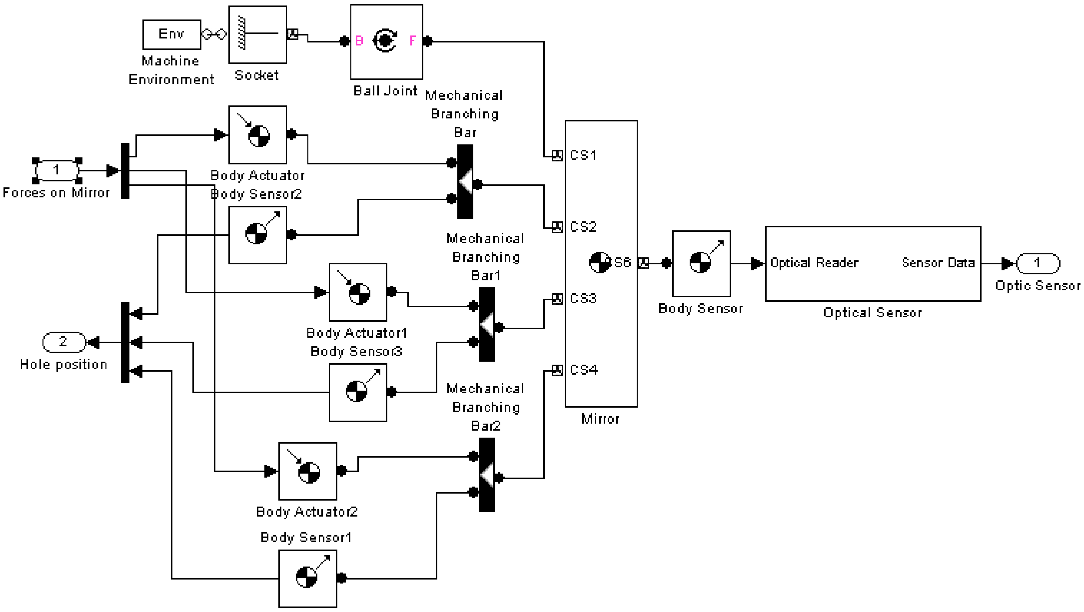

Figure 7. SimMechanics Physical Model of Mirror and Ball Joint Gimbal

3. Simulations and Results

A simulation was created to obtain data to compare the behavior of the servomotors alone, both with and without the optical sensor. Through this simulation, we are able to infer the approximate benefits of the optical sensor. To make the comparison eight simulations were created to allow for comparison in both time and frequency domain responses. The first four simulations are time domain representations, first a step response, followed by a step response that is then moved to a second position before returning to its initial position. In both of these cases the simulation was run with and without the optical sensor, yielding the four time domain simulations. The next four simulations were done in the frequency domain yielding the frequency response of the servo system under the four conditions used in the time domain analysis.

In the simulations involving the optical sensor, as depicted below, the inaccuracy of the optical sensor was used to calculated the expected steady state error, which was then added into the model in the same fashion as the steady state error previously expected according to the measured results. The steady state error of the servo was calculated by determining the inaccuracy the servomotor experience because of the inaccuracy in mirror position measurement.

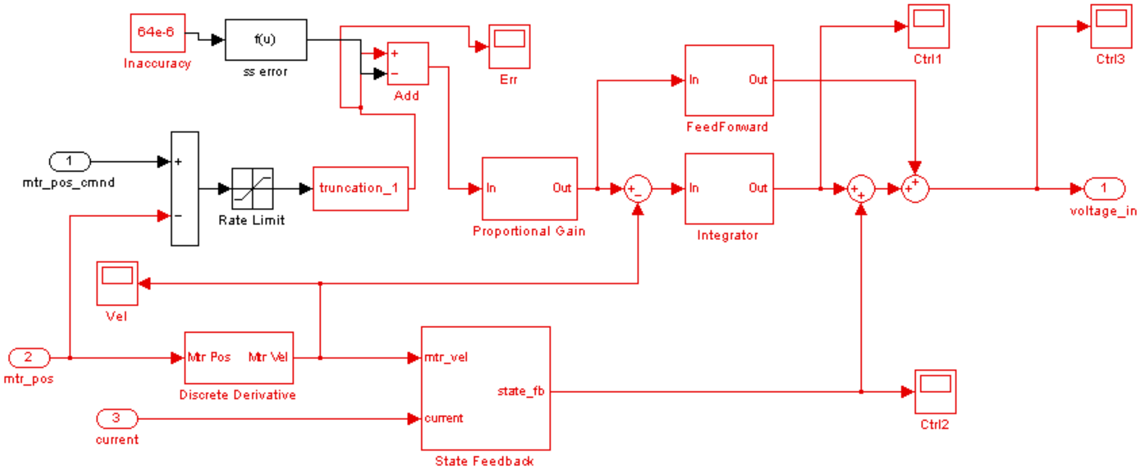

Figure 8. Control System Block of Servo Simulink Model

Using this model, we were able to produce the results previously mentioned. The first is the time domain step response of the servomotor without the optical device. This can be seen below, where the top graph is the position, and the bottom graph is the error in position.

The next simulation uses the optical sensor. The resulting graphs may be seen in Figure 10. When the optical sensor is added the steady state error shrinks to approximately 50μradians, compared to the 400μradians seen in the simulation seen previously in Figure 9.

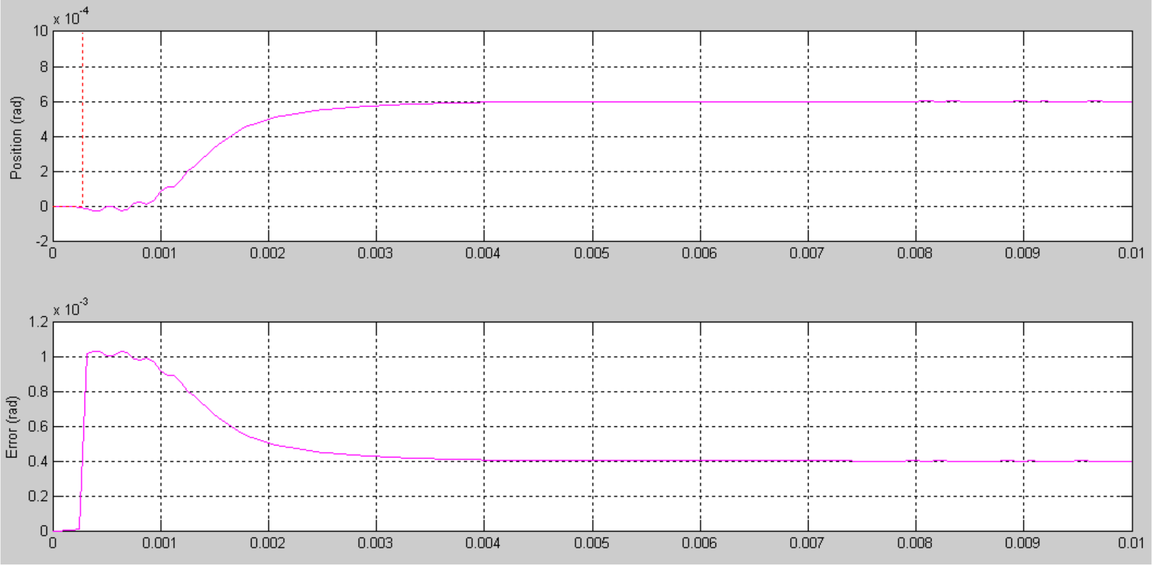

Figure 9. Step Response of Servo without Optical Sensor

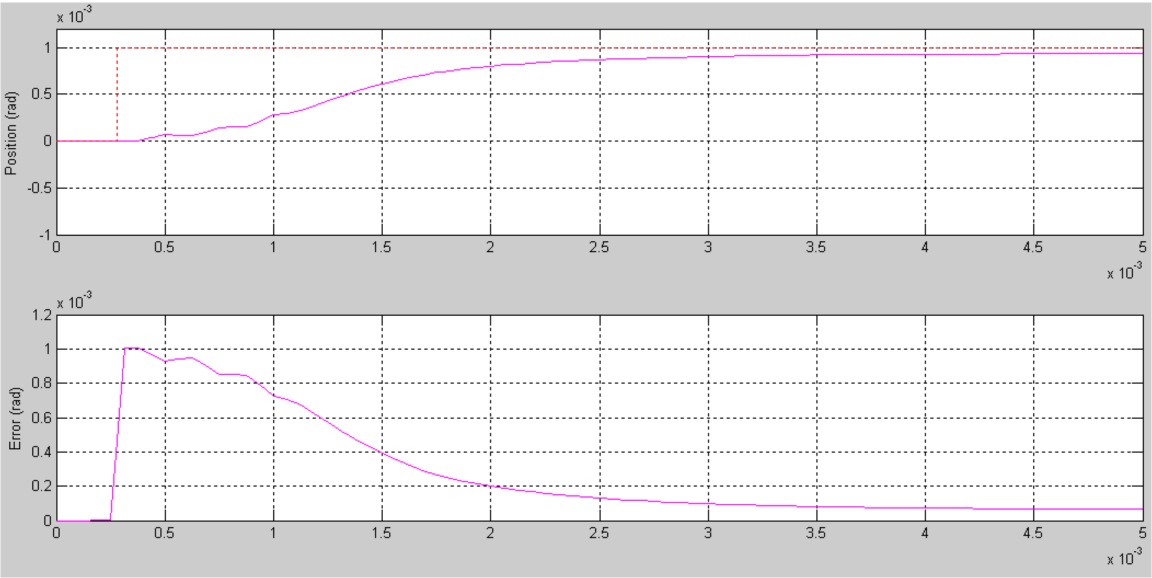

Figure 10. Step Response of Servo with Optical Sensor

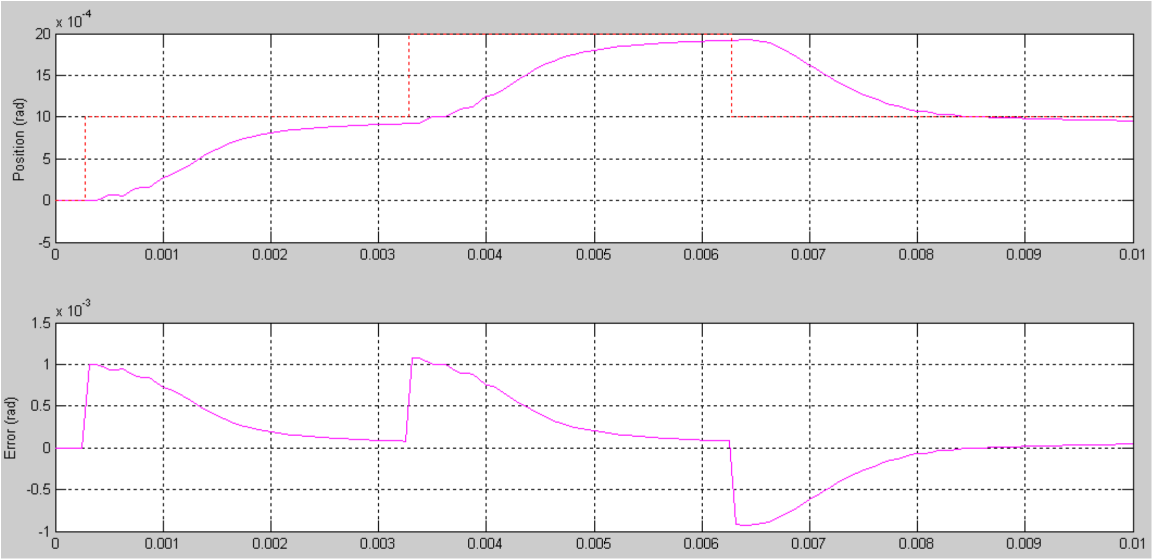

Figure 11. Double Step Response of Servo with Optical Sensor

4. Conclusions

The simulation results of both the time domain and frequency domain support the expected results. The relative benefits shown in the servomotor control will be seen in the total system. The addition of the optical sensor greatly improves the steady state error, as well as bandwidth and magnitude responses. The simulation model also allows the optical sensor accuracy to be altered to different specifications in the future.

5. Acknowledgements

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6. References

[1] Christison, Donald, et al; Ball Joint Gimbal System, US Patent 6396233, Issued May 28, 2002.