Cadet First Class Dustin Hayhurst

Lieutenant Colonel Joslyn

Department of Astronautics

20 October, 2011

Spacecraft to Remove Charged Particles from the Van Allen Belts

I. Introduction

The Tethered Environmental Reconditioning Satellite (TERSat), built by the Massachusetts Institute of Technology (MIT), will be launched into a circular orbit with an altitude of 700 kilometers and an inclination greater than 18.34 degrees. TERSat will use Arecibo, Puerto Rico as its ground station and will operate within L-Shell 1.3. The L-Shell number defines the distance of a set of Earth's magnetic field lines away from the center of the Earth in Earth radii. Upon achieving stable orientation and ensuring that all of its systems are functional, TERSat will deploy tethers of two kilometers in length on its nadir and opposite nadir side. These tethers will serve as a gravity gradient boom for the satellite and will emit Electromagnetic Ion Cyclotron (EMIC) waves whenever TERSat passes through the Van Allen Radiation Belts. These EMIC waves will propagate through the Van Allen Radiation Belts at the same frequency as the high energy particles from the Sun which are trapped in the Van Allen Belts. These EMIC waves will resonate with these electrons and protons, adjust the velocity vectors of these particles, and cause the particles to enter and be destroyed within Earth's atmosphere rather than continue to travel through the Van Allen Belts. The ground station at Arecibo will measure the amount of radiation encompassed within the Van Allen Belts that the satellite is travelling through to determine the effects of the satellite on the proton and electron levels. Upon completion of its mission, TERSat will use aerodynamic and electrodynamic drag to deorbit in less than 25 years.

The potential for the TERSat concept is limitless and may one day play an integral role in America's space industry and defensive capabilities. The Van Allen Belts are underutilized because the high concentration of high energy particles within the belts prevents satellites from operating safely and effectively in that area of space. High altitude nuclear explosions (HANEs) may one day pose a significant threat to the United States' capacity in space for the same reason. TERSat represents a solution to both of these problems and its development may one day be essential for protecting America's interests in space and ultimately the safety of the United States.

II. Tether Deployment Control System

The tether deployment of the satellite plays a critical role in determining the success of TERSat's mission. This research focused on developing the control law computer program to deploy the tethers safely and effectively. Specifically, the research was aimed at writing a computer program in Simulink that can slow or stop the tether deployment by interfacing with a braking mechanism applied to the tether. The tethers will be propelled from the satellite and spooled out to a length of two kilometers using constant 1 Newton force cold gas thrusters which are mounted on the end masses of the tethers. The tether braking mechanism prevents oscillations, characterized by the libration frequency, in the physical displacement of the tethers from becoming too large and destabilizing the satellite or damaging the satellite with arcing. The braking mechanism prevents these oscillations by decreasing the velocity of the end masses thus negating the Coriolis Effect and allowing the gravity gradient force to realign the tethers to the local vertical axis. The Coriolis Effect is represented in the equation below.

$$Coriolis\ Effect = 2\omega \times v \tag{1}$$

The braking mechanism also serves to prevent the tethers from snapping upon full deployment by preventing deceleration levels of a magnitude beyond the capacity of the tether strength. The braking mechanism also serves to prevent the end masses from bouncing back towards the satellite upon full deployment as a result of elastic deformation.

In parallel to this research, control specialist Denis Zanutto also conducted research on a control law that could be used to control the tether deployment of the satellite. Zanutto's code for the braking mechanism allowed for the development of a greater libration angle, a greater deceleration magnitude, and a significant number of bounces in the tethers due to elastic deformation. Zanutto's control law relied on the gravity gradient force to make one large correction at the end of the tether deployment whereas the approach developed in this research relied on the gravity gradient force to make several smaller corrections throughout the entirety of the deployment.

While the control law developed in this research afforded the satellite a more conservative and stable deployment, it also took much longer to deploy. The cold gas thrusters on the end masses have a limited amount of fuel and adding a mechanism by which to turn on and off the thrusters would exponentially increase the complexity of the control system as well as the likelihood that it would fail. Zanutto's models indicated that his control law could effectively deploy the tethers, albeit with less margin for error, and utilize a fraction of the fuel. Given the advantages and disadvantages of the two control laws, the TERSat team decided to utilize Zanutto's program in TERSat.

III. Control Law Development

The endeavor to develop a control law for TERSat began with an effort to create a control law for an Earth based system. This approach would allow the TERSat team to conceptually develop the model and test a protocol program before moving to a mature space design. The Earth model used gravity to simulate the thrusters and took into account spool inertia, spool friction, and the braking force which was initially controlled by a human. While the Earth model failed to account for elastic deformation, Coriolis Effect, and gravity gradient, the TERSat team believed that the Earth model could be used to generate a first order approximation of how the control law would perform in space. As such, the Simulink model illustrated in Figure 1 was developed for implementation in the Earth based physical system.

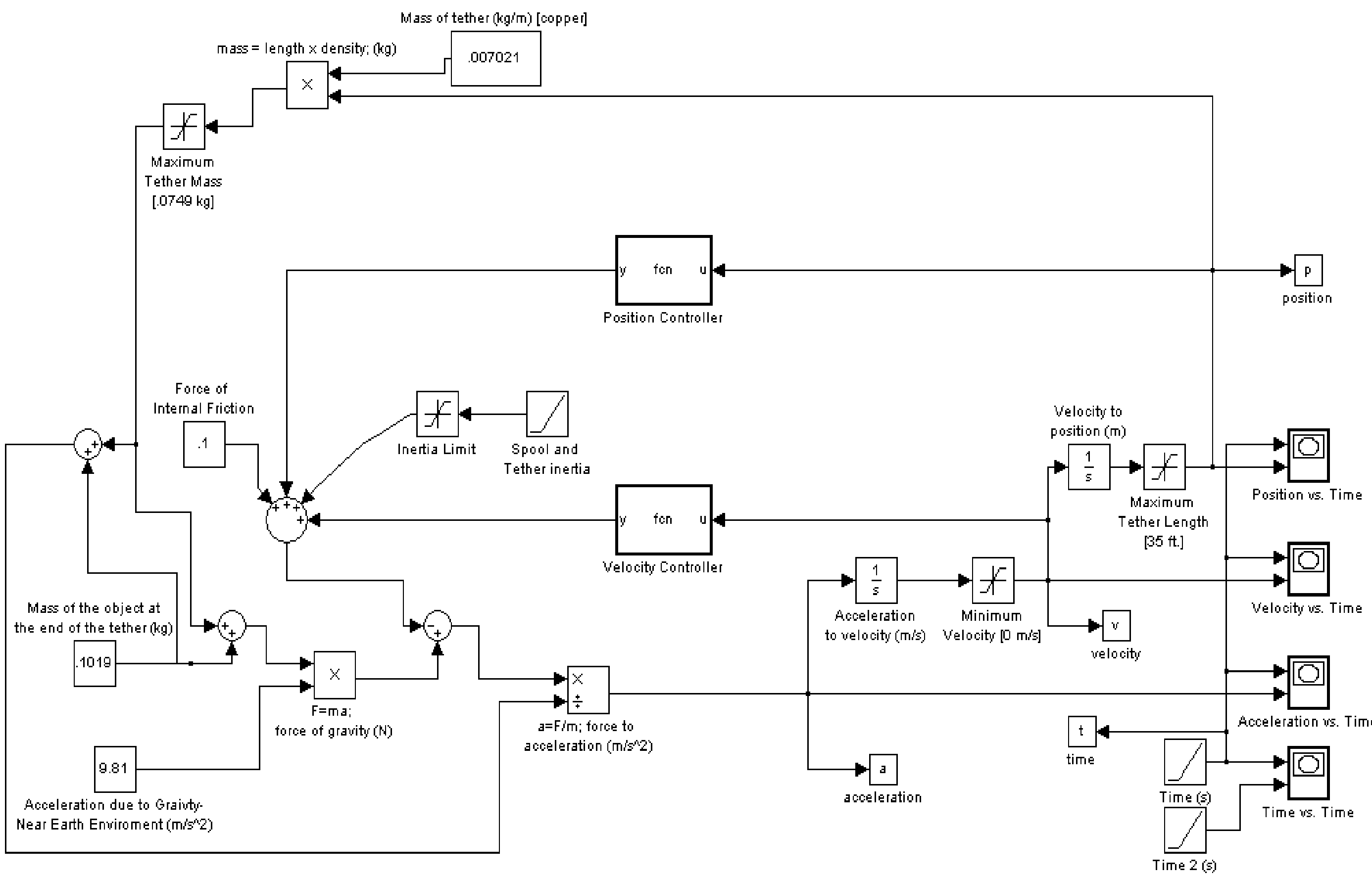


Figure 1. The control law for the Earth model.

Within this model, the position and velocity controllers can be adjusted to create different position, velocity, and acceleration profiles for the tether deployment as is needed. Refer to Appendices A, B, C, and D for various profiles. While the simulated results for this model indicated success, the TERSat team was never able to physically test the Earth based control law because the mechanical team's braking design was ineffective at varying the force applied to the tether. This inability was based on the fact that the braking method could only completely stop the end mass or allow the tether to spool out in complete free fall. Therefore, implementing the control law was not feasible.

Despite the setback with the Earth model, work on the space control law continued. Repeated efforts to create a workable control law yielded simulated results that were not realistic and indicative of an ineffective model. After continued efforts, the TERSat programming team realized that the model accounted for only one rotating frame between the satellite, end mass, and Earth. In order to create a successful model with this approach, the TERSat team would have needed to create a program of incredible complexity which accounted for two rotating frames. In lieu of this option, the TERSat programming team decided that it would be easier and just as effective to utilize the Clohessy Wiltshire equations represented below.

$$\ddot{x} + 2\Omega\dot{z} = \frac{F_x}{m} \tag{2}$$

$$\ddot{y} + \Omega^2 y = \frac{F_y}{m} \tag{3}$$

$$\ddot{z} - 2\Omega\dot{x} - 3\Omega^2 z = \frac{F_z}{m} \tag{4}$$

The Clohessy Wiltshire equations could be used in conjunction with state space modeling which is represented in the below equations.

$$\dot{\bar{x}} = A\bar{x} + B\bar{u} \tag{5}$$

$$\bar{y} = C\bar{x} \tag{6}$$

The Clohessy Wiltshire equations could also be used in conjunction with a time step iteration process represented in the below equations.

$$\ddot{x}_t = x_{t+1} + x_{t-1} - 2x_t \tag{7}$$

$$\ddot{z}_n = \frac{z_n - z_{n-1}}{\Delta t} \tag{8}$$

IV. Further Research Opportunities

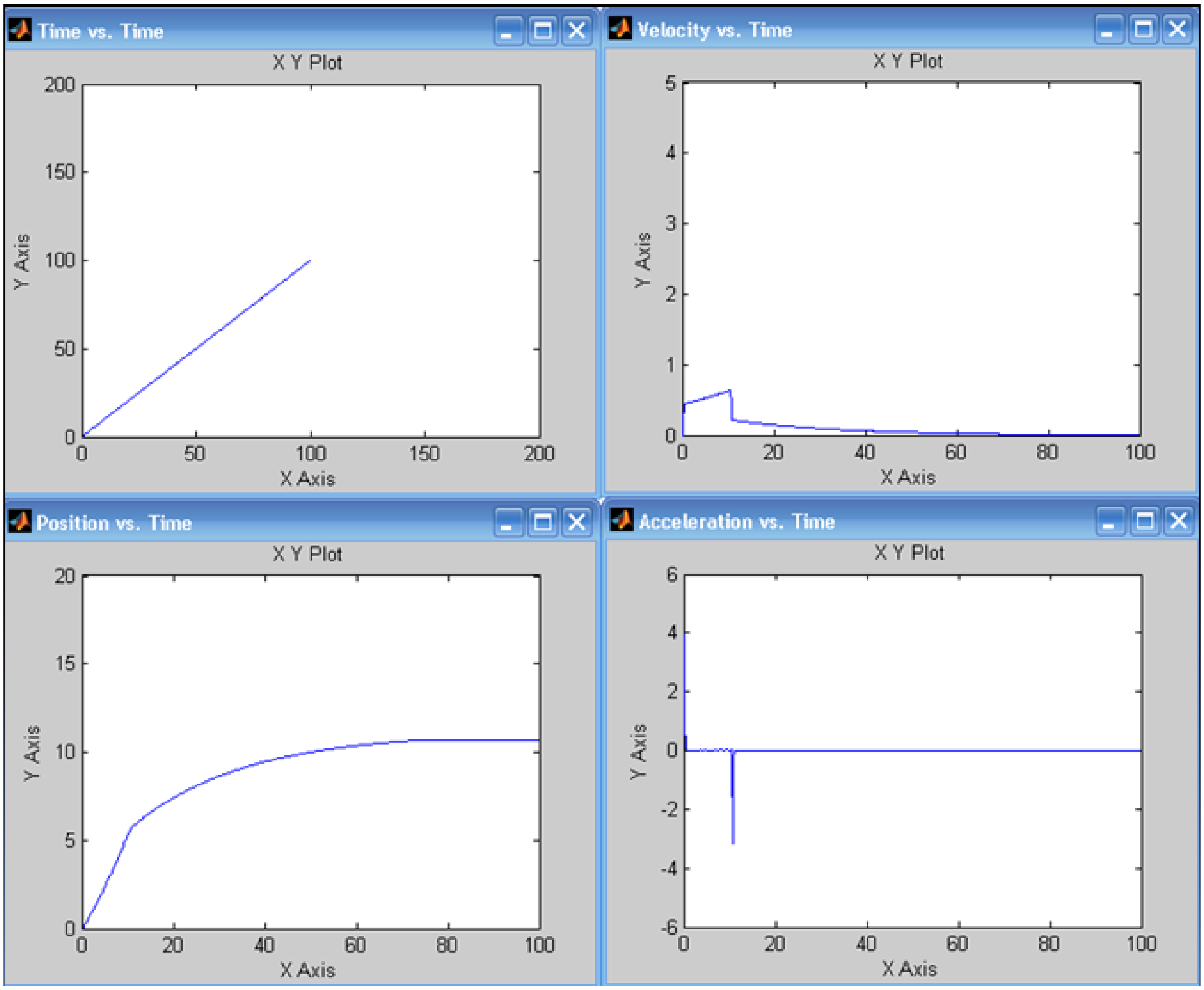
This research affords three primary catalysts for further research including the development of Zanutto's control law for a relatively aggressive tether deployment, the development of the control law used in this research for a relatively conservative deployment, and the development of an effective physical braking mechanism. Refer to Appendix E for potential ideas for the braking mechanism. If the TERSat team can demonstrate success in the tether deployment phase using Zanutto's program, then the TERSat program can be a model for future programs seeking to use tethers of approximately the same length. Future programs seeking to deploy longer tethers such as the 20 kilometer Small Expendable Deployer System 1 (SEDS-1) tether may require a slower, more conservative, and more complex system. In the case that a more conservative deployment is required, future programs can build upon the control law developed in this research. Any software control law will be dependent upon the physical system that it controls for a successful deployment. As such, investigating ways to enhance mechanisms such as the barber pole, worm gear, and friction pulley and integrate these mechanisms into satellite technology provides a tremendous sphere of research.

Tether deployments can be used to accomplish many useful tasks in space. Space tethers can be used to emit pulses, deorbit spacecraft, and stabilize satellites as is the case in the TERSat program. Tether deployments can be used during orbital maneuvers and spacecraft rendezvous to save delta-V and make space travel more efficient. Spacecraft can use tether deployments to safely and effectively place land exploration vehicles onto the surfaces of other celestial bodies without actually landing. Humans could one day use tether deployments for extraordinary endeavors such as creating a space elevator that connects a point on Earth to a spacecraft in geostationary orbit. The TERSat project and the research opportunities that it provides could enhance America's space industry, improve the military defensive capabilities of the United States, and assist in the incredible space exploration endeavor that belongs to all of mankind.

Appendix A

Early Position Controller and High Velocity Constant

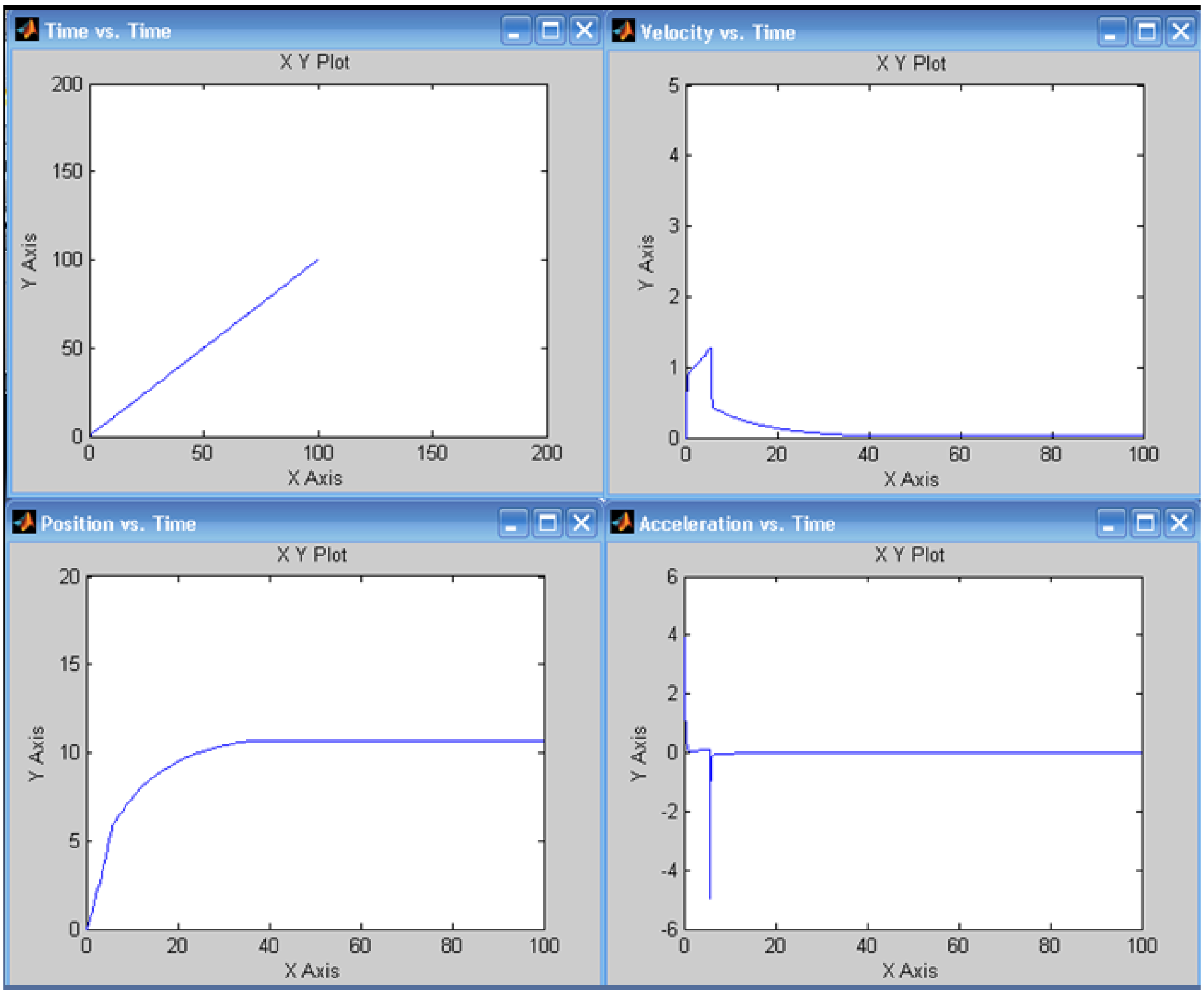
These plots show the acceleration, velocity, and position of the end mass on the Earth model plotted against time. These plots reflect the simulated performance of the model when the velocity controller reacts relatively strongly to counteract the speed of the end mass and the position controller begins to counteract the speed of the end mass relatively early in the tether deployment.



Appendix B

Early Position Controller and Low Velocity Constant

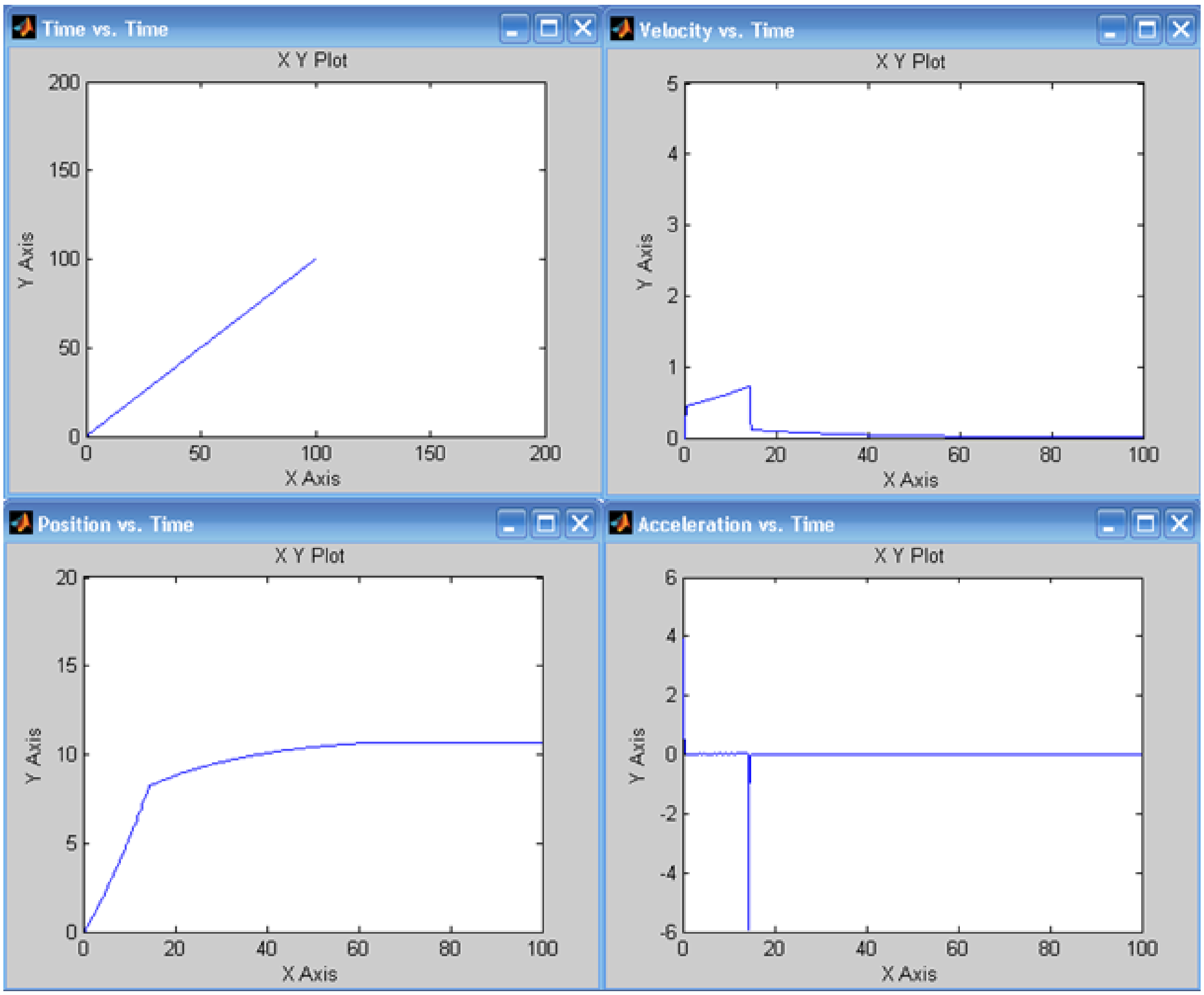
These plots show the acceleration, velocity, and position of the end mass on the Earth model plotted against time. These plots reflect the simulated performance of the model when the velocity controller reacts relatively weakly to counteract the speed of the end mass and the position controller begins to counteract the speed of the end mass relatively early in the tether deployment.



Appendix C

Late Position Controller and High Velocity Constant

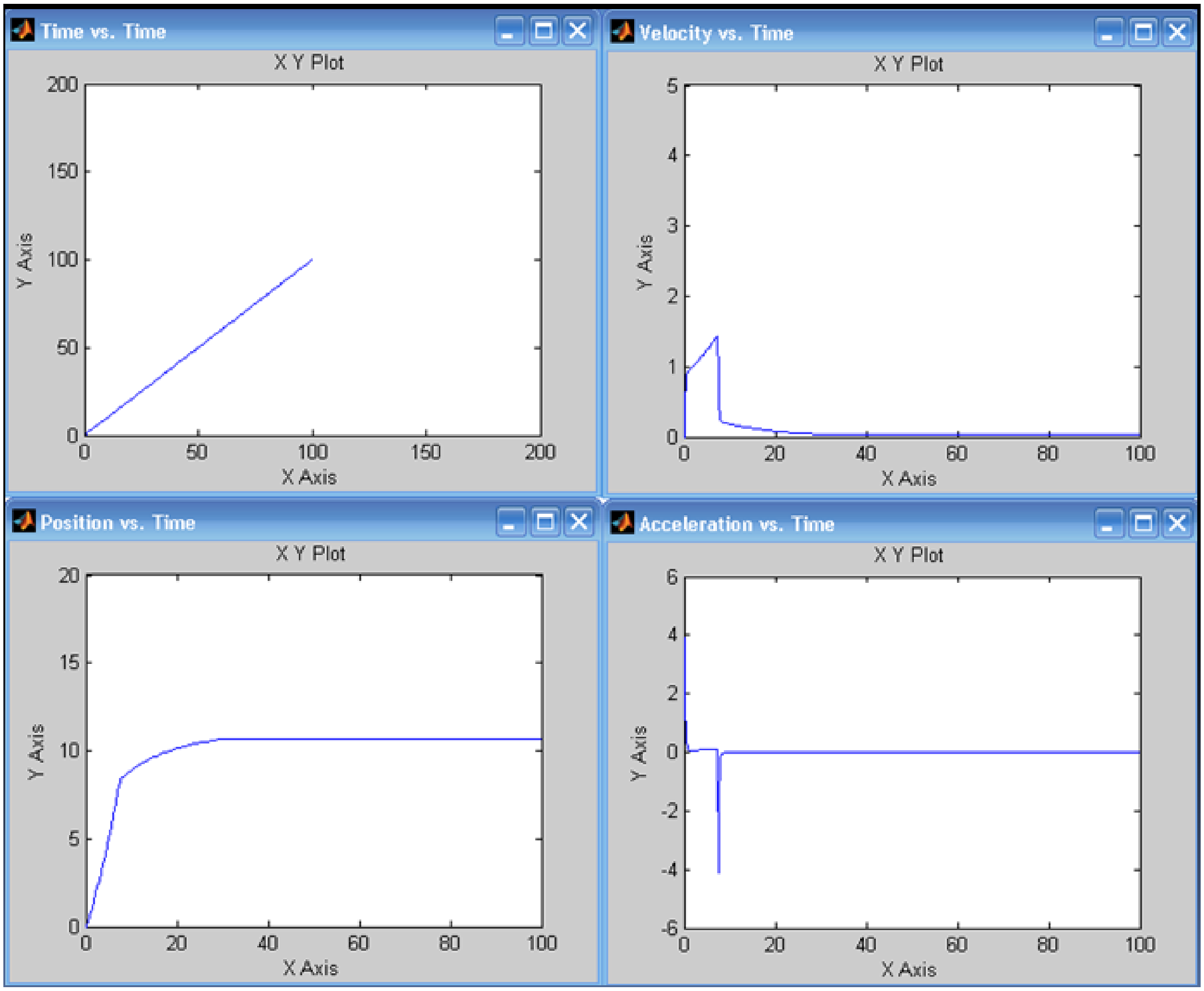
These plots show the acceleration, velocity, and position of the end mass on the Earth model plotted against time. These plots reflect the simulated performance of the model when the velocity controller reacts relatively strongly to counteract the speed of the end mass and the position controller begins to counteract the speed of the end mass relatively late in the tether deployment.



Appendix D

Late Position Controller and Low Velocity Constant

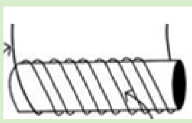
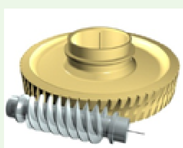
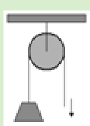
These plots show the acceleration, velocity, and position of the end mass on the Earth model plotted against time. These plots reflect the simulated performance of the model when the velocity controller reacts relatively weakly to counteract the speed of the end mass and the position controller begins to counteract the speed of the end mass relatively late in the tether deployment.



Appendix E

Potential Ideas for a TERSat Braking Mechanism

After the suboptimal performance of the original braking mechanism used in the Earth based model, the TERSat team developed new ideas for a braking system. Those ideas are represented in the table below.

Design	Problem	Solution
Guillotine 	• Already tried • No Control • Brake wore down	• Use alternative friction besides Kapton
Clamp 	• Low control • Brake wear	• Use a strong and controllable clamp
Barber Pole 	• Difficult to increase number of turns	• SEDS 2 Model
Worm Gear 	• No way to latch on • Prof Paul Bauer said, "That will never work"	• Find a way to attach tether to cylindrical part
Friction Pulley 	• Possibility of sliding • Where to put pulley	• Use a non-slip material

Potential Braking Mechanisms Idea Table; Courtesy of Cadet First Class John Krzyminski - TERSat Mechanical Team Member.

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Special thanks to Bryan McCarthy, John Krzyminski, Chris Pong, Eden Dahan, Konrad Makowka, Michael O'Connor, Tevis Nichols, and Maria De Soria-Santacruz for their help in this research project. I could not have achieved any of this without their support and guidance.