Modeling the Deployment of a Passive CubeSat Solar Array

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ABSTRACT

Satellites play significant role in supporting scientific inquiry, homeland security, and general societal needs. They provide surveillance, weather data, telecommunications, understanding of different phenomena related to the sustainability of life on Earth, and images of stars that are lightyears away. Since satellites were conceived in the early 1950's, their complexity and power demand has continued to grow. This inspired engineers to develop ways to simplify their design to decrease the likelihood of mission failure as well as to decrease weight and increase the payload. One way to accomplish this requirement is to introduce a passive solar array deployment method that does not require a motor, actuator, and controllers. By connecting the solar arrays to the main body with special hinges and carefully selecting the rotational spring stiffness coefficient, a deployment sequence can be created to effectively deploy the solar arrays in a desired amount of time, thus eliminating heavy and complex components of a typical deployment system. The goal of this paper is to demonstrate the relationship between the deployment time, spring stiffness coefficient, and torque created at the hinges. To achieve this goal, a simple MATLAB/Simulink model is developed and used to demonstrate that the spring stiffness coefficient can be selected to accomplish desired panel deployment time with minimal undesirable impact on satellite dynamics, specifically over-rotation due to hard stop in the deployment mechanism.

ABOUT THE AUTHORS

John Nelson is a Mechanical and Aerospace Engineering Master's student at the University of Virginia. He is also a 1st Lieutenant in the United States Air Force serving in Virginia, United Arab Emirates, Germany and parts of Africa. He graduated with a B.S. in Mechanical Engineering from Texas Christian University. While a student at Texas Christian University, John completed an internship with the National Reconnaissance Office and was the Cadet Wing Commander for Air Force ROTC Detachment 845. John's interests are in defense, robotics, high performance jet aircraft and satellite technology.

Dr. Mileta Tomovic received BS in Mechanical Engineering from University of Belgrade, MS in Mechanical Engineering from MIT, and PhD in Mechanical Engineering from University of Michigan. Dr. Tomovic is currently serving as Mitsubishi-Kasei Professor of Manufacturing Technology, Batten College of Engineering and Technology, Old Dominion University, Norfolk, VA. Dr. Tomovic has seventeen years of teaching and research experience at Purdue University. Dr. Tomovic served as W. C. Furnas Professor of Enterprise Excellence, University Faculty Scholar, Director of Digital Enterprise Center, and Special Assistant to Dean for Advanced Manufacturing. He has co-authored one textbook on materials and manufacturing processes that has been adopted by over 50 national and international institutions of higher education. He has co-authored four patents, and over 100 technical reports on practical industrial problems related to product design and manufacturing process improvements. In addition, Dr. Tomovic has been actively involved in applied research, and has been a PI or Co-PI on number of externally funded competitive grants exceeding $6 million. In addition, he has been engaged with industry in solving manufacturing problems. The estimated savings to industry, resulting from Dr. Tomovic's recommendations, exceed $5 million over the ten years that he has been actively engaged with Technical Assistance Program, Purdue University.

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INTRODUCTION

This paper is focused on deployment of a solar array for a CubeSat. Specifically, the analysis is focused on a 3-panel longitudinal set up, Fig. 1, which is discussed in "Dynamics of Spring-Deployed Solar Panels for Agile Nanospacecraft"[1]. The deployment sequence begins with three solar panels stacked along the side of the satellite, Fig. 2. The panels are connected to the main body at the main hinge that contains two torsional springs and is configured to limit the first rotation to 90 degrees, Fig. 3, [1]. The other two panels are connected to each other through similar hinges, however, these are configured to limit rotation to 180 degrees, Fig. 4, [1]. When the deployment sequence is initiated, a thermal cut is made at a wire that was constraining the solar array to their stowed position. Once the wire is cut, the potential energy from the torsional springs is released and the solar array rotates into position 2. Then, another thermal cut is made to release panels 2 and 3 to rotate about their hinges into position 3.

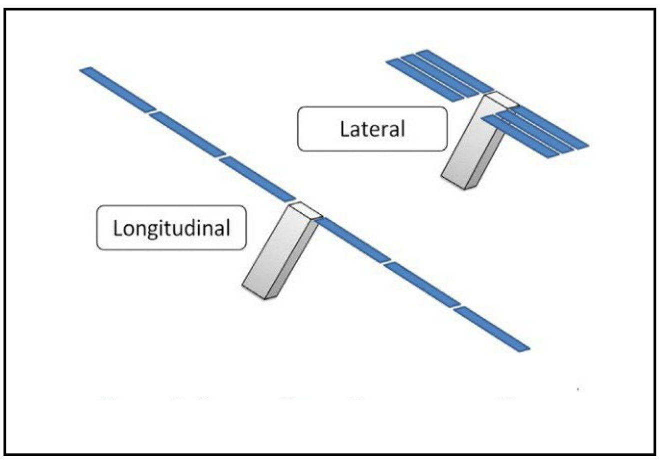

Figure 1 - 3-Panel Longitudinal Solar Array Configuration

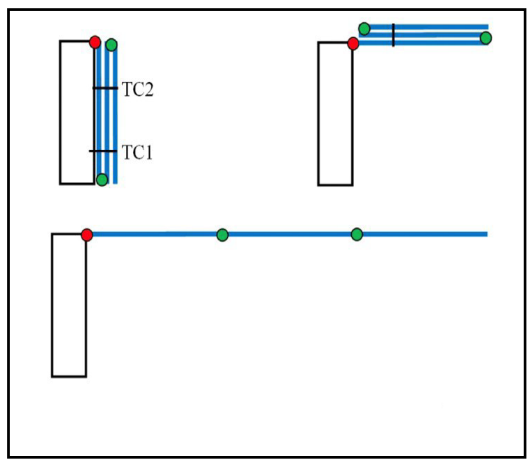

Figure 2 - Deployment Sequence

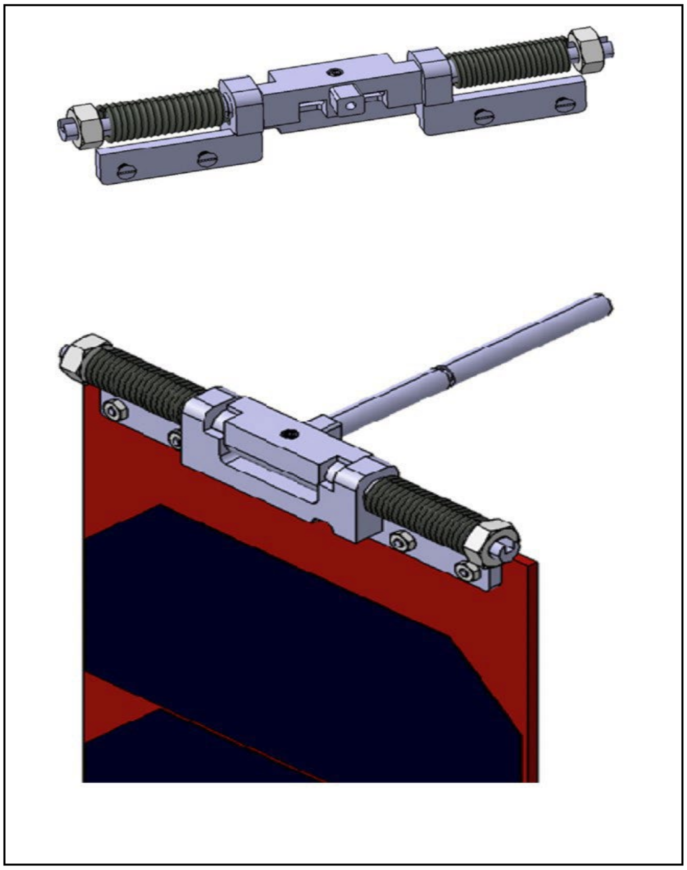

Figure 3 – Main Hinge Configuration

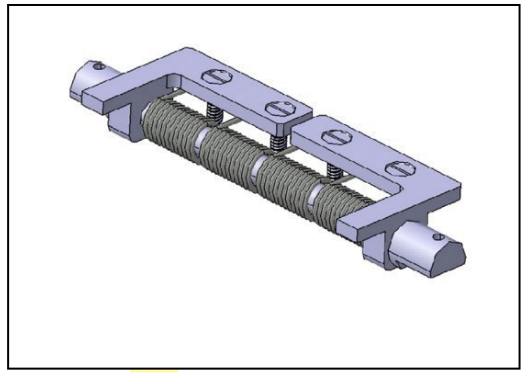

Figure 4 – Secondary Hinge Configuration

METHODOLOGY

The panel structure dynamics were modeled with MATLAB software. The unfolding process can be modeled with either Simscape Foundational Toolbox or Multibody Toolbox. Both of the approaches would produce the same or very close results. Since the later requires solid representation of the system, which can be time consuming in terms of generating the model, it was decided to address the problem using lumped parameter approach.

The timing, torque and effects on the main body along with a what-if analysis are further explored in the following sections. The model is applied to analyze existing design and perform a "what-if" analysis to demonstrate the relationship between deployment time, spring stiffness coefficients, and resultant torques within the joints.

The solar array deployment sequence was modeled with 3 separate simulations using Simulink's Rotational Dynamics Blocks to represent the three positions of the deployment sequence. The model consists of a rotational reference in the center representing the main satellite body, Fig. 5. The two inertial elements (solar panels) are connected to the satellite body with rotational springs on both sides of the inertial element (satellite). The hinge's rotational limit is modeled with a rotational hard-stop which is connected to the inertial body and the rotational reference. The rotational hard-stop was configured to apply the full stiffness and damping at the bounds with an undamped rebound because this provides the more realistic model. Additionally, rotational movement sensors and ideal torque sensors are connected to the inertial body to measure position, speed and torque of the solar array deployment, Fig. 5 and 6. Although it would be interesting to determine the resultant torque on the main body, it is not the focus of this paper.

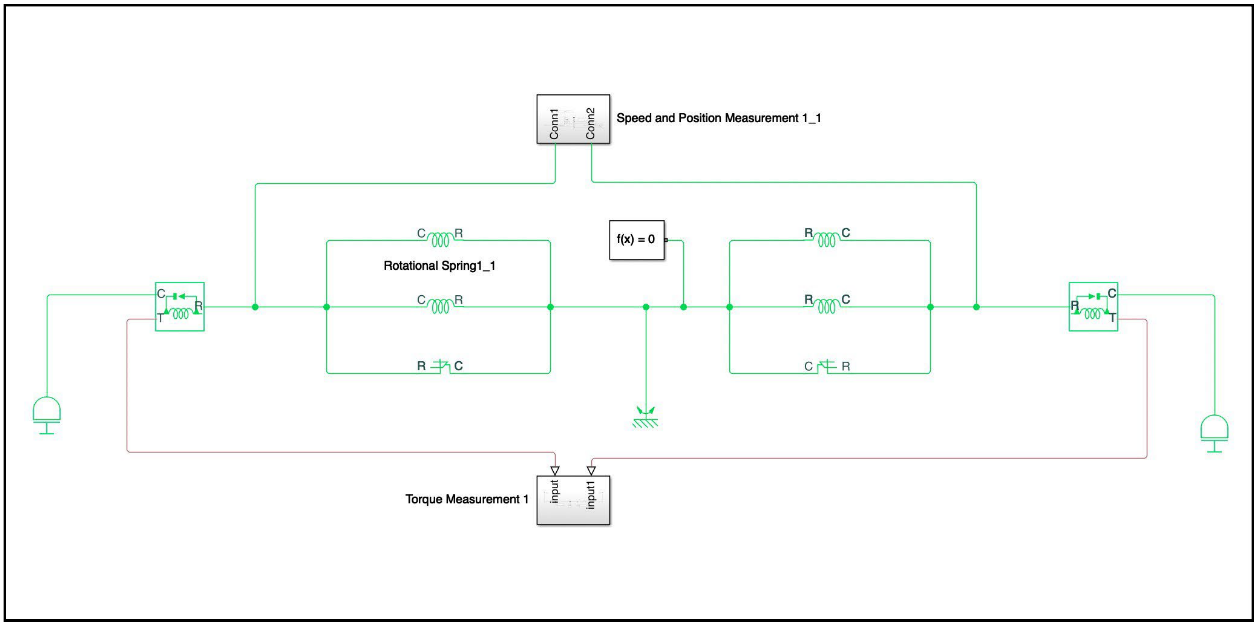

Figure 5 – MATLAB/Simulink Model

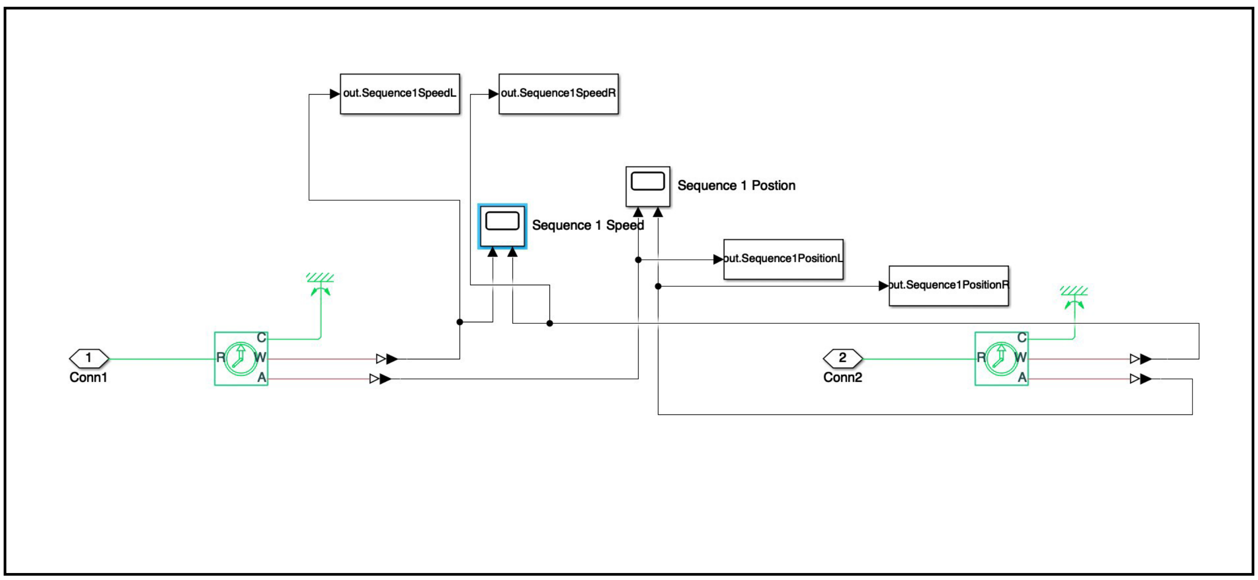

Figure 6 - Speed and Position Measurement

Assuming that both solar arrays are deployed at the same time, that the opposing hinges provide the same friction torque, and that moments of inertia of the two solar panel sets are equal the resultant forces will cancel out and the resultant moment will be zero. This is extremely difficult to execute in real life because most passive solar array deployments utilize the the burning wire method which is unreliable in producing simultaneous deployments. Therefore, any CubeSat that employs a similar deployment system must have a propulsion system on board in order to ensure the CubeSat is in the correct orientation for its intended purpose. Finally, PS-Simulink converters and scopes are included in the model for viewing the simulation results and for transferring data into the MATLAB workspace for analysis.

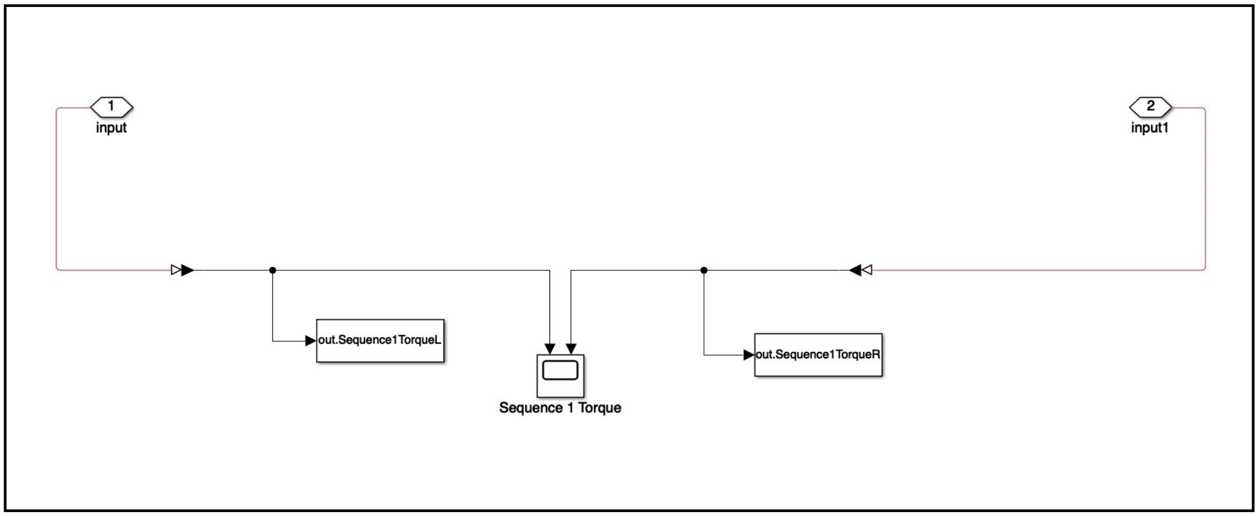

Figure 7 - Torque Measurement

Several parameters were set for the simulation. First, the hinge element was modeled as rotational joint with hard-stop and were given the upper and lower bounds depending on the panels that were connected to the hinge. The contact stiffness and contact damping were set to 1e6 Nm/rad and Nms/rad, respectively. The hard-stop was also configured to apply the full stiffness and damping at the bounds with a damped rebound because the rotational spring would still be active in the rebound. These parameters were selected and standardized as a proof of concept. The rotational springs are the components that cause the rotational motion of the joints. They were given an initial deformation angle based on their position in the deployment sequence, which is either +-90 for Position 1 or +/-180 for Position 2 and 3. The inertia of panels was determined using the equation for a thin rectangular plate where I = 1/3*m*l^2 where m is the mass and l is the length of the plate. The dimensions used in the model came from [1] whereas the mass came from [2]. Note that the moment of inertia for Position 1 is the highest because all three solar panels are rotated at the same time. Then in Position 2 only two solar panels are rotated, followed by rotation to Position 3 where one panel is being rotated. Finally, the ideal rotational motion sensor is included to measure angular displacement as a function of time.

SYSTEM PARAMETERS

The purpose of the What-If Analysis is to demonstrate the effect of changing the target deployment time has on the torque produced at the hinge. It should be noted that the deployment sequence is not controlled by an electric motor and a PID controller. The solar arrays are deployed by releasing the energy of loaded rotational springs at timed intervals. Therefore, the main method to change the deployment time is to change the rotational spring stiffness coefficient because all other factors are held constant. Three separate scenarios were performed with corresponding deployment durations of 10, 20 and 30 seconds per position and the spring coefficients were developed with Lagrangian Mechanics and were selected to match the desired deployment times. These coefficients were applied to 3 separate models with different initial deformations to represent the deployment sequence. Consequently, the What-if Analysis was performed on 9 individual simulations. The target deployment duration and corresponding rotational spring stiffness coefficients are listed in Table 1 and they are implemented into the model through a Matlab Script. As indicated by the results, the spring stiffness coefficients are very small and they may not be readily available, however, this is presented just as a proof of concept. As will be shown in the results section, the simulation outputs include torque measurements which would be the basis for selecting springs that are commercially available.

Table 1 - Spring Coefficient Selections

What-If Analysis	Position 1	Position 2	Position 3
Target Time - 10 Sec	.0023 Nm/rad	.024 Nm/rad	0.0274 Nm/rad
Target Time - 20 Sec	5.702e-4 Nm/rad	.0061 Nm/rad	.0068 Nm/rad
Target Time - 30 Sec	2.537e-4 Nm/rad	.0027 Nm/rad	.0030 Nm/rad

RESULTS AND DISCUSSION

The initial analysis was performed to determine the position of the solar arrays with respect to time. In order to interpret the results, imagine a clock surrounding the satellite with 0 degrees at the 6 o'clock position and increasing counter-clockwise so 90 degrees is at the 3 o'clock position and so on. Then, draw an arrow through the solar array from the hinge to the non-hinge end. Whatever degree the arrow is pointing at is the position of the solar array in the graphs. This is demonstrated in Figure 8. Therefore, it is apparent that the graphs represent an accurate model of the deployment sequence. The simulation results shown in Fig. 9 represent the 3 What-If Analysis applied at each position in the deployment sequence. Note that the lines are not continuous over the 3 sequences because each solar array is in the "loaded" position before it begins its motion. Hence, it makes sense that the arrays are +/- 180 degrees as solar arrays go through the deployment sequence. Note that the hinge configuration's hard-stop was effective, however, the selected spring stiffness coefficients did not meet the target time, especially for Position 3. While the target times were not achieved in any of the three simulations, the overall goal of demonstrating system behavior was accomplished.

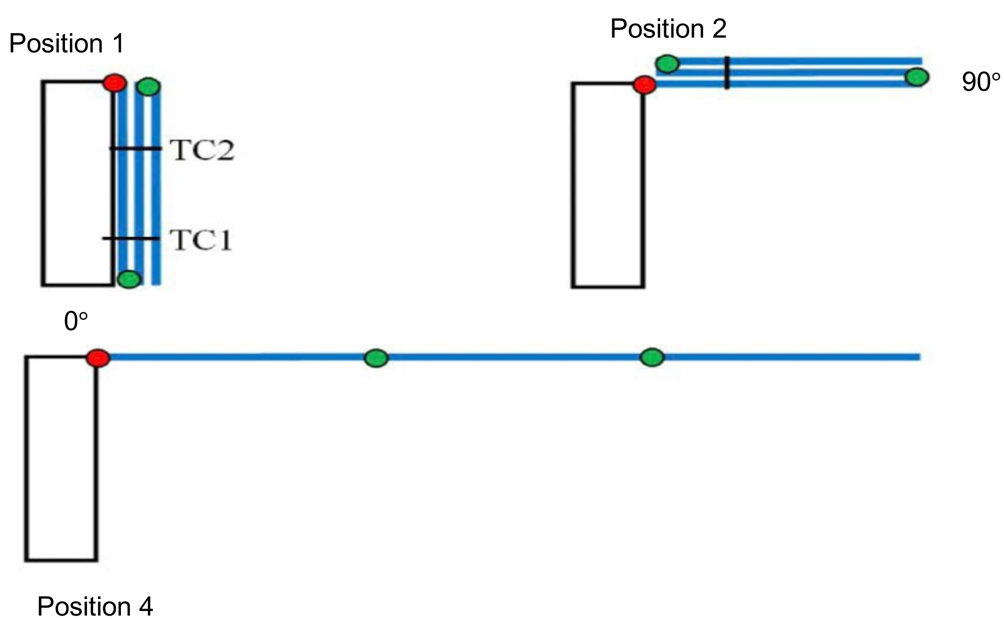

Figure 8 – Position Explanation

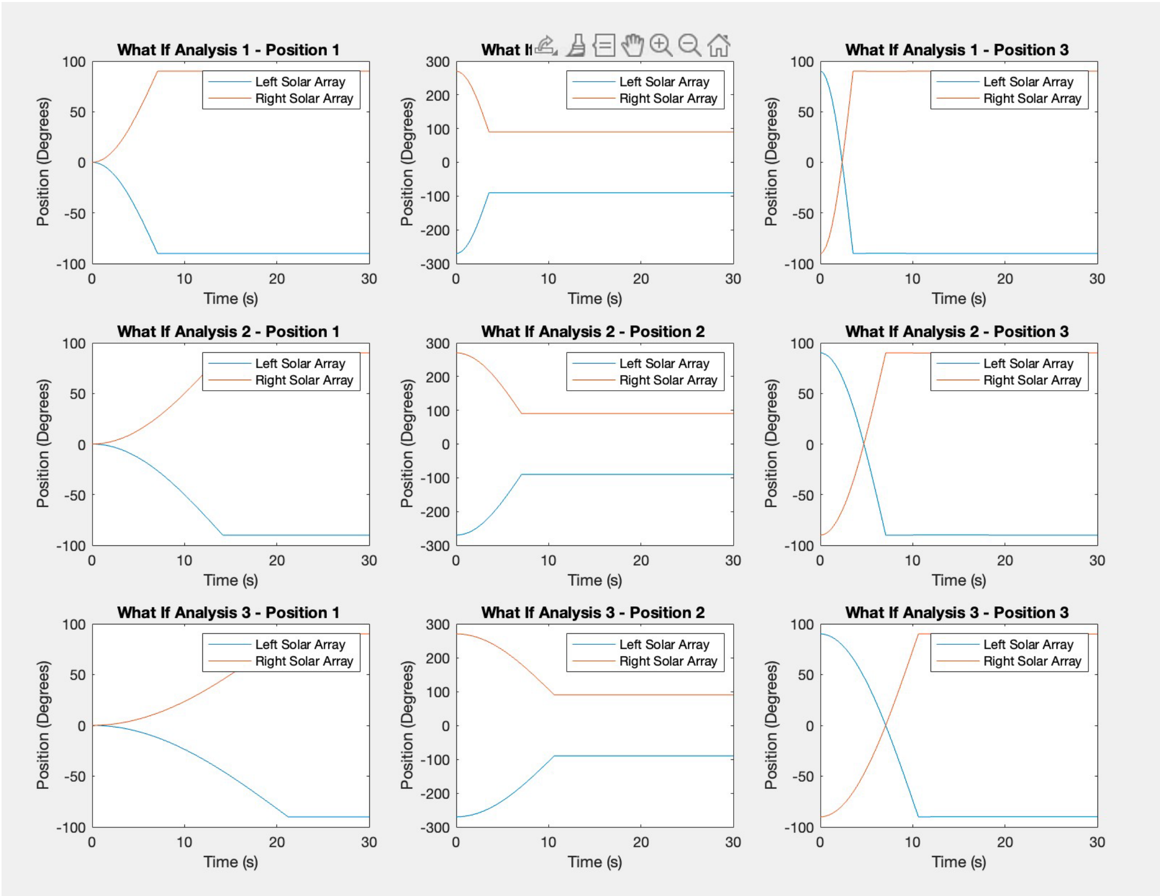

Figure 9 - Position Measurement

The model was also used to determine the torques in each of the joints. As indicated in Fig. 10, the simulation produced the torques for all 3 What-If Analyses at each position in the deployment sequence. As it can be expected the torque spikes when the solar panel reaches the hard stop, and that is the position at which the motion of the panels has the largest effect on the main body of the satellite. Note that the entire goal of the simulation was met because, as the deployment time increased, the torque decreased. The torque was measured above 10^5 Nm for all three scenarios which is a significant load for the CubeSat to handle. This makes it more important for the deployment sequence to be synchronized to minimize the net force felt by the CubeSat. Additionally, similar to the position measurement, this demonstrates an error in the calculation of the spring coefficient calculation because it is clear that solar array deploys more quickly than prescribed in the what-if analysis.

CONCLUSIONS

This what-if analysis of the solar panel deployment process presented in this paper, while relatively simple, presented several challenges. These challenges are summarized up below.

- The model of the satellite body, hinges and solar panels was simplified by using rotational elements from the Simulink/Simscape library. More accurate model can be developed using elements from Multibody library.
- The second main challenge was developing a method to accurately model this system in orbit. The analysis did not take into consideration 6-DOF of satellite but simply modeled satellite as single degree of freedom rotational body. While is the approach is simple it is still powerful enough for a preliminary design.

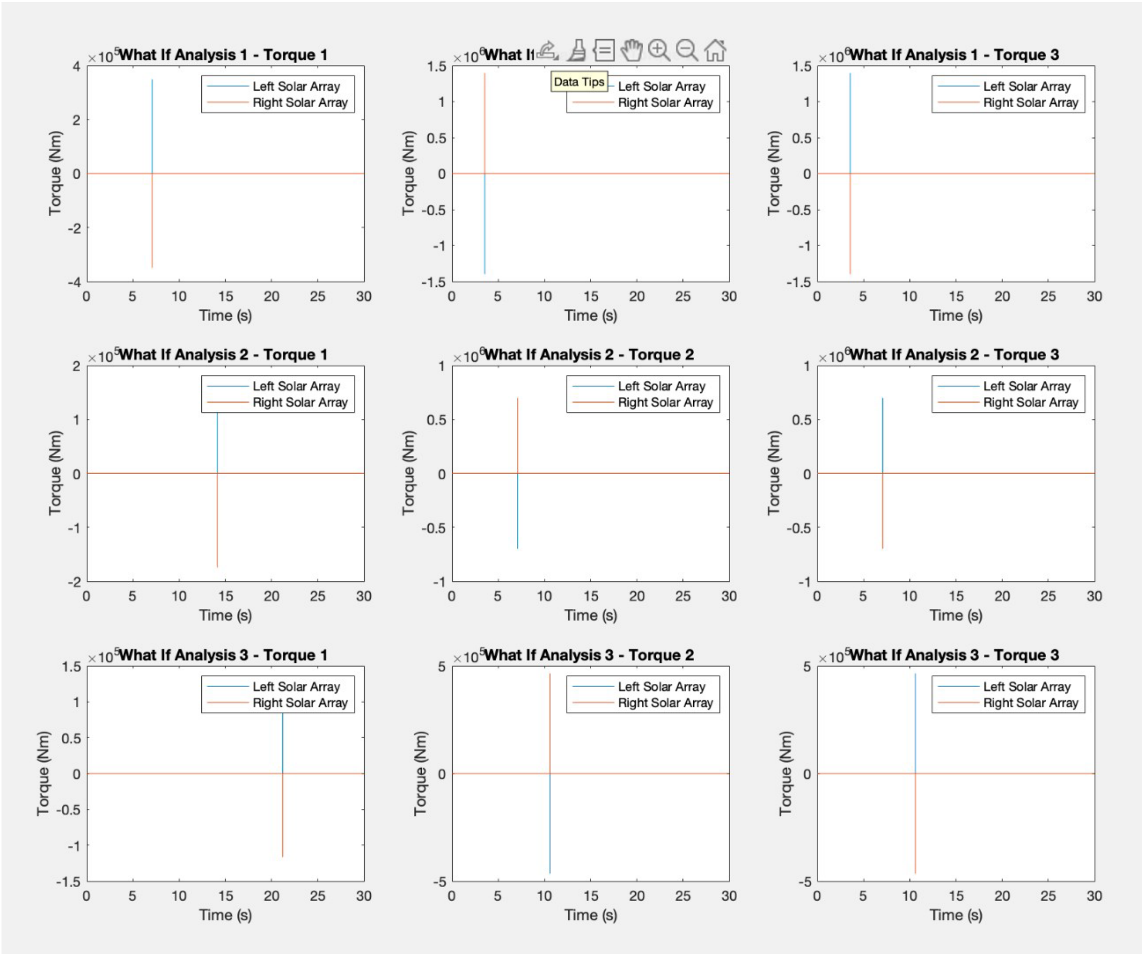

Figure 10 - Torque Measurement

However, there were many positive outcomes from this as stated below

- The main goal of demonstrating the relationship between the deployment time, spring coefficient and torque was achieved. The results proved that as the deployment time is increased, the required spring stiffness coefficient increases due to the increased moment of inertia which also results in an increase oftorque.
- The simulation indicates the rotational hard-stop can be effectively used to model a hinge configuration that limits rotation.
- The results indicate that the model effectively represents the position of the solar arrays in all three steps of the deployment sequence.
- The Lagrangian Mechanics resulted in the equation of motion for all three steps in the deployment sequence and presents accurate method to determine the spring stiffness coefficient that will result in a desired deployment duration.

REFERENCES

[1] F. Santoni, "Dynamics of Spring-Deployed Solar Panels for Agile Nanospacecraft," J. Aerosp. Eng, vol. 28, no. 5, 2015

[2] Endurosat,“3U Single Deployable Solar Array”, 21 June 2022