Focus Control System for Solar Thermal Propulsion

Steven R. Wassom, Ph.D, P.E.
Thiokol Propulsion[*]
Brigham City, UT

Background

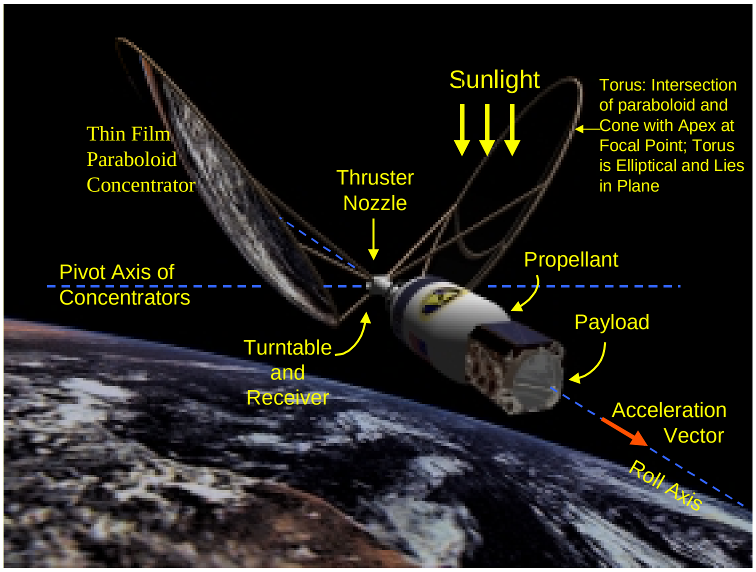


Figure 1. Solar Thermal Propulsion System (illustration provided by AFRL)

The concept of solar thermal propulsion (STP) has been around for many years [1-6]. One approach, shown in Figure 1, uses an off-axis parabolic concentrator mirror like a large magnifying glass to focus the sun's energy and heat a working fluid such as hydrogen to very high temperatures (3,000 K). The hydrogen is then expelled through a nozzle to produce thrust. This innovative concept is predicted to have twice the specific impulse of currently used chemical upper stage propulsion systems, and can therefore place twice the payload mass into geosynchronous orbit. Alternatively, smaller and cheaper launch vehicles can be used for the same payload size. The main drawback is the low thrust level of 0.1 to 10 lb, thus requiring trip times of 30-60 days. However, many payloads can tolerate longer trip times.

One of the largest challenges is the packaging, accurate construction, and deployment of the large concentrators. Both rigid and inflatable designs have been proposed. Thiokol and its partner SRS Technologies have been developing inflatable space structures since the early 1980's. Inflatable solar concentrators can be packaged much more efficiently than rigid concentrators of equal power.

A few years ago, two different divisions of the Air Force Research Laboratory (AFRL) were developing alternative concepts for STP. AFRL/RK at Edwards AFB, California, was funding Thiokol (prime) and SRS (sub) on the STP Critical Flight Experiment (CFE), which was to be a proof-of-concept test of an inflatable concentrator on a high-altitude balloon. Another lab, AFRL/VS at Kirtland AFB in New Mexico, was funding Boeing on the Solar Orbital Transfer Vehicle (SOTV) to build and fly an STP experiment

---

in orbit using a folding rigid concentrator. Air Force upper management decided to merge the two programs. The CFE program was changed to an integrated ground test to support SOTV, and Boeing was directed to baseline the Thiokol/SRS inflatable concentrator (Figure 2) on their spacecraft, with the rigid concentrator as a backup.

Figure 2. Thiokol/SRS Inflatable Concentrator in Integrated Deployment Test

The struts are produced by Thiokol and are composed of an S-glass fabric tube impregnated with a UV-curable resin. A thin-film bladder inside the tube acts as the “mold” when it is inflated. After inflation in space, the resin cures in the natural UV environment, forming a stiff structural member. The torus and lens are made by SRS out of a NASA-developed film called CP-1, and require continuous low-pressure inflation in space. Research efforts are developing a rigidizable torus to increase mission life for operational systems.

Significant progress has been made in both programs. The SOTV program has completed its System Requirements Review and Initial Design Review, and is now performing risk reduction trade studies. Under the CFE program, the accomplishments are:

- Component trade studies completed for struts, torus, lenticular
- Rapid prototyping and hardware-in-the-loop system installed and verified
- Inflation control system designed, fabricated, and tested in both ambient and simulated space environments
- Integrated system fabricated and deployed in simulated space environment (see Figure 2)
- Sun sensors for focus control system fabricated and tested
- Conceptual design and 3-D dynamic model made of focus control system
- Modal testing of inflatable concentrator completed in ambient conditions

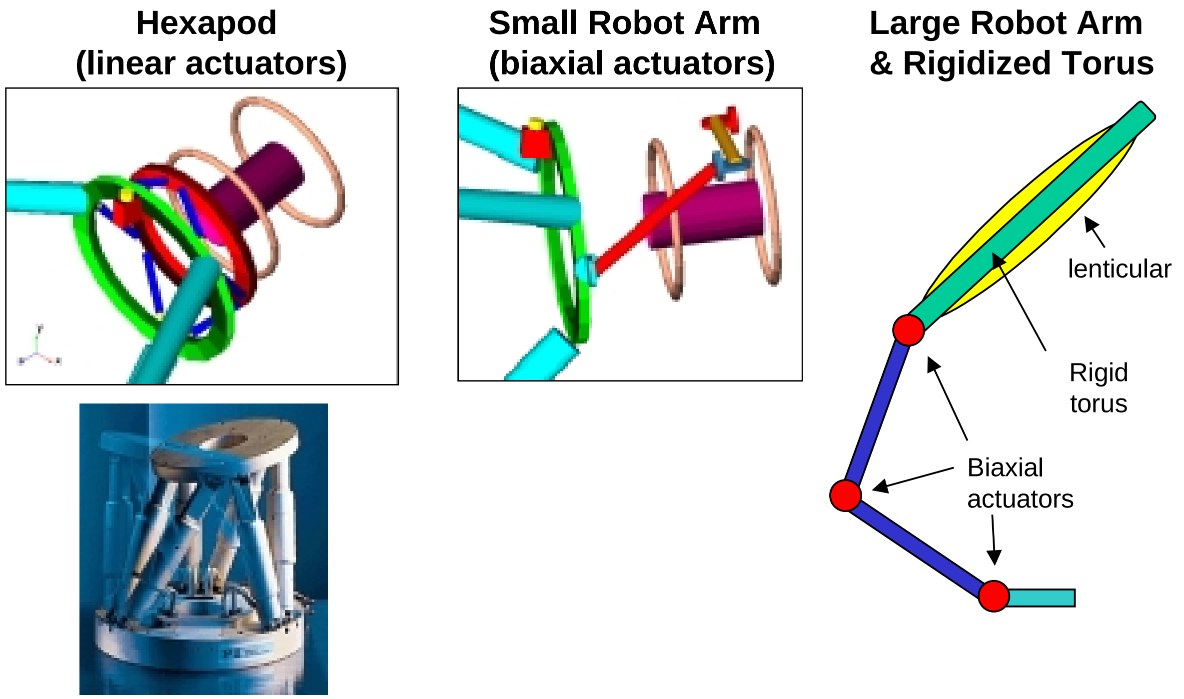
Focus Control System (FCS) Philosophy

Focusing the energy of the sun into the engine using an off-axis parabolic reflector is much like focusing a large magnifying glass. Rotating the concentrator about two axes focuses the energy to a theoretical point. Then, translating the concentrator in 3-dimensional space puts the focal point at the desired point in the engine. This requires then a minimum of 5 degrees of freedom (DOF): 2 rotations and 3 translations. However, since the engine is not really a “point” but rather has an aperture into which the energy must be directed, a third rotation is required, for a total of 6 DOF. Preliminary optical ray-tracing studies suggest that the angular accuracy must be 0.1 deg, and the translational accuracy 0.1 inch.

There are two popular STP engine concepts that determine the amount of rotation required from the concentrator pointing mechanism. They are known as storage and direct gain. In the storage concept, first the entire spacecraft (including the concentrators) rotates to point at the sun to within 1 deg error. Next, the FCS reduces the error to 0.1 deg, enabling the engine mass to absorb the sun's energy and store it for later use. After a time, the spacecraft re-orients to point the nozzle in the desired direction, and the propellant is passed through the engine and out the nozzle, generating thrust. Thus, the FCS only needs to do small motions to fine focus the energy. In the direct gain approach (Figure 1), the concentrator continually tracks the sun during the "burn" while the spacecraft remains pointed along the desired orbital trajectory. This requires that the concentrator be able to rotate up to 180 deg while the spacecraft rolls 180 deg. The remainder of this paper will deal with the storage concept, which is the near-term emphasis of the SOTV program. The direct-gain concept will eventually require that the concentrator be mounted on a turntable capable of the large deflections.

Trade Studies

Several different concepts have been proposed for obtaining the 6 DOF for fine focusing. These are shown together in Figure 3, and consist of a hexapod with linear actuators, a small robot arm with bi-axial rotary actuators, and a long robot arm with a rigid torus which also uses bi-axial rotary actuators. Trade studies are underway using the following discriminators: Adequacy of kinematics, weight, thermal compatibility, cost, failure modes, processor and sensor requirements, accuracy, stability, and scalability to larger systems. Table 1 provides some of the pros and cons of the



Hexapod (linear actuators)

Small Robot Arm (biaxial actuators)

Large Robot Arm & Rigidized Torus

Figure 3. Various Concepts for Focus Control

Type of FCS	***Pros***	***Cons***
Hexapod (linear actuators)	• High stiffness for accuracy • Parallel structure (nonlinear inverse kinematics are closed-form solution) • Traceable flight heritage	• All actuators must be thermally protected
Small Robot Arm at Base Ring (biaxial actuators)	• Fewer actuators subjected to heat flux	• Lower stiffness • Serial structure (nonlinear inverse kinematics may require iterative solution)
Large Robot Arm with Rigidized Torus (biaxial actuators)	• Fewer actuators subjected to heat flux	• Higher development risk (torus, booms) • Lower stiffness • Serial structure (nonlinear inverse kinematics may require iterative solution)

Table 1. Pros and Cons of FCS Concepts

different FCS concepts. Funding is not sufficient to develop quantitative designs and analyses of each of the concepts, and so a more qualitative decision will be made. Since the hexapod is currently the most favored because of its stiffness and flight heritage, the remainder of this paper will focus on this concept.

Figure 4 schematically describes the focusing operation of the hexapod. First, sun sensors mounted on the base ring detect the orientation of the sun with respect to the

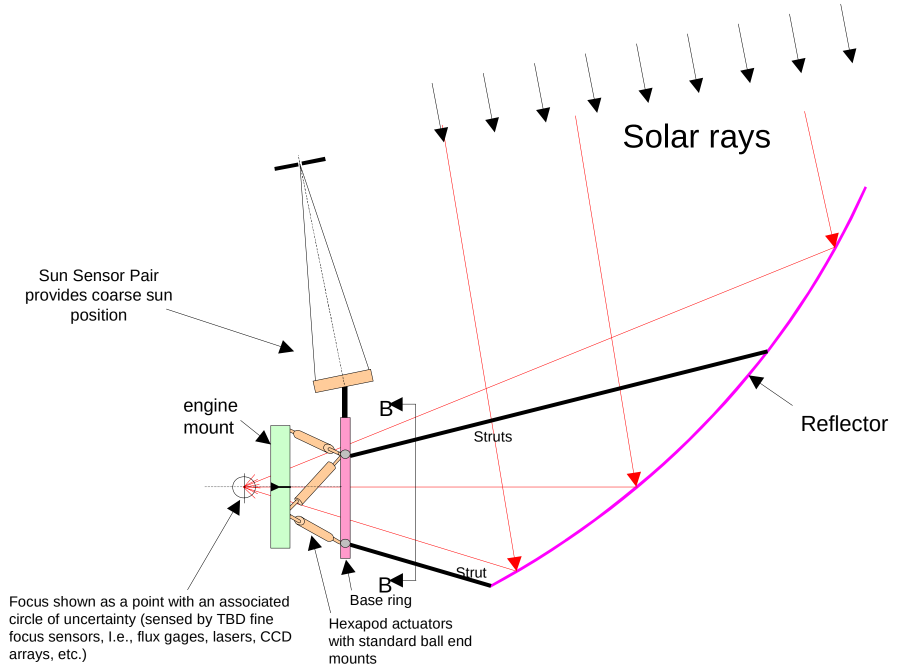


Figure 4. Schematic of Hexapod FCS

base ring, and the hexapod linear actuators move in response to the control law to null the sun sensor output. This in effect is the coarse focusing and gets the focal point in the vicinity of the desired point. However, the inflatable concentrator has additional errors because of thermal contraction and expansion, structural inaccuracies, and dynamic motion. Hence, control is handed over to another suite of sensors for the fine focusing. These sensors, which detect the quality and intensity of the focal point, are yet to be determined; possibilities include flux gages or thermocouples mounted around the aperture in the base ring, lasers, cameras, etc. The actuators then move to maximize the quality of the focus.

Development Environment and Approach

The set of tools which together comprise a rapid prototyping environment is illustrated in Figure 5, and consists of I-DEAS from SDRC (www.sdrc.com) for solid modeling, ADAMS from MDI (www.adams.com) for multibody dynamics, and MATRIXx from Wind River (www.isi.com) for control system design and hardware-in-the-loop (HIL) testing. The MATRIXx system was used in the design, fabrication, and testing of the Inflation Control System for the concentrator, going from concept to successful vacuum chamber testing in 6 weeks [6]. The SOTV prime contractor also uses the MATRIXx system for the full spacecraft model, enabling the efficient sharing of code.

This first iteration on the hexapod FCS was done without the benefit of the new ADAMS/Controls interface. The components were sized, modeled as rigid bodies, and assembled into a mechanism in I-DEAS. The concentrator, struts, and base ring were grouped together as a single rigid body. Each of the 6 linear actuators was modeled as 2 separate rigid bodies with a translational joint. The engine, which is connected to the spacecraft, was connected to ground with a spherical joint to simulate the motion of the

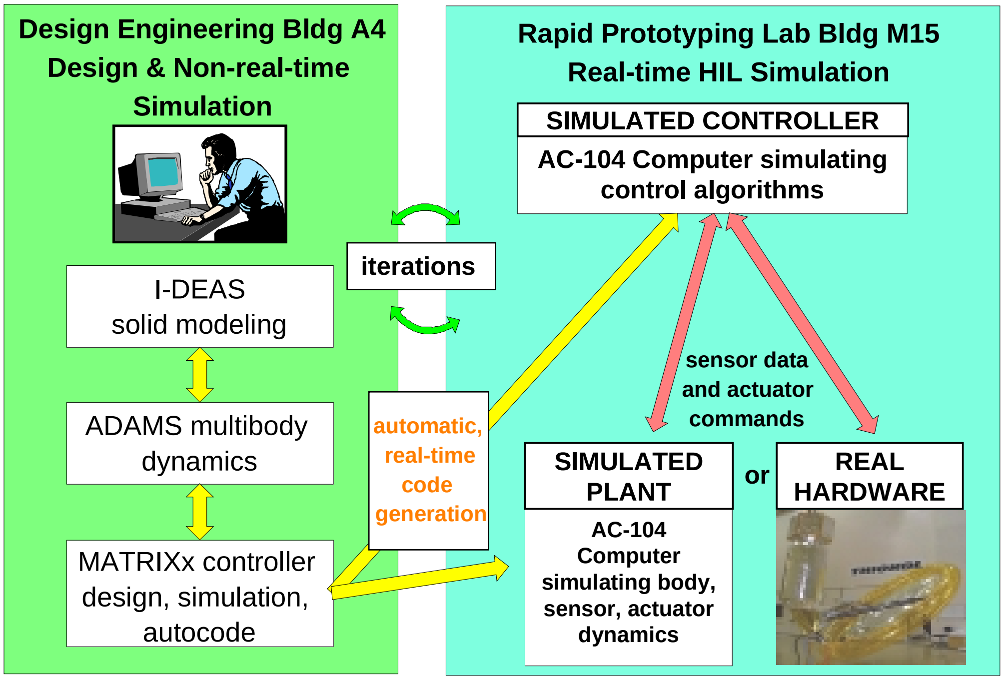


Figure 5. Rapid Prototyping Environment

spacecraft. The total model was thus comprised of 14 rigid bodies (not including ground). Special markers were created to simulate the sun vector (referenced to ground), the ideal focal point inside the engine (referenced to the engine), and the displaced "focal point" of the concentrator (referenced to the concentrator).

An ADAMS (.adm) file was generated from the I-DEAS Export feature and the file was imported into ADAMS. The IGES transfer between I-DEAS and ADAMS was not working properly, and so the graphic representations of each component were crudely re-built inside ADAMS. (This problem has since been resolved in later versions of I-DEAS and ADAMS.) See Figure 6 for an overall view of the model, and Figure 3 for a close-up of the hexapod.

The concentrator rigid body was manually perturbed in each DOF and a static equilibrium solution was used to numerically define the kinematic relationship between the linear actuator strokes and the focal point motion. This was important in the control law so that the actuator strokes would orient the concentrator correctly. The kinematic equations have since been derived analytically, and result in a closed-form solution for the parallel structure of the hexapod. This is one advantage of the hexapod over the serial structure of a robot arm, which in general requires an implicit iterative numerical solution.

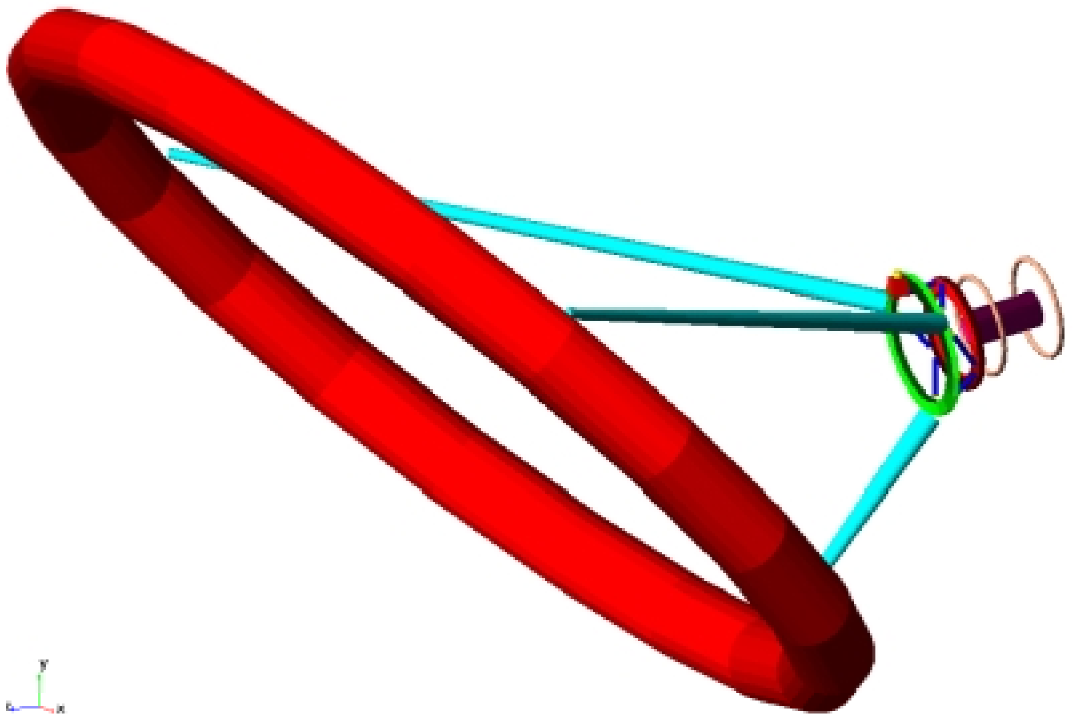


Figure 6. Overall View of ADAMS Model

MATRIXx was used to model the dynamics of the linear stepper actuators and design the feedback control law. The detailed model includes the voltage and current transients in multiple phases, the sinusoidal nature of the torque, the digital logic for generating the pulse stream, and the rotor dynamics. However, the formidable task of converting this complex discontinuous model into the ADAMS language was avoided by simplifying the stepper model to a simple gain and integrator. A comparison of the data from both models showed that this reasoning is sound as long as the load forces and torques on the stepper do not cause it to miss any steps. (Since this study, the detailed stepper model has been converted to ADAMS using the STEP and AINT functions to approximate the digital logic.) A study was also made of the detailed stepper actuator driving a highly flexible inertial load, and a lead-lag compensator was identified which successfully turned the stepper on and off to damp out undesired dynamics. However, since this first iteration only dealt with a rigid-body ADAMS model, the compensator was not included in ADAMS.

Figure 7 is a general representation of the closed-loop block diagram that was converted from MATRIXx to ADAMS. The sensor and compensation blocks shown as “undefined” in the feedback loop were actually implemented as simple unity gains in the ADAMS model, representing a “perfect” sensor suite. The “plate to actuator transform” block (with the numbers shown below) is the linearized matrix transformation between the concentrator motion and the actuator commands that was numerically derived by perturbing the concentrator. For this simple model, only 4 degrees of freedom were assumed for the concentrator motion: translation in x, y, and z, and rotation in yaw. The “comparator with deadband” block is a Schmitt trigger that converts the actuator commands to an on-off signal and a direction signal for the stepper actuator. The gain and integrator represent the simple stepper actuator model.

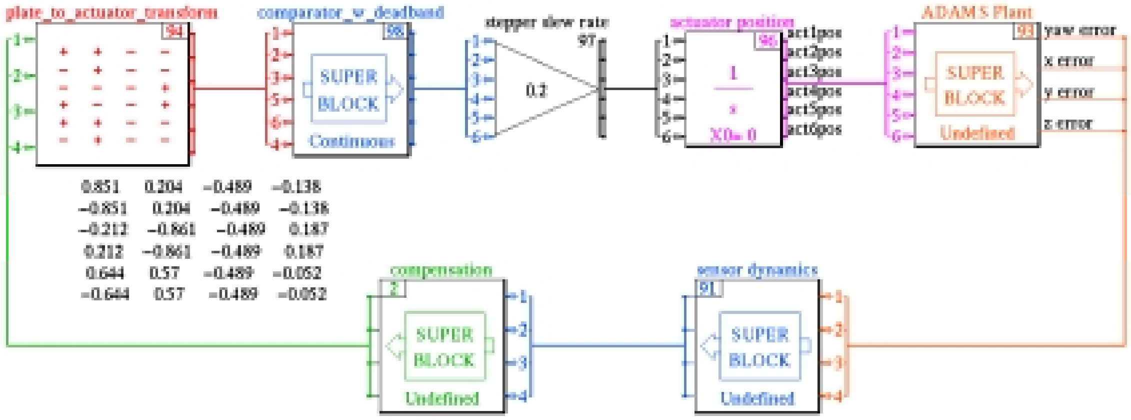


Figure 7. General Block Diagram of Closed-Loop Model

Analysis and Results

The resulting closed-loop ADAMS model was used to analyze the ability of the system to focus the concentrator in response to disturbances. These disturbances were assumed to be an initial condition error and a yaw motion of the engine due to the spacecraft’s attitude control system. This yaw motion was assumed to be a 1 deg amplitude sine wave with a frequency corresponding to a 1 deg/sec peak angular velocity. The initial condition errors approximate the estimated worst-case structural tolerances of the inflated struts and concentrator:

- 0.75 inch error in the x, y, and z location of the concentrator “focal point” with respect to the desired focal point in the engine
- 0.5 deg angular error in yaw with respect to the sun vector

Figures 8, 9, and 10 show the results of the analysis. The translational error time history is shown in Figure 8, and represents the difference between the concentrator focal point and the engine focal point. Figure 9 shows the time history of the engine (and spacecraft) yaw angle, and the angular error of the concentrator with respect to the sun vector. Despite the continued motion of the engine, the control system maintains a near-zero concentrator angular error. Figure 10 is the motion of the linear actuators, illustrating how the actuators continue to extend and retract to keep the error of the concentrator small while the engine and spacecraft move.

Conclusions and Recommendations

This effort has demonstrated the feasibility of using the hexapod approach with stepper actuators to perform the fine focus of a solar concentrator. It has also served as a valuable exercise to understand the process of using 3 different software tools together to design a closed-loop control system for a complex multibody mechanism. Future analyses and refinements include:

- Use of the latest I-DEAS-to-ADAMS and ADAMS-to-MATRIXx (ADAMS/Controls) interfaces to speed up the process, improve the graphics, and improve the accuracy and fidelity of the design
- Incorporation of the nonlinear kinematic equations for the hexapod

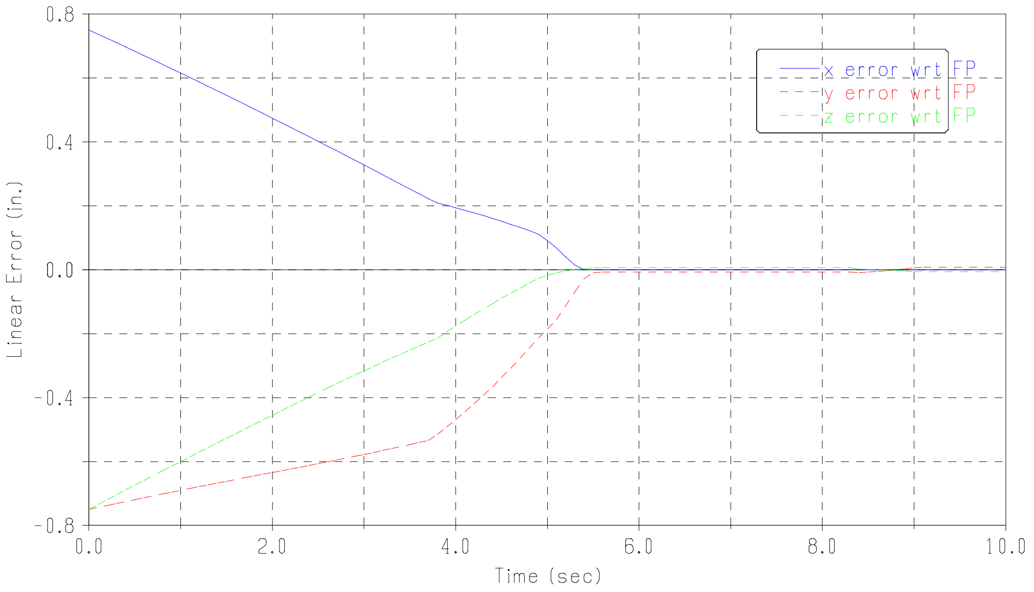


Figure 8. Focal Point Translational X, Y, and Z Error

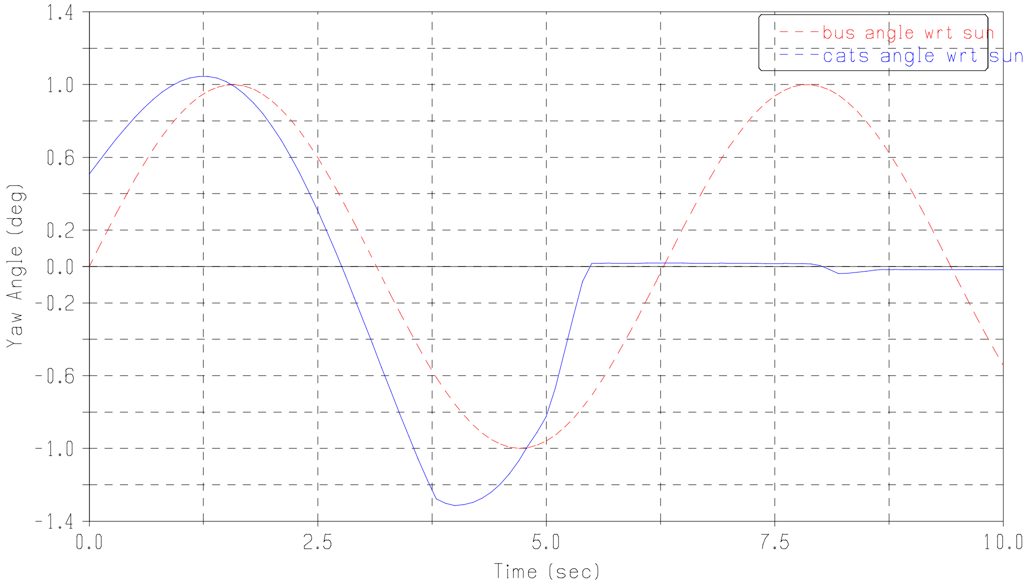


Figure 9. Concentrator and Engine Rotational Motion

- Changing the simplified stepper model to the detailed model
- Selection and modeling of the focal point sensors
- Addition of flexible modes of the concentrator and other disturbances (sensor noise, thermal expansion)
- Design of a more robust closed-loop controller to handle the disturbances
- Refined sizing of actuators and struts based on more accurate loads
- Transfer of the finished model to the prime contractor for integration with the spacecraft model
- Conversion of the model to real-time code for HIL simulation and testing

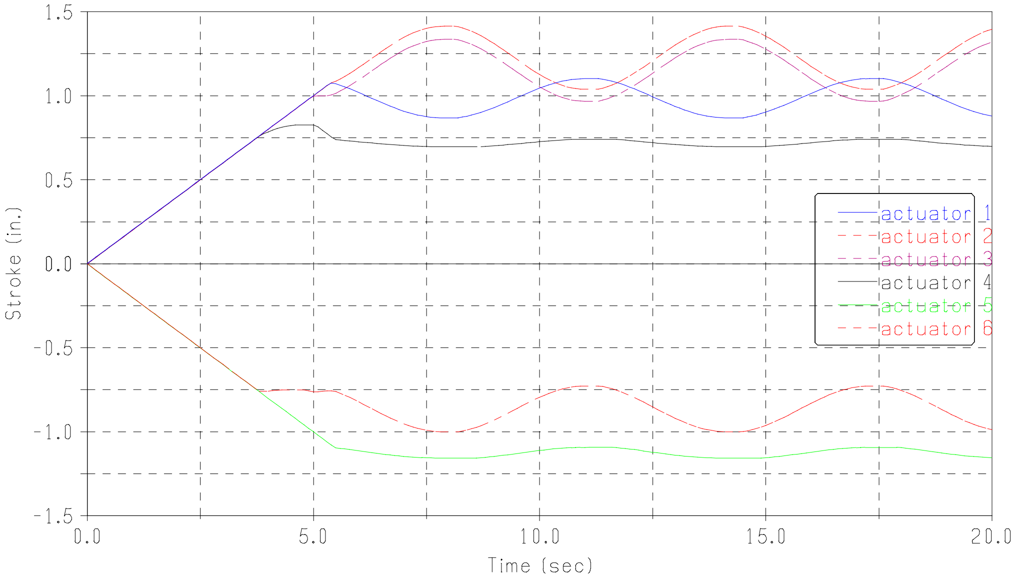


Figure 10. Linear Actuator Stroke

Acknowledgements

This effort was sponsored by the Air Force Research Laboratory, Edwards Air Force Base, California, as part of an IHPRPT contract #F04611-97-C-0033. Appreciation is extended to the program manager, Dr. Michael Holmes, for his support and timely review of the paper.

References

1. Laug, Kristi, “The Solar Propulsion Concept is Alive and Well at the Astronautics Laboratory,” 1989 JANNAF Propulsion Meeting, CPIA
2. Paxton, Jim, and Gierow, Paul, “Concentrators Designed for a Solar Thermal Propulsion Upperstage,” 1995 JANNAF Propulsion Meeting, CPIA
3. “Boeing to Build Orbital Transfer Vehicle,” Space News, 2-8 March 1998, p. 3.
4. Anselmo, Joseph, “Inflated Power,” Aviation Week and Space Technology, 14 Dec. 1998, p. 17.
5. Pearson, Jim et. al., “Near Term In-Space Demonstration of an Inflatable Concentrator,” AIAA 37th Aerospace Sciences Mtg., AIAA-99-1073
6. Lester, D.M., Wassom, S.R., Hancey, B.D., Siefkas, P., “Solar Concentrator Inflation Control System,” AIAA 41st Structures, Structural Dynamics, and Materials Conference, AIAA-2000-1571