THE CHARACTERIZATION OF A VISION-BASED NAVIGATION SYSTEM FOR SPACECRAFT PROXIMITY OPERATIONS AND ON-ORBIT MAINTENANCE

A Senior Honors Thesis

by

ROBERT T. EFFINGER IV

Submitted to the Office of Honors Programs
& Academic Scholarships
Texas A&M University
In partial fulfillment of the requirements of the

UNIVERSITY UNDERGRADUATE
RESEARCH FELLOWS

April 2003

Group: Engineering

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April 2003

Group: Engineering

ABSTRACT

THE CHARACTERIZATION OF A VISION-BASED NAVIGATION SYSTEM FOR SPACECRAFT PROXIMITY OPERATIONS AND ON-ORBIT MAINTENANCE

(APRIL 2003)

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To transport humans into space routinely and safely a spacecraft must be capable of proximity operations (maneuvers close to other spacecraft), and on-orbit maintenance. These operations require an intelligent system that identifies and informs neighboring spacecraft of their relative positions and orientations.

VISNAV[1][2][3] is a VISion-based sensing and NAVigation system that is able to determine the position and orientation of objects in 3-D space. The non-contact nature and quick update rate of this system make it an attractive option for spacecraft autonomous on-orbit maintenance, proximity operations, rendezvous and docking, and many other motion-tracking applications.

The VISNAV system has been explored as an option for autonomous spacecraft rendezvous and docking applications. In these tests the VISNAV system loses some accuracy as the beacons move away from the boresight of the sensor. Also, the system can become singular for certain vehicle and target light configurations. If the VISNAV system

is to be used on real spacecraft it must be robust and failsafe, which means the model cannot become singular.

The focus of this student project is to characterize the system accuracy as a function of distance and angle from boresight of the sensor. The use of two sensors to create a "stereo" version of the VISNAV system will also be explored to increase the reliability and operating range of the system.

ACKNOWLEDGMENTS

I would like to thank Dr. John Valasek and Dr. Declan Hughes for their excellent guidance and support. I cherish the knowledge and friends I have gained during this Research Fellows project.

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INTRODUCTION

A system that quickly and accurately measures relative position and attitude data between two objects would have many attractive applications in the field of space vehicle control. A solution to this problem would also find applications in fields as far-reaching as speech recognition, motion-tracking, robotic vision, and autonomous UAV refueling.

The VISNAV research project[4] led by Dr. J. Valasek, Dr. J. L. Junkins, and Dr. D. Hughes of the Texas A&M University Aerospace Engineering Department is developing a system that can calculate relative position and attitude information in real-time with a high update rate and high accuracy.

Two alternative technologies currently under development to measure real-time relative positions and orientations are differential GPS, and the Active Sensor System from Marshall Space Flight Center (MSFC). Differential GPS uses the existing Global Positioning System satellite infrastructure to triangulate relative positions and orientations, while the Active Sensor System at MSFC uses laser diodes to illuminate retro-reflectors, and a solid-state camera equipped with a frame-grabber and a digital signal processor to find relative positions and attitudes. Both of these technologies look promising, however differential GPS currently has trouble attaining sub-meter resolution without some type of pattern recognition software, and the Active Sensor System suffers from a computationally intensive frame-grabbing process that taxes the digital signal processor. The frame-grabbing process limits the real-time update rate of the system, and requires a lock-on target configuration to reduce the computational load.

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The VISual sensing and NAVigation system, called VISNAV. VISNAV is comprised of infrared active sensors and beacons rigidly attached to the vehicles of interest. Each sensor measures the angles between several light-emitting beacons and its own bore-sight. These measurements are transformed into a line-of-sight vector between the two vehicles using a Gaussian Least Squares Differential Correction Algorithm. This system can provide relative position and orientation data between vehicles with a high degree of accuracy and with a high update rate. This algorithm is computationally efficient compared to a frame-grabbing process, and achieves greater accuracy as the vehicles get closer, unlike differential GPS.

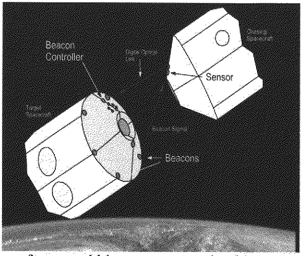

Figure 1. VISNAV Sensor and Beacon System

BACKGROUND

The VISNAV system implements the fundamental truth that the determination of a body frame (position and orientation) in a base reference frame is possible if at least three points of the body frame are known in the base frame.[2] Using this axiom of rigid body mechanics, the VISNAV algorithm was developed that takes three points on a body and automatically calculates the position and orientation of that body in real-time using digital signal processing and signal analysis techniques.

Physically, light beacons that emit light at a certain frequency represent the three points. The VISNAV system can see these points by using sensors that detect only the frequency of light emitted by the beacons. The VISNAV system implements this technology to precisely calculate the relative positions and orientations of two bodies. Beacons are placed at strategic places along one body, and sensors are placed rigidly on a second body. The sensors then record the relative motion of the beacons. In this way, relative body motions can be monitored in real time and used to control the two vehicles.

HARDWARE

This section covers the VISNAV system hardware and electronics. The system is comprised of five components, or subsystems, that when connected together output relative position and orientation measurements that can be used to control the position, velocity, and acceleration of neighboring vehicles. Figure 1 shows the VISNAV setup. There are five subsystems in the VISNAV system. Each subsystem will be explained in the following sections of this paper.

VISNAV Subsystems:

1. Infrared light-emitting-diode (LED) beacons
2. Sensor with Position Sensing Diode
3. Data communications link (RS-232 or wireless radio)
4. Processor that performs calculations, and inputs and outputs data (DSP)
5. VISNAV Algorithm-converts the sensor PSD voltage inputs into position and orientation data.

Beacons

Each beacon is an array of infrared LEDs placed at a strategic location on the target vehicle. The beacons are commanded to turn on and off so the sensors can successively measure the line-of-sight vector to each beacon within it's field of view.

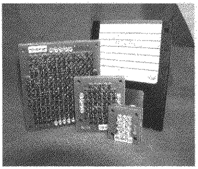

Figure 2. Beacon – LED Array

Sensors

The sensors collect incoming light from the beacons with a focusing lens and use a position sensing diode (PSD) to record the angles at which the light comes into the sensors field of view. The sensor then outputs this angle information to the processor through an RS-232 data link or a wireless link, depending on the application.

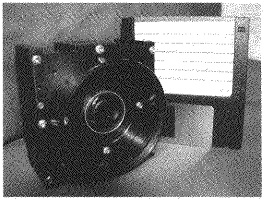

Figure 3. VISNAV PSD Sensor

Data communications link

In the VISNAV system, communications between the central processor and the sensor are achieved using an RS-232 communications protocol. Communications between the central processor and the beacons located on the remote vehicle are achieved through wireless data transfer. In the lab environment, all communications are accomplished through RS-232 data transfer. RS-232 is just one way to network electronic devices. Several other common electronic communications protocols are RS-422, USB (Universal Serial Bus), Firewire, and fiber optic links. RS-232 is ideal for the VISNAV system because it is simple and cheap. Figure 2 shows how an RS-232 link is used to transmit information from the sensor to the processor.

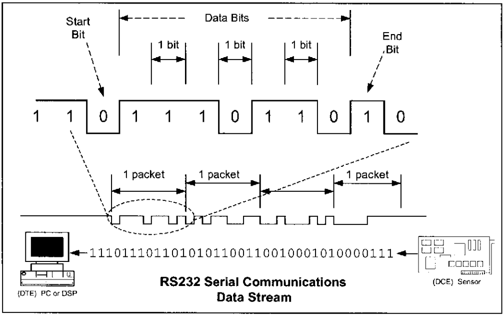

Figure 4. Data Communications Protocol

Most people are aware that electronic devices communicate bitwise, using 1's and 0's. For one device to talk to another they must agree on the format, or structure, of the 1's and 0's they will be sending each other. This data format is called a protocol. A protocol is for computers what language is for humans. Computers can communicate using different protocols, just like humans can communicate using different languages.

The RS-232 protocol uses one start bit to initiate the conversation, transmits seven data bits(in our case the angles of the beacons relative to the sensors), and then uses one stop bit to end the conversation. This process is repeated each time a sensor wants to send data to the central processor. Having the start bit and stop bit surrounding every seven bits of actual data may seem inefficient. However, having these extra bits allows the central processor to perform other tasks while it is waiting for the sensors to send data and also eliminates errors that could occur due to noise in the electronic signal.

Central Processor (Digital Signal Processor)

The central processor is the brain of the VISNAV system. This subsystem orchestrates all actions performed by the other subsystems. The processor can be either a personal computer (PC) or a digital signal processor (DSP). A DSP is analogous to a computer with no monitor or keyboard. Whereas a PC can be programmed at any time to

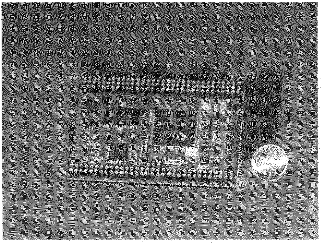

Figure 5. Digital Signal Processor

perform new functions, a DSP must have its commands loaded into memory from an external device called an emulator. To program a DSP, the DSP and emulator are hooked up to a PC and commands in the form of computer code are loaded into the DSP's memory. The host PC essentially acts as the DSP's eyes and ears while it is connected to the emulator.

The central processor performs several duties:

a. Sends Beacon Signal and Receives Sensor Signal

First, the processor sends a signal commanding the beacon to flash on and off. The processor then reads voltage inputs coming from the sensors through an RS-232 link. These voltages are proportional to the relative angles between the beacons and the sensor.

b. Sends Sensor Data to VISNAV algorithm

Then, the processor sends the input voltages to the VISNAV algorithm. Within the algorithm, the voltages are converted (with a calibration function) into their respective angles, then into the position and orientation of the target vehicle, and finally the relative position and orientation data can be sent back to the target vehicle.

VISNAV Algorithm

The VISNAV algorithm consists of several steps of calculations that determine the relative line-of sight vector between two vehicles. The sequential steps performed by the VISNAV algorithm are outlined below[2]:

1. Input voltage readings to processor and compute normalized voltages.
2. Correct Distortion due to lens
3. Reparameterize to reduce function non-linearity
4. Convert Image space(sensor and beacon data) into Object space(X,Y,Z)
5. Gaussian Least Squares Differential Correction Algorithm(required for real time navigation to get 6 DOF position and orientation estimate)
6. Output (X,Y,Z,P,Y,R) i.e. position and orientation commands to the remote vehicle

Prior to operation, the system must be calibrated to account for non-linearities in the mapping from object to image space. There are several ways to achieve this calibration, and Chebysev orthogonal polynomials is the method currently employed. The calibration process is documented in reference [2].

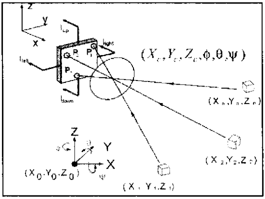

Figure 6. VISNAV Linearized Pin-Hole Model

The linearized transformation from Object space to Image space, can be written as follows[2]:

$$y_i = g_{yi}(X_i, Y_i, Z_i, X_c, Y_c, Z_c, \phi, \theta, \psi) \tag{1}$$

$$= y_o - f\frac{C_{21}(X_i - X_c) + C_{22}(Y_i - Y_c) + C_{23}(Z_i - Z_c)}{C_{11}(Xi - X_c) + C_{12}(Y_i - Y_c) + C_{13}(Z_i - Z_c)} \tag{2}$$

$$z_i = g_{zi}(X_i, Y_i, Z_i, X_c, Y_c, Z_c, \phi, \theta, \psi) \tag{3}$$

$$= z_o - f\frac{C_{31}(X_i - X_c) + C_{32}(Y_i - Y_c) + C_{33}(Z_i - Z_c)}{C_{11}(Xi - X_c) + C_{12}(Y_i - Y_c) + C_{13}(Z_i - Z_c)} \tag{4}$$

$$i = 1, 2, \ldots N \tag{5}$$

where the constants C_{jk} are the elements of the direction cosine matrix that describe the image space orientation with respect to the object space in 3-2-1 Euler angle form:

$$C = [C_{jk}(\phi, \theta, \psi)] \tag{6}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\psi & s_\psi \\ 0 & -s_\psi & c_\psi \end{bmatrix} \begin{bmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} c_\phi & s_\phi & 0 \\ -s_\varphi & c_\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_\theta c_\phi & c_\theta s_\phi & -s_\theta \\ -c_\psi s_\phi + s_\psi s_\theta c_\phi & c_\psi c_\varphi + s_\psi s_\theta s_\phi & s_\psi s_\theta \\ s_\psi s_\varphi + c_\psi s_\theta c_\phi & -s_\psi c_\varphi + c_\psi s_\theta s_\phi & c_\psi c_\theta \end{bmatrix} \tag{7}$$

where:

- Xc,Yc,Zc are the unknown object space location of the sensor
- ϕ, θ, ψ are the unknown object space orientation of the sensor
- $C_{ij}(\phi, \theta, \psi)$ are coefficients of the direction cosine matrix that rotates the inertial frame to the body frame.
- X_i, Y_i, Z_i are the PSD image space measurements of the i[th] beacon
- f is the known focal length of the wide-angle lens

The sensor location and orientation variables represent six independent unknowns. Since each sensor outputs two voltages, y_i and z_i, there must be three separate beacons in the sensors field of view. Therefore, if four beacons are placed on an object, and the beacon array fills at least 10% of the sensors field of view, the objects position and orientation can be determined in real-time using the Gaussian Least Squares Differential Correction Algorithm described below[2].

Gaussian Least Squares Differential Correction Algorithm (GLSDC)

The Gaussian Least Squares Differential Correction Algorithm is an iterative model that predicts a geometric best estimate of a body's position and orientation[5]. VISNAV uses the GLSDC algorithm to find the light beacon locations in real-time. The elements of the GLSDC algorithm are listed below:

$$X = \begin{bmatrix} X_c \\ Yc \\ Zc \\ \phi \\ \theta \\ \psi \end{bmatrix} \quad (8) \qquad G = \begin{bmatrix} g_{y1} \\ g_{z1} \\ \vdots \\ g_{z3} \end{bmatrix} \quad (9) \qquad \Delta G = \begin{bmatrix} \tilde{y}_1 - g_{y1} \\ \tilde{z}_1 - g_{z1} \\ \vdots \\ \tilde{z}_3 - g_{z3} \end{bmatrix} \quad (10)$$

$$A = \begin{bmatrix} \frac{\partial_{g1}}{\partial X_c} & \frac{\partial_{g1}}{\partial Y_c} & \frac{\partial_{g1}}{\partial Z_c} & \frac{\partial_{g1}}{\partial \phi_c} & \frac{\partial_{g1}}{\partial \theta_c} & \frac{\partial_{g1}}{\partial \psi_c} \\ \frac{\partial_{g2}}{\partial X_c} & \frac{\partial_{g2}}{\partial Y_c} & \frac{\partial_{g2}}{\partial Z_c} & \frac{\partial_{g2}}{\partial \phi_c} & \frac{\partial_{g2}}{\partial \theta_c} & \frac{\partial_{g2}}{\partial \psi_c} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial_{g6}}{\partial X_c} & \frac{\partial_{g6}}{\partial Y_c} & \frac{\partial_{g6}}{\partial Z_c} & \frac{\partial_{g6}}{\partial \phi_c} & \frac{\partial_{g6}}{\partial \theta_c} & \frac{\partial_{g6}}{\partial \psi_c} \end{bmatrix} \quad (11)$$

$$W = \begin{bmatrix} \frac{1}{\sigma^2_{y1}} & 0 & \cdots & 0 \\ 0 & \frac{1}{\sigma^2_{z1}} & & \\ \vdots & & \ddots & \\ 0 & & & \frac{1}{\sigma^2_{z3}} \end{bmatrix} \quad (12)$$

$$w_{ii} = \frac{1}{(i,i)^{th}\, measurement\_covariance} \quad (13)$$

where:

- X is the sensor/spacecraft position attitude
- G is the PSD output predicted by X and the sensor/beacon model
- ΔG is the difference between the actual noisy PSD measurements and the predicted values using the pin-hole model
- A is the Jacobean matrix of all first order differenctials for the sensor/beacon model.
- W is the inverse of the measured error covariance matrix

The GLSDC algorithm is an iterative solution that computes an estimate for X, given ΔG, that minimizes a weighted sum of the elements of the error ΔG. The GLSDC algorithm is as follows[5]:

$$\Delta X_k = P_k^{-1} A_k^t W \Delta G_k \quad (14)$$

$$X_{k+1} = X_k + P_k^{-1} A_k^t W \Delta G_k \quad (15)$$

$$P_k = A_k^t W A_k \quad (16)$$

- P_k is the X covariance matrix and it provides an estimate of the derived data covariances

$X_k \Rightarrow G_k$ and A, and PSD measurements $\Rightarrow \Delta G_k$, and $W \Rightarrow X_{k+1}$ etc.

Once the beacon locations are determined, that data can be translated into the appropriate commands to control the target vehicle.

CHARACTERIZATION OF THE VISNAV SYSTEM

My contribution to the VISNAV project is to assemble a VISNAV demonstration in the Flight Simulator Lab and to characterize it's accuracy as a function of distance and angle away from sensor boresight. This is accomplished be setting up the VISNAV hardware, and setting up a test matrix of accuracy vs. distance and sensor bore-sight angle. I am currently finishing the demonstration setup and will begin taking data in the coming weeks. The experimental setup is shown below:

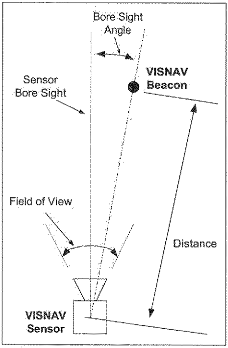

Figure 7. Characterization of VISNAV

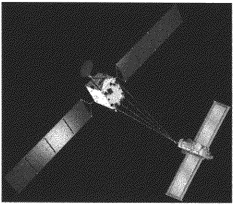

Figure 8. "Stereo" VISNAV Concept

<u>"Stereo" VISNAV Concept</u>

Current work on the VISNAV system has focused on autonomous spacecraft rendezvous and docking [2] and autonomous UAV aerial re-fueling [5]. These applications require precise attitude and position information in a very narrow field of view. Therefore a configuration consisting of one sensor and multiple beacons is desirable. However, the VISNAV system also has the potential to provide attitiude and position information over a larger area of operation.

This type of configuration would be desirable for spacecraft on-orbit maintenance and proximity operations around the spacecraft. For the VISNAV system to span a larger area multiple sensors are needed.

Three configurations that will be tested are:

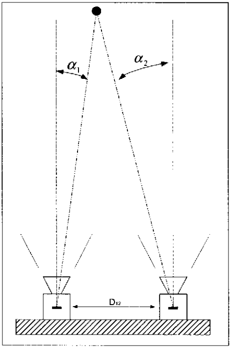

Figure 9. Adjacent Sensor Configuration

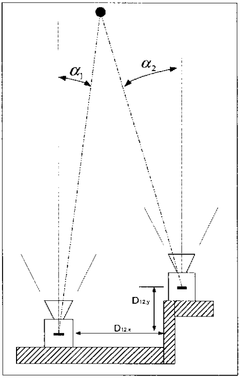

Figure 10. Offset Sensor Configuration

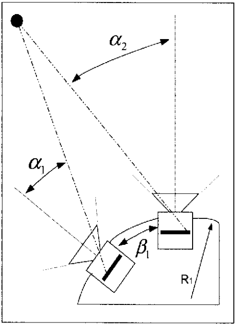

Figure 11. Angled Sensor Configuration

Using two sensors, as shown in the figures above reduces the VISNAV algorithm to a simple triangulation problem. A line-of-sight vector to every beacon is acquired from each sensor. Then the smallest distance between the two lines is calculated, and the midpoint of that line is the new estimate of beacon position.

Interestingly, the calibration procedure takes care of the relative offsets between multiple sensors in the configurations listed above. By its nature, the calibration function developed for the VISNAV system with one sensor corrects for small deviations in beacon and sensor position and orientation. This correction also takes into account the larger position and orientation offsets of the multiple beacons.

Initially a 2-D "stereo" VISNAV demonstration will be tested. Then, 3-D configurations of the sensors and beacons will be tested to mimic the actual application. This VISNAV demonstration will ultimately be sent to Johnson Space Center for analysis and testing on the air-bearing table in the Navigation and Control Lab.

CONCLUSIONS

- The VISNAV system is capable of quickly and accurately determining the line-of-sight vector between two neighboring vehicles to high accuracy with a high update rate.

- Characterizing the system is possible by determining the accuracy of the sensor vs. beacon distance and angle from sensor bore-sight throughout the entire field of view.

- Adding additional sensors to create a "stereo" VISNAV configuration could significantly increase accuracy and allow larger areas of operation for applications such as spacecraft on-orbit maintenance and proximity operations.

FUTURE WORK

- Calibrate the VISNAV sensor with respect to distance and angle from boresight. Investigate the improvements in accuracy by using multiple VISNAV sensors.

- Create a 3-D demonstration of the "stereo" VISNAV concept.

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Curriculum Vitae

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Education and Experience:

I love the idea of space travel! My dream job is to ferry people into Earth orbit and to the Moon for research, fun, and leisure. To learn more about space I have held three internships at NASA centers and contributed to several space-related research projects. I plan to study Aeronautical and Astronautical Engineering at MIT in graduate school and explore the research topics of autonomy and reliability in space system design. This area of study will teach me how to increase manned space system reliability and safety while simultaneously reducing space mission cost. Both of these are necessary to enable safe, cheap, and routine human access to space.

My sophomore year I performed my first internship at NASA Johnson Space Center (JSC). I helped to repair and refurbish space suits and EVA tools. It was amazing to think that the tools I tested would soon be zooming around the Earth going 17,000 mph in the hands of an Astronaut! This internship inspired me to learn about all aspects of the manned space program, and to pursue a job at Johnson Space Center after graduation.

In the summer of my junior year I performed my second internship at NASA JSC. During this term I worked in the Automation, Robotics, and Simulation Division. I helped to develop a robotic arm training simulation that teaches Astronauts how to use the remote manipulator system (robotic arm) on the Space Shuttle.

My next internship was at Langley Research Center. I worked in the Advanced Materials and Processing Branch and tested piezoelectric ceramic actuators. These devices are very neat because they deform when an electric current is applied. My mentor and I tested piezoelectric pumps that did not have any moving parts! The pump parts are rigid but deform relative to one another when an electric current is applied to create a pumping action.

In addition to internships, I also contribute to space-related research projects at my university. Currently I am helping to characterize a visual navigation system that will be used to enable autonomous spacecraft rendezvous and docking, proximity operations, and on-orbit maintenance. Also, I am leading a KC-135 Reduced Gravity Student Experiment on the "vomit comet". This is a NASA-owned jet that flies parabolas through the sky and subjects its passengers to periods of simulated microgravity. Our project is titled Asteroid Anchoring: Low Velocity Solutions to Landing on an Asteroid, and we are testing a way to attach thrusters to an asteroids surface. These thrusters could be used to move Near Earth Asteroids away from a collision course with our planet. Another project worth mentioning is my senior design project in which we are designing a pressurized, manned, Mars rover. We are investigating safe and redundant rover designs that incorporate inflatable materials technology similar to the Transhab module planned to provide crew quarters on the International Space Station.

I have enjoyed my internships and research projects and cherish the knowledge and friends that I have gained from each of them. This summer at NASA Academy I hope to learn more about the Astrobiology side of space research, and also how the NASA centers interact and coordinate to further the human exploration of space.

Extracurricular interests:

My hobbies include playing soccer, attending space-related conferences and seminars, and spending time with my friends and family. For three years I was a member of the Texas A&M Mens Club Soccer Team, and I also play city league and intramural soccer whenever I get a chance. I enjoy sand-volleyball, tennis, surfing, running, hiking, and anything active.

I am an avid space enthusiast and enjoy space-related conferences and organizations. I am a member of the National Space Society and the Space Frontier Foundation, and I participate in AIAA student meetings and conferences.

In addition to space and sports I spend the rest of my time with family and friends. My friends and I like going to clubs on the weekend and just hanging out. My parents and grandparents live on a ranch so it is fun to go home and hike, fish, or just relax.