REAL-TIME MODELING OF SPACECRAFT SIMULATORS USING SYSTEMS TOOL KIT (STK)

Alex Friedman
Advisor: Dr. Troy Henderson
Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University, Blacksburg, VA, 24060

Abstract

The research presented in this report focuses on the spacecraft simulators, Whorl-I and Whorl-II, in the Space Systems Simulation Laboratory (SSSL) at Virginia Tech. The goal of this research is to develop a program to visualize the attitude of the simulators in real-time through Analytical Graphics Inc.’s Systems Tool Kit (STK). Spacecraft missions are high-risk and high-expense; therefore, extensive hardware testing prior to launch is important to spacecraft missions. Air-bearing systems are often used to simulate spacecraft because of their ability to reduce the friction on the simulator due to gravity. Creation of a program to simulate attitude of a spacecraft in real-time further improves pre-flight testing capabilities. A three-axis accelerometer and a three-axis magnetometer are used to collect data, which is then processed using the TRIAD method for attitude determination. Quaternions are then sent to STK by Connect commands; furthermore, Connect commands are used to propagate an orbit in STK. The simulator attitude is continually sent from the simulator to STK to create a real-time visualization of spacecraft attitude in orbit establishing a more accurate test bed for new spacecraft hardware prior to launch.

1. Spacecraft Simulators

The Space System Simulation Laboratory (SSSL) at Virginia Polytechnic Institute and State University (Virginia Tech) houses two spacecraft simulators, formally known as a Distributed Spacecraft Attitude Control System Simulator (DSACSS). The DSACSS uses an air-bearing system with a low-friction sphere and clean, dry air filtered from an air compressor for testing of attitude control hardware and sensors. The first simulator, Whorl-I, depicted in Figure 1, uses a “tabletop” platform with ±360° of rotation in the yaw axis and approximately ±6.5° of rotation in the roll and pitch axes. The second simulator, Whorl-II, depicted in Figure 2, uses a “dumbbell” form with two vertical platforms placed at the end of two circular metal arms which are connected to the low-friction sphere. Whorl-II has ±360° of freedom in the yaw and roll axes and approximately ±15° of freedom in the pitch axis.

Figure 1. Distributed spacecraft attitude control system known as “Whorl-I.”

Figure 2. Distributed spacecraft attitude control system known as “Whorl-II.”
Both simulators contain linear actuators with moveable masses, momentum wheels, cold gas thrusters, a MotionPak (gyroscopic and three-axis accelerometer), and a three-axis magnetometer for attitude determination and control. Additionally, Whorl-I contains a control moment gyro and a Newtonian fluid damper. Both simulators are controlled from a central computer in the lab which communicates with PC-104 stack flight computers on each simulator using a dedicated wireless bridge connection. Programs for operating the simulators are written in C++ through the VI command line editor.

1.1 Open-SESSAME Framework

Currently, there exist several spacecraft simulation software packages which are either commercial or open-source. The commercial packages are either expensive, can only be expanded through the manufacturer, or are dependent on other software. Open-source packages do not have these shortcomings, but the current available packages do not have the capabilities for broad spacecraft simulation. As a result of the previous shortcomings of current commercial or open-source spacecraft simulation software packages, an Open-Source, extensible spacecraft simulation and modeling (Open-SESSAME) framework was developed for the DSACSS. The Open-SESSAME framework provides researchers the ability to test spacecraft algorithms; furthermore, the code developed for such algorithms can be easily viewed and adapted. The overall goal of the Open-SESSAME framework is to provide researchers with a spacecraft simulation tool which can be easily viewed and extended without the need to learn a new scripting language or develop a whole software package. Even though the Open-SESSAME framework was developed as a broad spacecraft simulation tool, it can also be supplemented with current spacecraft simulation software packages. One package in particular, Analytical Graphics Inc.’s Systems Tool Kit (STK), excels in orbit propagation and 3D graphics spacecraft visualization. The Open-SESSAME framework was built with the capability to interface with other software packages which is utilized in this research to create a real-time visualization of the DSACSS.

2. Real-Time Spacecraft Simulator Modeling

2.1 Motivation

Development of real-time spacecraft simulation software was motivated by NASA’s Science Mission Directorate (SMD). The SMD aims to use space research and exploration to search for new knowledge and understanding of Earth, the Sun, the solar system, and the universe. This knowledge can be achieved through launching satellites containing new experiments into orbit. Due to the expense necessary to place a satellite in orbit, testing of new hardware prior to flight is important. Spacecraft simulators do not completely match the environment of a satellite in orbit, but supplementing the hardware with orbit propagation programs such as STK is a way to increase the accuracy of spacecraft simulators. Therefore, real-time spacecraft simulation software which operates with the DSACSS adds the ability to more accurately test new spacecraft hardware before a costly launch into orbit.

2.2 Attitude Determination

The attitude of a spacecraft refers to the orientation of the body-fixed coordinate frame in reference to another known coordinate frame, typically an inertial reference coordinate frame. Three independent attitude parameters are required for attitude determination; however, a unit vector, a reference coordinate frame in this case, is only composed of two independent parameters. Therefore, the attitude determination problem is underdetermined with only one measurement, resulting in only two parameters. Also, with two measurements, the attitude determination problem is overdetermined since two measurements will result in four parameters. Therefore, the attitude of an object cannot be exactly determined, but instead attitude is estimated.

There are two methods to determining attitude, deterministic and statistical. Deterministic attitude determination is a method of calculating the rotation matrix of a spacecraft from the body-fixed frame to a
known reference frame. Statistical attitude determination is a method that uses more than two measurements to statistically determine the rotation matrix from the body-fixed frame to a known reference frame. This research uses a deterministic attitude determination method known as the TRIAD method to obtain the orientation of the simulators.

2.2.1 Attitude Sensors

The simulators are equipped with a BEI MotionPak II unit that has three-axis accelerometers and rate gyros for attitude determination. Interfacing with the PC/104 via a serial connection, this device can sense rates up to ±75 °/s and accelerations up to ±1.5 g in each axis. Also, a Honeywell HMR2300 three-axis strap down magnetometer, which is capable of measurements in the range of ±20 000 nanoteslas with an uncertainty of 6.7 nanoteslas is used for attitude determination.

2.2.3 TRIAD Method

Due to the limited sensing capabilities of the DSACSS, the TRIAD method is used to determine the attitude of the simulator. Also, the TRIAD method was selected for its simplicity. TRIAD which stands for “Tri-Axial Attitude Determination” is a method for obtaining the rotation matrix of an object from two vectors. The two vectors used for the TRIAD algorithm come from various sensors on a spacecraft. In this instance, a three-axis magnetometer and three-axis accelerometer are used to determine the vectors. The TRIAD method constructs two orthogonal “triad” vectors which are used to create the rotation matrix between the body-fixed frame and the inertial reference frame. The accuracy of the TRIAD method depends on the accuracy of the sensors. Table 1 lists some common sensors with the accuracy of each. The TRIAD method begins with selecting the vector from the more accurate sensor of the two to reduce the error in attitude estimation. Next, two orthogonal triads are constructed which then form the rotation matrix.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetometers</td>
<td>1.0° (5000 km alt)</td>
</tr>
<tr>
<td></td>
<td>5.0° (200 km alt)</td>
</tr>
<tr>
<td>Earth sensors</td>
<td>0.05° (GEO)</td>
</tr>
<tr>
<td></td>
<td>0.1° (LEO)</td>
</tr>
<tr>
<td>Sun sensors</td>
<td>0.01°</td>
</tr>
<tr>
<td>Star sensors</td>
<td>2 arc-sec</td>
</tr>
<tr>
<td>Gyroscopes</td>
<td>0.001 °/hr</td>
</tr>
<tr>
<td>Directional antennas</td>
<td>0.01° to 0.5°</td>
</tr>
</tbody>
</table>

Using the TRIAD method with the DSACSS returns a rotation matrix which describes the attitude of the body-fixed frame with respect to an inertial reference frame.

2.2.4 Attitude Representation

Using the rotation matrix determined from the TRIAD method, the attitude of a spacecraft can be represented in several different ways. The most common representations are Euler angles and quaternions. When only using three parameters to describe the relative orientation of a body-fixed frame to a reference frame, at least one geometric singularity exists. Furthermore, this geometric singularity results in a singularity in the kinematic differential equations. The singularity can be eliminated in the system by using a redundant set of four parameters. Euler angles are a three parameter set which are easiest to visualize out of the attitude representations, but since Euler angles only use three parameters, at least one singularity exists. A quaternions is a four parameters set which eliminates the singularity from attitude representation; however, a four parameter set is difficult to visualize.

Quaternions were selected as the attitude representation for this project because of the avoidance of singularities. The quaternions are determined at a time step specified by the user on program run. Furthermore, the quaternions are sent to Systems Tool Kit through an external connection and connect commands to update the attitude of the spacecraft.
2.3 STK Connect

As mentioned in the introduction of the Open-SESSAME framework, the architecture of the system was built with the capability to interface with external software packages. Some of Analytical Graphics Inc.’s Systems Tool Kit (STK) capabilities are high-fidelity orbit propagation and visualization of spacecraft attitude. STK uses a Connect module to establish a client-server environment. Once a connection is established, commands can be sent to STK to create any desired scenario.9 This research utilizes Connect commands to update attitude information in real-time and propagate a high-fidelity orbit while creating a 3D visualization in STK.

2.4 Orbit Propagation

2.4.1 Two-Body Problem

Since the DSACSS are limited to attitude determination, a supplementary program is necessary to model a spacecraft in orbit. The simplest model used to do this is a two-body propagation of the orbit. Initially, without using STK for the computation of the propagation, constant orbital elements, except for true anomaly, were used in the orbit propagation. Although this does not accurately simulate the perturbations experienced by a spacecraft in orbit, the two-body problem does simplify the orbit propagation aspect of the real-time program.

2.4.2 STK Orbit Propagation

Using STK Connect commands, an orbit is established that more accurately simulates a satellite in orbit than the two-body problem. The specific command used to establish the orbit is the SetState command.10 The inputs of the SetState command are the type of propagator, the time of the orbit, the step size, and the orbital elements. STK has many options for orbit propagation; the most common options are TwoBody, J2Perturbation, J4Perturbation, and HPOP. The orbital elements, step size, and orbit time are selected by the user on run of the real-time program. J2Perturbation was selected as the orbit propagator; however, this option can be easily changed if a more precise propagator is desired. With the external connection to STK, the DSACSS is able to simulate both the attitude and orbit propagation of a spacecraft.
3. Results

Using the accelerometer and magnetometer for attitude determination and STK for orbit propagation, a real-time simulation of Whorl-II is created as shown in Figure 3. As Whorl-II is rotated, the attitude changes are displayed in the 3D graphics window of STK.

4. Conclusions

As a result of this research, a better understanding of the Open-SESSAME framework has been acquired. The DSACSS were developed during the late 1990s and early 2000s. In recent years, fewer projects have utilized the capabilities of the DSACSS. Therefore, some of the knowledge for operation of the DSACSS has been lost. Analyzing the software to complete this research has increased the understanding of the software architecture. In order to create a real-time connection between the DSACSS and STK, several processes need to occur. First, data from the magnetometer and accelerometer is obtained from the DSACSS in the form of serial data. Next, the data is processed to obtain vectors of accelerometer data and magnetometer data. Then, the TRIAD method is used to determine the attitude of the DSACSS. Finally, using STK Connect commands, attitude and orbit information is sent to STK for visualization. The creation of a real-time model of the DSACSS requires a detailed understanding of the Open-SESSAME framework and the external connection to STK.

5. Further Work

5.1 Improvements to Attitude Determination

Interference with the magnetometer from the simulator base is the source of some error in attitude determination. Also,
magnetometers and accelerometers are not the most accurate sensing devices used by spacecraft as seen in Table 1. The accuracy of attitude determination may be increased with the addition of more precise sensors, such as star sensors. With the aid of the Optics lab at Space@VT, the simulators could be equipped with star sensors and the optics lab could produce star patterns for the simulator to analyze for orientation information.

In addition to applying more sensors to the simulators, other forms of attitude determination besides the TRIAD method could be used. Statistical methods, such as QUEST (QUaternion ESTimator) or ESOQ (Estimator of the Optimal Quaternion), use two or more sensor measurements to estimate the attitude of a spacecraft. These statistical methods of attitude determination are more accurate and efficient than the TRIAD method.

5.2 Momentum Wheel Demonstration

This research was conducted to demonstrate a proof of concept of real-time simulation capabilities of the DSACSS using STK. Control demonstrations are not being used in conjunction with the program to connect to STK in real-time. Therefore, a program can be created to utilize feedback-loop control programs previously developed to correct for perturbations using the momentum wheels. In addition, previous work has been conducted on formation flying between Whorl-I and Whorl-II; the real-time simulation program could be used with the formation flying work to visualize formation flight between the simulators in STK. The orbit propagation capabilities of STK could possibly even be used to send feedback of orbit perturbations to the simulators for more accurate pointing or stabilization.

5.3 Data Processing Speed

With more consideration to the operations being performed for attitude determination and construction of an orbit in STK, the operating speed of the real-time program could be improved. Also, improvements to current sensors could increase the data processing speed. Furthermore, a faster connection to STK may be able to be established rather than sending Connect commands.

6. Acknowledgements

The author thanks the Virginia Space Grant Consortium for funding on this project, Dr. Henderson for his advice on this project and the ability to work in his lab, Robbie Robertson for help with the simulators, Steve Edwards, Joe Derlaga, and Brent Pickering for debugging help, and those at Space@VT who helped move the simulators to the new SSSL and getting them running again.

7. Literature Cited

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