THE DISTRIBUTED SPACECRAFT ATTITUDE CONTROL SYSTEM SIMULATOR: DEVELOPMENT, PROGRESS, PLANS

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ABSTRACT

Virginia Tech has developed a testbed comprised of two independent spherical air-bearing platforms for formation flying attitude control simulation, the Distributed Spacecraft Attitude Control System Simulator (DSACSS). The DSACSS provides the flexibility to experimentally implement many types of control techniques. Novel individual platform control options include nonlinear compensation of an under-actuated system and coupled attitude control and energy storage techniques. Formation control schemes could consider integrated orbit and attitude control. Multi-actuator attitude control algorithms are being developed and tested on DSACSS, combining momentum/reaction wheel, control moment gyro, and thruster hardware. We are testing the effects of a moving baseplate on the performance of a magnetic bearing. The appropriateness of person-in-the-loop controllability is being investigated by linking DSACSS with Virginia Tech's Cave Automatic Virtual Environment (CAVE). Further, the CAVE can be used to unify two testbeds — DSACSS and the Formation Flying Testbed at NASA-Goddard Space Flight Center — for complete formation flying experimentation. This paper provides details on projects using DSACSS.

INTRODUCTION

Complex space systems are often both high-visibility and high-risk. However, programs that might benefit from hardware demonstration and testing often forego these stages because the influence of gravity and friction render Earth-based behavior unrealistic. An air bearing offers a nearly torque-free environment, perhaps as close as possible to that of space, and for this reason it is the preferred technology for ground-based research in spacecraft dynamics and control. Spherical air bearings are one of the most common devices used in spacecraft attitude dynamics research because they (ideally) provide unconstrained rotational motion. As the name implies, the two sections of the bearing are portions of concentric spheres, machined and lapped to small tolerances. One spherical section rotates on an air film bounded by the other section in three degrees-of-freedom. The rotating surface is rarely a 4π steradian sphere as equipment affixed to the bearing limits the range of motion. Of course, other mechanical arrangements can serve a similar purpose — ball-and-socket joints, for example — but air bearings yield much lower friction.

Virginia Tech has developed a unique new facility comprised of two spherical air-bearing platforms. The uniqueness of this system stems not from particular individual capabilities of either platform, but rather from the ability to demonstrate decentralized control algorithms. Coupled with a third, stationary system, the Distributed Spacecraft Attitude Control System Simulator (DSACSS) provides an experimental facility for attitude control simulation of a three-satellite formation.[1]

In this paper, we describe the overall design of the DSACSS system. We open with a discussion of the

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custom hardware and software we have developed. The body of the paper presents information on some of the unique experimental projects under investigation in the Space Systems Simulation Laboratory that capitalize on the functionality of DSACSS.

HARDWARE

The ideal spherical air-bearing testbed would allow its payload unconstrained angular motion in three axes. Actually providing this rotational freedom is difficult and in practice requires constraining payload volume. "Tabletop" style platforms (Figure 1a) provide full freedom of spin in the yaw axis but pitch and roll motion are typically constrained to angles of less than ±90°. The main structural deck of a tabletop mounts to the flat face of a hemispherical bearing and components then attach to this structure. The "dumbbell" style requires a fully spherical bearing; this configuration offsets the mounting area away from the center of rotation by means of two opposing arms (Figure 1b). Dumbbell-style air bearings greatly reduce structural interference within the rotation space of the payload and thereby provide unconstrained motion in both the roll and yaw axes. Note that the yaw axis for both configurations is defined to be nominally parallel to the gravity vector. For dumbbell systems the roll axis is defined by the mounting arms; roll and pitch are indistinguishable for a generic tabletop system. The bearings illustrated in Figure 1 must, of course, each rest on top of a pedestal, not shown here for clarity.

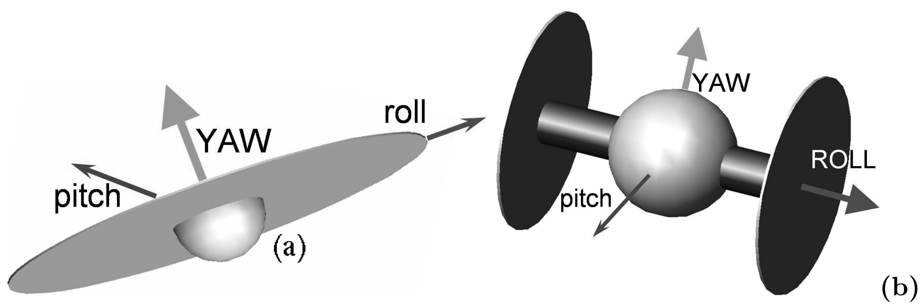

Figure 1: "Tabletop" and "Dumbbell" Style Air Bearings

The DSACSS consists of two air bearings from Space Electronics, Incorporated: one tabletop- and one dumbbell-style. Each can host a payload of up to 300 lb. The tabletop platform provides full freedom in yaw and ±5° of tilt in pitch and roll. The dumbbell platform provides full freedom in both yaw and roll with ±30° of freedom in pitch. The three-satellite formation is completed by a third, stationary, simulator.

At the core of each of the simulators (including the stationary one) is a PC/104+ form-factor computer. Each computer includes a 32-bit, 133MHz Tri-M MZ104+ ZFx86 processor with 64MB of RAM. The processor board can control two EIDE devices and includes interfaces to both an ISA and a high-speed PCI bus (as per the PC/104+ standard), two 100/10 Base-T Ethernet ports, two USB ports, two serial ports, and one parallel port. The operating system (a lean, customized version of Slackware Linux) and command software is stored on a 288MB DiskOnChip solid-state memory device. Analog devices interface to the computer via a 16-bit Diamond Systems DMM-32 A/D board. Along with the 32 analog channels, the DMM-32 also provides 24 programmable-direction and eight fixed-direction digital lines for logic switching.

The three simulators communicate via the standard TCP/IP network protocol. Each computer system includes a Linksys WLAN-11 wireless network device. Each simulator can communicate directly with each of the other two through a wireless access point hosted by an external desktop computer. For reasons of internet security this desktop also serves as the gateway to the internet for the simulator network.

Each air bearing is equipped with three-axis accelerometers and rate gyros for attitude determination. These sensors are packaged as a BEI MotionPak II unit from Systron Donner Inertial Division. 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.

Both air bearings possess several control options. A suite of three custom aluminum/steel 0.075 kg·m^2 wheels mounted on SM3430 Smart Motors can be used as either momentum or reaction wheel devices with a maximum angular momentum of 10 N·m·s and a maximum torque output of 1 N·m. Another SM3430 can be outfitted with a smaller wheel and slewed through a ±45° range of angles as a control moment gyro (CMG). Current hardware only supports a single-CMG configuration with a maximum angular momentum of 1.75 N·m·s and a maximum torque of 2 N·m; a pyramidal configuration of four CMGs for integrated power and attitude control is under consideration for both air bearings.

Another option for three-axis control is through a compressed-air thruster system. Supplied by a 21 ft^3 nitrogen gas tank, the Evolutionary Concepts, Incorporated, solenoid valves can operate from a nominal system pressure set prior to operation below the 100 psi operational threshold. Alternatively, line pressure can be continuously varied via a computer-controlled variable-output regulator, Norgren model VP-50.

An important design consideration for air-bearing testbeds is collocation of the center-of-rotation of the bearing with the center-of-mass of the system. If this design criteria is not observed the attitude equations of motion of the simulator differ from those of an orbiting satellite: a satellite is free to rotate about its center-of-mass while the simulator is constrained to rotate about its center-of-rotation, resulting in an additional external torque to be modeled. However, modelling the mass distribution of the payload to a sufficiently high resolution is prohibitively complex (*e.g.* including connectors, wiring, or non-uniform density commercial components). Instead, each air bearing is equipped with three LPS-8-30 linear actuators from Servo Systems. Each actuator can support up to 30 lb of ballast across an 8 in. travel distance. Initially, these systems will be installed with small ballast weights on the order of a few pounds and used exclusively for center-of-mass placement. Another possible control scheme entails traversing much larger ballast weights, perhaps 20 lb, for energy shaping by center-of-mass motion.

As shown in Figure 2, the tabletop system, dubbed "Whorl-I," is complete. The primary structure is a 3 ft octagonal aluminum honeycomb plate. Large components are mounted directly to threaded inserts installed in the honeycomb, and smaller components are clustered onto brackets. The dumbbell system, "Whorl-II," has undergone final design review and is under construction. The final configuration of this system is shown in Figure 3.

OPEN-SOURCE SOFTWARE

There are many spacecraft simulation software packages, both commercial and open-source. Commercial packages are typically proprietary, expensive, and difficult to customize. Open-source programs are have usually been developed to serve one narrow function and as such are difficult to modify and interface with in new ways. For these reasons, as well as the educational value of developing a new tool, students in the Space Systems Simulation Laboratory are writing and maintaining a pair of open-source software packages.

Open-source software is released to the public under a license which ensures that modifications to the code, as well as the code itself, remains freely available to all users. A well-known example of a successful open-source project is the Linux operating system. Examples of other open-source software projects include advanced mathematical libraries, graphical user interfaces, and visualization tools. Most of these tools are hosted on public repositories that assist in storing the software and providing useful development tools and forums for developer and user discussion. This sharing of software offers great benefits to academic users because useful tools are kept free of cost and are maintained by a community of developers throughout the world. Software bugs are fixed and new functionality is constantly being added and resubmitted to the community at large. Projects that are released under an open-source license tend to live beyond their original creators and beginnings, helping to ensure that useful ideas and developments continue to be used.

The Open-Source, Extensible Spacecraft Simulation And Modeling Environment (Open-SESSAME) framework is a design architecture for building spacecraft simulation and modeling applications.[2,3‡] The framework does not dictate how a user must employ the libraries. For example, the math library includes integration routines that can be used independently of satellite modeling. However, the design of the libraries and

‡Available for download at `http://spacecraft.sourceforge.net`.

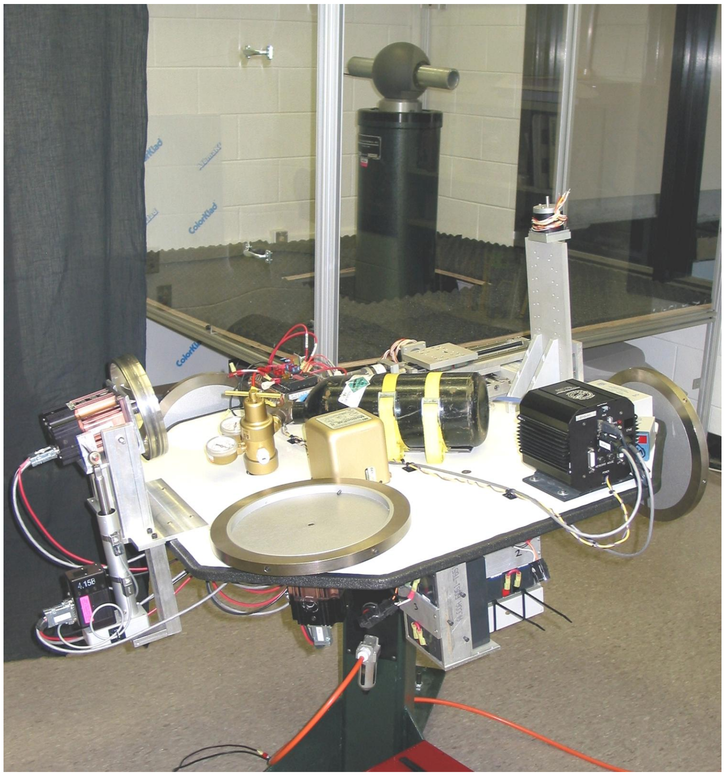

Figure 2: Virginia Tech's Distributed Spacecraft Attitude Control System Simulator

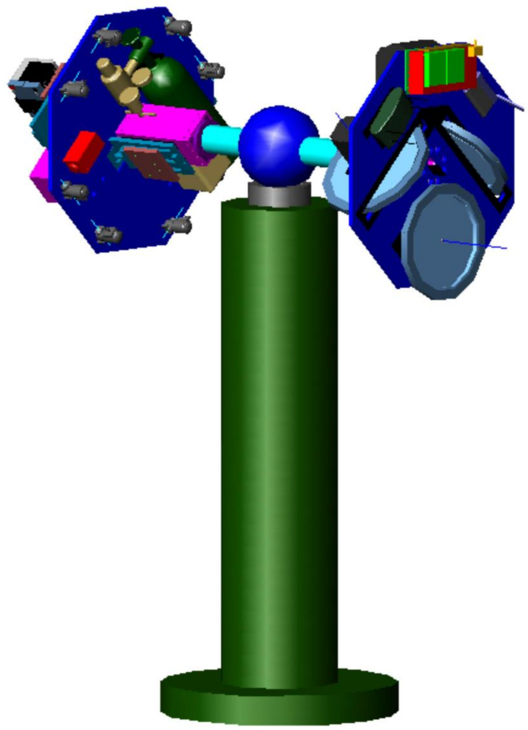

Figure 3: Whorl-II Configuration

their interconnection is based on a regime of target applications that are typical in satellite simulation. The current target domain of Open-SESSAME is in dynamics modeling and simulation. These applications can include attitude or orbit modeling, coupled orbit and attitude simulation, hardware in-the-loop testing and verification, space environment assessment, and control algorithm validation. Possible areas of expansion include algorithms for modeling the power, structural, and thermal environments experienced by an orbiting spacecraft. The architecture is designed to allow for easy extension with new custom libraries, as well as external engineering software.

The Open-SESSAME framework is programmed in C++. This language was chosen due to its prevalence in engineering curriculums and applications. Furthermore, C++ is designed to use Object-Oriented Programming (OOP), upon which the Open-SESSAME framework is laid out. By using OOP the framework is designed to encapsulate data and operation within classes. Classes then use a specified interface to allow the user access to the data without worrying about the underlying implementation. The main components of the framework are as follows:

1. Math: Useful math operations and tools such as matrix, vectors, integrators, interpolators, and conversions.
2. Utilities: Assorted miscellaneous tools, and classes for dealing with time.
3. Rotation: Collection of coordinate transformation representations and their conversions.
4. Attitude: Spacecraft attitude dynamics equations, reference frames, and state representations.
5. Orbit: Spacecraft orbit dynamics equations, reference frames, and state representations.
6. Dynamics: Algorithms for propagating the dynamics of spacecraft orbit and attitude, coupled or uncoupled in varying degrees.
7. Environment: Models of central bodies and space environment disturbances.
8. Data handling: Data and system level file handling for saving and loading spacecraft applications or models, as well as integrating with external applications.
9. Communications: Utilities for setting up networks and communications between simulation applications and hardware components.

The DSACSS-Operational (DSACSS-Ops) software tools are more custom-designed with particular DSACSS hardware in mind.[§] However, the same level of OOP abstraction is maintained in the design of this software. As such, a research group using a similar payload outfitted with different hardware components would only have to modify the hardware-driver level of the code; all higher-level useability interfaces would remain unchanged. The DSACSS-Ops code includes:

1. Configuration parsing: Rather than recompiling the code in order to accommodate a new hardware configuration or controller gain setting, all options are defined in a configuration file that is read in at run time.
2. Algorithms: Includes observers and controllers. Adding a new control law is as simple as writing the equation in C++ syntax. We have written a family of Kalman Filters, ready to customize for the dynamics of a particular system.
3. Logical devices: The algorithm interface with the hardware. This code is generic for a type of hardware (*e.g.* "rate gyro") rather than a particular component.
4. Physical devices: The driver interface with the hardware. This code is customized for the particular components used on the DSACSS (*e.g.* "Systron Donner Motion Pak II rate gyro").
5. Data logging: Save a file of the behavior of any state of interest during an experiment.

[§]Available for download at `http://dsacss.sourceforge.net`.

PROJECTS

The DSACSS provides the flexibility to experimentally implement many types of control techniques. Novel individual platform control options include nonlinear compensation of an under-actuated system (such as simulation of a failed component) and coupled attitude control and energy storage techniques.[4,5] Formation control schemes could consider integrated orbit and attitude control[6] or coordinated pointing at terrestrial targets.[7,8]

Multi-actuator attitude control algorithms are being developed and tested on DSACSS, combining momentum/reaction wheel, control moment gyro, and thruster hardware. We are testing the effects of a moving baseplate on the performance of a magnetic bearing. The appropriateness of person-in-the-loop controllability is being investigated by linking DSACSS with Virginia Tech's Cave Automatic Virtual Environment (CAVE). The remainder of this paper provides details on these projects.

Single-Platform Experiments

Each of the two DSACSS air bearings can serve as a novel experimental facility in its own right. This section describes two projects currently being implemented on Whorl-I.

Magnetic Bearing Research

An Active Magnetic Bearing (AMB) system uses electromagnetic forces to maintain both the radial and axial positions of the rotor. By applying current to a set of coils positioned radially about the stator the rotor is simultaneously attracted in all directions and will begin to levitate. A similar simultaneous-attraction configuration is used to suspend the rotor axially between the stators.

Using AMB systems in combination with flywheels has several advantages. The frictional losses that occur in conventional bearings are greatly reduced in a magnetic bearing because the levitation forces minimize contact between the rotor and the stator. As a result, a magnetic bearing offers increased lifetime operations over conventional bearings, without the need for an oil supply system.

Most of the current literature focuses on stationary AMB systems even though proposed applications include use of these devices as alternative power source for cars, submarine propulsion systems and combined momentum / energy storage for spacecraft. Few studies have included the effects of base motion on such a system.[9,10] Whorl-I is an ideal platform to provide controlled base motion for an investigation of the performance of a magnetic bearing subjected to a wide range of base motion maneuvers. As shown in Figure 4, we have built a custom top-deck to support all relevant hardware, including an additional PC/104 computer for dedicated data logging. Magnetic bearing research in the Space Systems Simulation Laboratory makes use of an MBRotor Research test stand from Revolve Magnetic Bearings Incorporated. This system includes an MB350BT controller for the bearings and motor and the MBResearch BNC interface pod. This system is designed specifically for research applications; its flexibility makes it well suited for base motion experimentation.

This project is nearing readiness for initial experimental testing. Completed work includes system design and hardware acquisition and fabrication. Initial hardware drivers are written and incorporated within the DSACSS-Ops framework; simulation software is written and tested. The ideal gyrostat is the underlying model for the simulations: it consists of a rigid body with an internal rotor that can spin freely about a body-fixed axis. From this model we have derived expressions for the transverse and axial torques on the rotor. These torques represent the disturbances that the magnetic fields within the bearing must compensate for.

Mixed Control Schemes

A spacecraft can use either internal or external actuators to control its attitude. Generally, external actuators such as thrusters are used for large-angle, rapid slewing maneuvers. However, thrusters are not ideal for precision attitude control because they typically only provide discrete control authority. Internal actuators

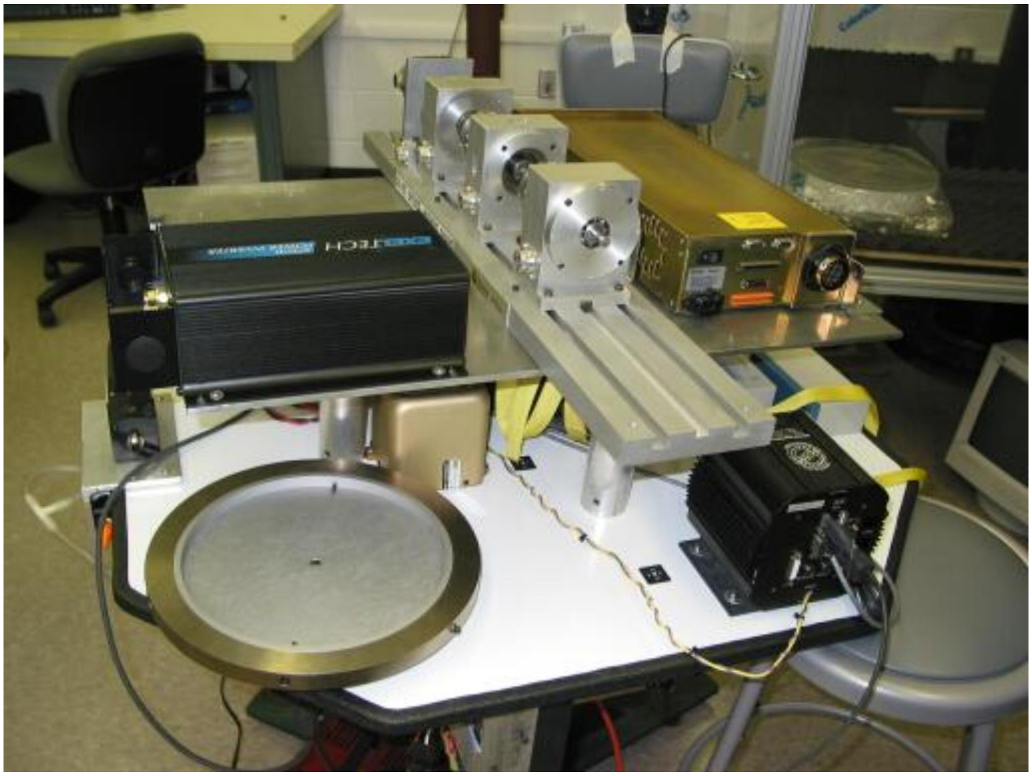

Figure 4: Whorl-I with Magnetic Bearing System Installed

include momentum exchange devices such as momentum wheels and control moment gyros, and non-moving devices such as magnetic torquers. Momentum wheels can perform precise maneuvers and maintain attitude. However, fixed-axis wheels require input torques proportional to the desired control torque. Therefore, momentum/reaction wheels are not ideal for rapid slewing. A CMG creates large torques that are dependant upon flywheel speed, flywheel inertia, and gimbal angle rate: these actuators are better suited to the demands of rapid slewing.

Figure 2 shows Whorl-I with three-axis momentum/reaction wheels and a single-axis CMG. We have developed several nonlinear control laws for attitude and velocity control with CMG actuators that rely on commanding gimbal velocity. This approach takes advantage of the torque amplification factor while preventing the undesirable gimbal rates caused by gimbal acceleration controllers. Further, we use a control strategy that uses one CMG for coarse, large-slew maneuvering and three-axis reaction wheels for precise control and error reduction due to initial conditions. Control laws developed to use thrusters for coarse slew control and momentum wheels for precise control or to reduce errors due to initial conditions have been proven to be effective. We believe mixing CMGs and momentum wheels for attitude control to be a novel approach.[11]

Formation Flying Experiments

Spacecraft formation flight has been the topic of a great deal of research since the mid-1990s. The Earth Orbiter-1 (EO-1) mission was chosen to be a part of the New Millennium Program in 1996. At that time, NASA had only a few formation flying concepts under consideration. Since its launch in 2000, EO-1 has successfully demonstrated autonomous formation flying as part of its earth science mission. Meanwhile, the number of formation flying concepts has grown to 35.[12] Formations of spacecraft can be used for many diverse goals: relative orbit control enables extensive multi-point observing and look-ahead targeting; coordinated pointing allows for autonomous co-observation of terrestrial and deep-space targets; combining these techniques within a single formation improves the effectiveness of space-based interferometry.[13]

The DSACSS only provides attitude freedom; the pedestals themselves cannot move. A planar air bearing could be used to recapture the relative orbital dynamics of the formation. Such testbeds provide one rotational and two translational degrees-of-freedom; the other two axes of rotation and out-of-plane motion are arguably less important in the investigation of relative orbital dynamics, at least for the level of effort required. There are several contemporary planar air-bearing facilities being used for the evaluation of formation flying algorithms.[14–18]

The most elaborate air-bearing systems combine these two types of motion into simulators that provide up to six completely unconstrained degrees-of-freedom. NASA-Marshall Space Flight Center's Flight Robotics Laboratory, described by the NASA Federal Laboratory Review in 1994 as "a facility that provides a quality, capability, capacity, product, technology, condition, or process recognized by the world aerospace community as among the best in the world" has a 44 ft $\times$ 86 ft precision floor. The Air Bearing Spacecraft Simulator used on the planar floor provides a 400 lb payload six degree-of-freedom motion via a floating spherical air bearing coupled with a cylindrical lift.[19] Lawrence Livermore National Laboratory has an ongoing effort to foster the development of autonomous, agile microsatellites: payloads up to 70 lb are provided full freedom in yaw, $\pm 15°$ in pitch and $\pm 30°$ in roll on their Dynamic Air Bearing test vehicle. The vehicle can then either be floated on a 5 ft $\times$ 25 ft glass top Dynamic Air Table or can be mounted on one of two perpendicular 50 ft Dynamic Air Rails. The linear rail system yields five relative (four individual) degrees-of-freedom for a pair of payloads.[20] These two world-class facilities provide high resolution simulations of on-orbit operations. However, facilities of this caliber are prohibitively high cost for widespread use.

Much of the initial analysis of spacecraft formations has investigated only the relative orbital dynamics among the vehicles. Several techniques have been proposed. A distributed system such as a satellite formation can be maintained through a centralized or decentralized architecture. Such a controller requires only one "capable node" or "chief satellite" to command the other vehicles in the formation. A centralized controller is locally computationally intensive. Moreover, it is high risk, as a failure of the capable node can lead to failure of the entire formation. However, a centralized controller only requires each of the "subordinate nodes" or "deputy satellites" to communicate with the chief. Thus the overall communications requirements are low.[21–25]

A decentralized architecture distributes the computational effort among the nodes and mitigates the risk inherent in a centralized scheme. However, a fully distributed scheme requires communication between every pair of satellites, an effort which may be prohibitively high cost. Several partially decentralized techniques have been proposed in an effort to balance these costs and risks. Proposed options include controlling the formation with more than one capable node, treating the formation as a virtual structure, or running the controller through a perceptive framework.[26–29]

We intend to develop and implement such control schemes on DSACSS and experimentally evaluate their performance. Because the DSACSS testbed is, itself, distributed, we can verify the true distributed performance of the system, including the effect of communication between nodes. We intend to demonstrate several metrics of precision formation flying, particularly finding the balance between maintenance of a desired geometric configuration and the required control frequency and tightness. Possible satellite formation figures of merit include:[30]

1. Relative position: The estimated value of relative position between any pair of nodes.
2. Formation control: The controlled separation between any pair of nodes.
3. Communications bandwidth: The number of bits of data passed between any pair of nodes.
4. Formation geometric dimension: The number of dimensions in free-space spanned by the desired formation.
5. Spacecraft-to-spacecraft relative bearing: The angle composed of a combination of the relative attitudes and the three-dimensional position vectors between any pair of nodes, indicative of the ability to maintain those nodes in some desired relative formation in six degrees-of-freedom.

CAVE Simulation

Virtual reality provides the experience of user-tracked, computer-generated, multi-sensory information. The Electronic Visualization Laboratory at the University of Illinois at Chicago introduced an immersive, multi-person virtual reality system in 1992: a room constructed of large screens onto which graphics are projected and viewed by users wearing stereo glasses, the CAVE Automated Virtual Environment (CAVE). As a viewer wearing a position sensor moves within the CAVE, modified graphics are projected onto the floor and walls: the images move with and surround the viewer; the projection screens become transparent and the three-dimensional virtual image appears to extend to infinity.

The Virginia Tech CAVE is a theater 10 ft $\times$ 10 ft $\times$ 9 ft, made up of three rear-projection screens for the front, right and left walls and a down-projection screen for the floor. Electrohome Marquis 8000 projectors throw full-color workstation fields (1024 $\times$ 768 stereo) at 96 Hz onto the screens, producing virtual images with a combined resolution of approximately 2000 linear pixels. The user's head and hand are tracked with Ascension tethered electro magnetic sensors. Stereographics' LCD stereo shutter glasses are used to separate the alternate fields going to the eyes. A Silicon Graphics Power Onyx computer with three Infinite Reality Engines is used to create the imagery that is projected onto the walls and floor.[31]

Recent work in the Virginia Tech CAVE led to the development of a dynamic virtual model of Whorl-I, shown in Figure 5. This model receives attitude sensor data from the Whorl-I air bearing during a maneuver and displays a virtual model of the motion in real time. The CAVE interface software makes use of a shared memory architecture among computers — the PC/104 on the tabletop updates this memory space and the display computer in the CAVE reads from it in order to update the virtual model's state. Future work with the CAVE includes plans for control of DSACSS via the virtual interface of the CAVE.[32]

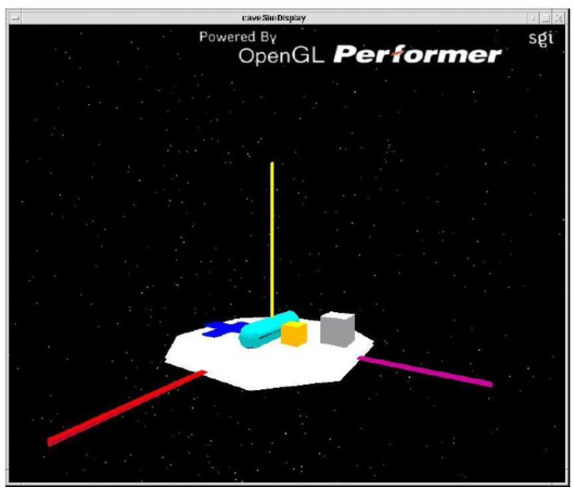

Figure 5: Whorl-I CAVE Simulation

Teaming with the NASA-Goddard Space Flight Center Formation Flying Testbed

As the DSACSS air bearings cannot move, the orbital dynamics is less interesting than the attitude dynamics. Thus, coupling the complete nonlinear attitude equations of motion with a two-body model for orbit propagation is not unreasonable. A possible extension of this technique would be to propagate the formation's orbit using a commercial software simulator such as FreeFlyer or Satellite Tool Kit. Either of these programs would provide orbital state data along with environmental parameters. Open-SESSAME can also provide this level of simulation.

A more interesting idea is to maintain the hardware-in-the-loop experimental nature of the simulation by linking with the orbit simulation capabilities of the Formation Flying Testbed (FFTB) at NASA-Goddard Space Flight Center. Unification of these facilities can provide consistent experimental resolution for complete validation of formation flying schemes.

Rather than providing a low-force environment for linear travel, the FFTB simulates three degree-of-freedom translational motion through a high-fidelity Global Positioning System (GPS) and radio frequency (RF) communications simulator. Virginia Tech also has a pair of GPS simulators; initial formation flying experimentation is being developed with this in-house system. Briefly, the FFTB is a modular simulation facility for the development and end-to-end testing of guidance, navigation, and control hardware and software, with a focus on formation flying.[12] The FFTB simulates each satellite distinctly while interacting with the formation as a unit. Actual payload flight hardware and software can be installed in the FFTB, providing a uniquely customizable test facility.[33]

Preliminary experimentation using the FFTB has validated decentralized concepts within the context of formation flying and relative orbit control.[21,22,24,26] However, all of this validation effort is missing experimental representation of spacecraft attitude. The DSACSS can fill this void and help to further demonstrate the efficiency of formation control techniques. Initial work in the Virginia Tech CAVE (discussed previously) has suggested a novel technique for further unifying DSACSS and the FFTB. Simulation data from both facilities can be written to a shared memory space and recaptured in the CAVE. As such, the virtual representation in the CAVE can display the full experimental state of the formation: both the orbital and attitude dynamics can be observed and, if appropriate, manipulated through this interface.

CONCLUSIONS

New concepts in formation flying and spacecraft attitude dynamics and control are continually being developed. It is impractical to even consider the idea of implementing each of these ideas on an orbiting formation. However, an entirely software-based simulation cannot hope to have sufficient resolution as to capture system performance. A laboratory-based, hardware-in-the-loop facility for the testing and validation of such concepts is essential to the improvement of the field.

The DSACSS provides a convenient testbed for both individual component development and testing of distributed architectures. We have outlined only a few of the capabilities of the system in this paper. Teaming with the FFTB provides an even closer replication of real-world applications within the safe environment of a laboratory. The two systems provide very different perspectives of the same operation; working together, a more complete picture of formation performance can be obtained. We hope that demonstration of new hardware configurations and innovative control techniques on DSACSS will lead to the implementation of such systems on operational spacecraft in the not-too-distant future.

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