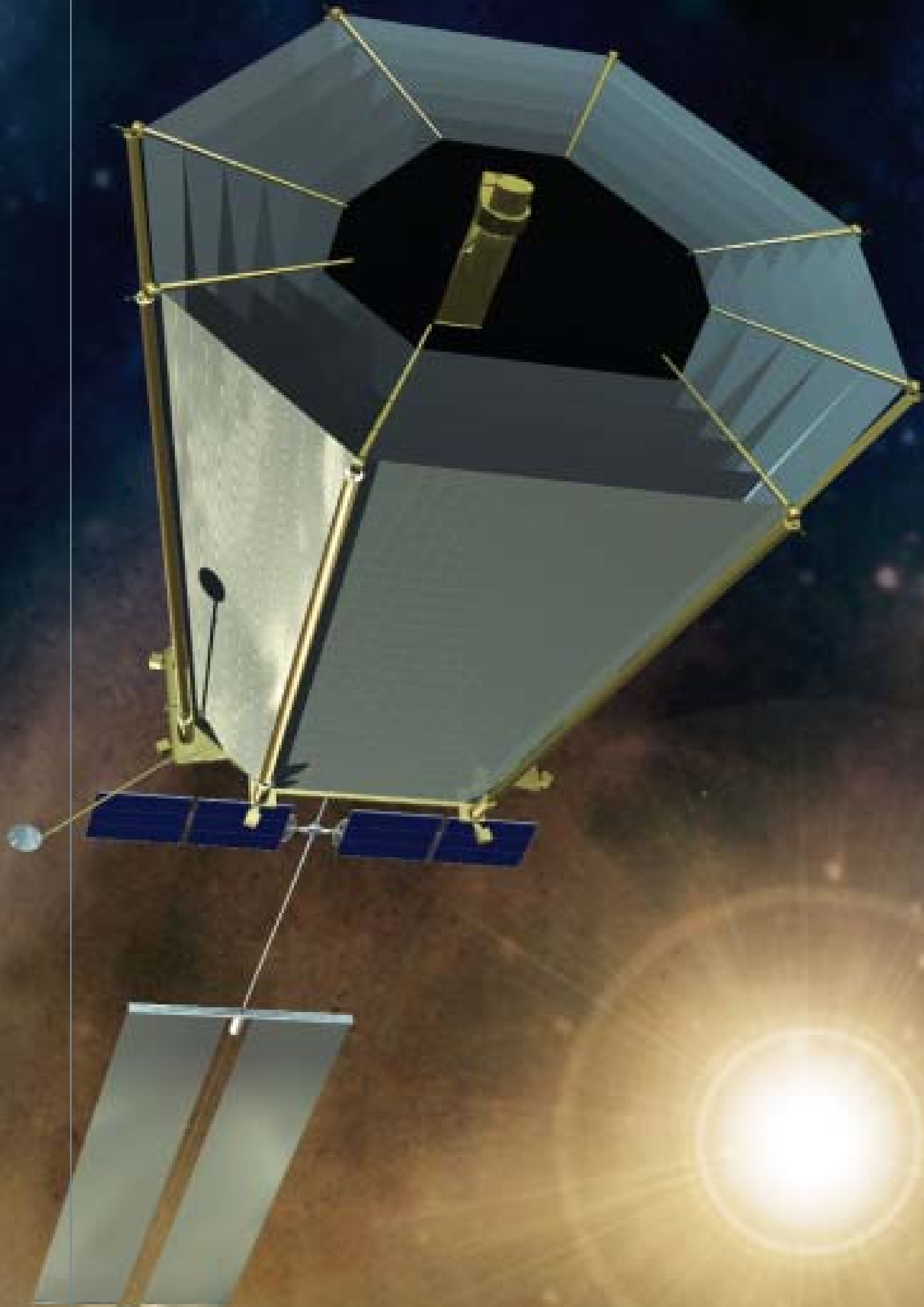
by James Oberg

Explore Satellite Formation Flying

Space Spheres

Star Wars Inspiration Triggers MIT ISS Research



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You know you're involved in real robotics laboratory work when two totally separate gadgets suddenly interfere with each other in astonishingly unexpected ways. And when that happens, you also know you're the luckiest geek on campus when that interference causes passive freeze-up, not maniacal *Terminator*-style runaway of either or both gadgets.

And you know when *real* robotics laboratory work comes to the International Space Station when the incident occurs there, 220 miles above the Earth moving at 17,850 miles per hour, probably the most unusual setting for such a laboratory – but potentially the most productive. A side benefit is that the operators confronted by the mishap were able to curse in both English and Russian.

MIT SPACE SYSTEMS LAB

The incident occurred last year during a test run of the free-flying robot fleet deployed as part of the SPHERE investigation. Developed by faculty and students at the Space Systems Laboratory of the Massachusetts Institute of Technology and funded mainly by the Department of Defense (with NASA support), the project – the "Synchronized Position Hold Engage Reorient Experimental Satellites" – was from the start designed not simply to test a fully developed autonomous maneuvering autopilot. Instead, its purpose is to use repeated runs to allow the robotics team to experiment with different control algorithms, assess results, modify the commands and try again—and again—as needed.

If the experiment, dubbed SPHERES, sounds like science fiction, perhaps that's because it was inspired in part by it. In 1999, while studying techniques for automated "formation flying" for satellites, Dr. David W. Miller, the director of the laboratory, assigned his students the task of designing and building prototypes. "I rented the first *Star Wars* movie and showed the class the scene where Luke is practicing the use of the Force with a floating droid," he told a reporter. "I said: 'I want three of those. How do we start doing this?' "

STUDENT-DESIGNED

The result was a nine-pound bowling-ball-size sphere, together with its wall-mounted tracking beacons. Students designed the structure, the onboard computer and its software, the navigation sensors (using acoustic signals from the beacons and each other), the radio links with a base station and other free-flying units, the power system (a battery pack with a two-hour lifetime) and the techniques for uploading new software.

The dozen small thrusters used spurts of pressurized gas to turn and shift position. When considering the design, one student fell back on a hobby of his and proposed using carbon dioxide cartridges from a paintball gun. The idea caught on, in large part because the devices were relatively low pressure (860 psi) and had already undergone significant safety reviews to qualify as air freight. A shorter cartridge—six inches long instead of nine inches—was custom manufactured by the vendor.

This "beacon" unit communicates with the SPHERES using ultrasound signals that plot position and speed.

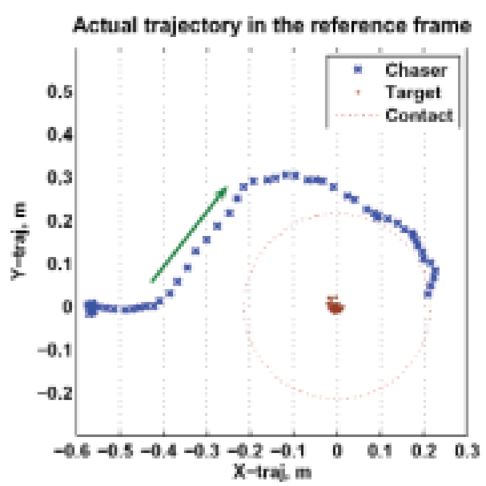
Carbon dioxide, however, is a waste gas from human metabolism and in large concentrations can become toxic. It therefore needs to be cleansed from the station atmosphere with special equipment. But the flyers' small size and engine efficiency cause them to emit only about a quarter as much CO2 as a living, breathing human—hardly enough on an occasional basis to overload the space station's life support system.

Prototypes were tested on Earth and in NASA's zero-g airplane. Three operational units were fabricated, verified, and then sent up into space one at a time on board Russian and American transport ships in 2006. As each was built it had been given a different external color—orange, red, and blue—to aid in interpreting the video history of their maneuvers. But for some reason involving different schedules for Russian and American space cargo, they were launched in the sequence of red (serial #2), then blue (#3), and finally orange (#1).

As each additional drone and wall-mounted navigation beacon arrived, a sequence of more complex exercises was carried out. More tests will occur this year.

Mike Lopez-Alegria, commander of increment 14, was the prime operator for SPHERES test session five, and participated in test sessions seven and eight (eight sessions had been run as we went to press).

"We're doing this because these missions have a lot of new, untried technology," Miller continued. "Testing inside the space station will allow us to mature these technologies in a less risky



micro-gravity environment," meaning inside the warm, air-filled station, rather than outside in the hazardous conditions of space.

This approach, added lead project scientist (and program manager) Dr. Alvar Saenz-Otero, "allows scientists to push the algorithms to their limits in various realistic mission scenarios, learning about both their theoretical and physical limitations."

Launching an all-or-nothing fully designed space robot mission can fall far short of hopes if unexpected developments cannot be worked around (as with NASA's autonomous robot two years ago that was supposed to circle its target but instead rammed directly into it). In a technical paper presented at a recent Guidance, Navigation, and Control conference held by the American Astronautical Society, Saenz-Otero continued: "A need exists to provide scientists with a development facility which closely simulates the operational environment without having the risks associated with the planned high-cost missions."

ROBOTS TO CREATE VIRTUAL APERTURES

Eventually, autonomous space vehicles with much more mature versions of the algorithms now being tested will fly on their own in open space. They will maintain their precise relative positions via radio links. Analogous to the Multi-Mirror Telescopes now using "aperture synthesis" to reinvigorate earth-based astronomy, future huge multiple-mirror space-based telescopes can't rely on a physical frame to guarantee alignment. Instead, each individually controlled element will be "tweaked" frequently to keep the holistic instrument "in tune" for optical interferometry that will deliver orders of magnitude improvement in the resolution – the smallest visible angle – that can be detected.

The European Space Agency is building exactly such a telescope, called "Darwin," which will use several free-flying spacecraft with infrared spectrometers to search for Earth-like planets around other stars and then analyze their atmospheres for the chemical signature of life. Because of the great distance between the components (several hundred meters), the central unit can employ one interferometric technique to null out the light of the central star, and then a second technique to allow the light from the planet to be combined to a signal strong enough to be analyzed. The "virtual aperture" should also allow detailed images 10 to 100 times sharper than expected from NASA's next-generation Webb Space Telescope.

NASA is designing a similar multi-element space instrument called the "TPF," or "Terrestrial Planet Finder." Like the Darwin it would be deployed far beyond the moon where very smooth gravity fields permit super-high-precision formation flying.

ROBOTIC DOCKING

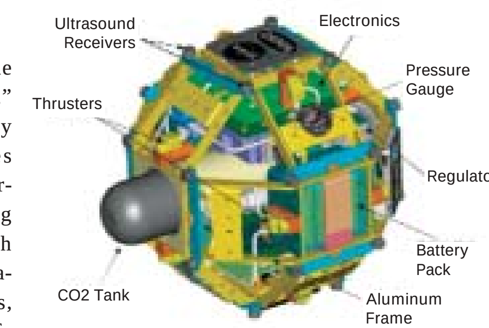
By the end of 2006, five sessions with the flyers (the students call them "satellites," not "droids") had been completed. They achieved a wide range of successes including the demonstration of both formation flight and autonomous docking algorithms. The testing climaxed with two of the satellites performing cooperative docking to wall-mounted targets, then demonstrating capabilities for safe dockings (detecting when to break off a failed approach and saving itself), and then performing the first-ever robotic docking to a tumbling target in space.

The first two test sessions (May 18 and May 20, 2006) operated with only one satellite and a limited measurement system (only one beacon). The first session was geared toward hardware checkout and initial demonstrations of basic maneuvers, but the second test session began the iterative research process for the development of formation flight, docking, and fault detection algorithms that continued throughout. The third test session (August 12) was the first to operate with two satellites, with initial demonstrations of formation flight. The fourth test session (August 19) utilized the complete measurement system to demonstrate incrementally complex docking algorithms. The fifth test session (November 11) utilized the earlier results of docking maneuvers and fault detection to demonstrate "safe docking" maneuvers and the first docking to a rotating target in microgravity.

LEARNING FROM FAILURES

Saenz-Otero reported: "Of course, there were several failures of the hardware, procedures, and algorithm implementations along the way. But, due to the risk-tolerant environment developed for SPHERES, these failures provided significant information to improve the facilities and algorithms without any being mission critical."

On the first run, scaling factors used by the inertial measurement unit to determine orientation somehow got corrupted – and were fixed for the second run. One docking approach was too rapid, and on other



approach, the drone swerved unexpectedly, then recovered. On one run, a pressure spike in the thruster gas supply caused a software inhibit to some of the jets, so a few maneuvers couldn't be accomplished.

During some of the later runs, a failing, flickering fluorescent light bulb in the station—and later, the flash of the camera being operated by an astronaut to record the event—seem to have confused one satellite's navigation sensors. It falsely triggered a reset in the time clock that the satellite needed to measure duration of the acoustic pulses that determine range to other objects, so it stopped moving and held a constant position, as it was supposed to do when confused. It then recovered from its "stage fright" once the astronaut stopped taking pictures, and successfully completed the session.

Saenz-Otero was philosophical. "The presence of multiple unforeseen sources of noise in the system stressed the need to implement FDIR [Fault Detection, Identification, and Recovery] algorithms at all levels," he reported. "Even after several years of testing the system in ground-based facilities, the deployment aboard the space station presented new and unexpected failure modes which could have been caught by FDIR algorithms, but which otherwise prevented full functionality."

He is taking the "long view" of the robotics control software development process, and he has earned the right. Due to delays in the shuttle program, none of the original students on the design team remain at MIT, except Saenz-Otero, who now is on the staff as a postdoctoral associate professor. A new generation of graduate students has stepped into the process and is already hard at work developing new control algorithms for testing and, along the way, as M.S. and Ph.D. theses that they will eventually defend. By the time a future spacecraft project needs such capabilities implemented, these students and others at similar laboratories around the world will be experienced and ready for new challenges. And the technology enabling robotic satellites to fly in complex, changing formations will be mature. For a video illustration of such flights, visit http://dst.jpl.nasa.gov/.