# Eye in the sky

## Canada's vision system navigates the final frontier

Technology made in Kanata, Ontario, "sees" and "reacts" to changing conditions in space to help astronauts position payloads with swift accuracy. The system helps take the risk out of one of the most dangerous jobs on space missions.

**by Steven Miller, MASc, P.Eng.**

IMAGINE that you have been selected as a Canadian astronaut to help assemble the International Space Station (ISS). After months of training and preparation for your flight, the day finally arrives where you find yourself orbiting the Earth in the shuttle. Your mission objective is to operate the Canadarm to align two, billion-dollar station payloads before they are assembled.

The operation isn't as simple as it sounds. First, you must observe it from the flight deck of the shuttle by looking out of the small windows at the rear left. The assembly is to occur 9 metres away from, and high above, the shuttle. You have to crane your neck to get an oblique view of the mating interface high above you. You may use the cameras located in the shuttle payload bay, but they, too, look steeply upward to the assembly, offering no direct view of the assembly planes. Finally, you have been instructed that failure to align the payloads correctly before mating (i.e. firing the shuttle thrusters) would not just be a failure of the mission, but would also damage the vehicle and possibly even lead to loss of life.

### An eye for accuracy

How do you take the risk out of a payload operation? The National Aeronautics and Space Administration (NASA) decided that the solution was a precision guidance system enabling astronauts to accurately position and orient one payload relative to another–namely the space vision system (SVS). The SVS has been used on the Space Shuttle Orbiter and is currently undergoing integration testing with the ISS. It was also used to complete the first assembly stage of the ISS, involving the mating of the Russian Zarya module, with the American Unity module.

The SVS comprises several key elements, including video cameras with pan/tilt control, lighting sources, video distribution, as well as a core processing unit called the Space Vision Unit (SVU). The SVU is designed, manufactured and space qualified by Neptec Design Group Ltd. of Kanata, under contract with NASA. Collectively, the system is referred to as the Space Vision System (SVS). Neptec also designed the hardware, software and mechanical enclosures for the system.

**Neptec's space vision system was used during mating of the Russian Zarya module (top payload) and the American Unity module (bottom payload). Zarya will provide propulsion control, power and fuel storage throughout the early stages of assembly, while Unity will serve as a juncture point for six critical station components, including the U.S. Laboratory and U.S. Habitation Module.**

The SVS is integrated into the video systems used on the shuttle orbiter and the future ISS. It digitizes video inputs and processes digital data. The processed video data is used as inputs to the software to calculate position and orientation measurements of the payloads with respect to any known coordinate.

### Development

The SVS had its beginnings with photogrammetric research conducted at the National Research Council (NRC) in the 1980s. Photogrammetry is the science of extracting three-dimensional information from an original two-dimensional image. Neptec was founded in 1991 to continue work on the SVS. In collaboration with the Canadian Space Agency (CSA), Neptec used NRC's patented photogrammetric algorithms to continue the SVS research program. The company developed a precursor to the SVS named the Advanced Space Vision System (ASVS), which was flown on three shuttle missions. These flights proved that the system was capable of accurate vision guidance in a space environment, and provided invaluable experience on how to plan missions to use the system.

To date, there have been five shuttle mission flights of the SVS. The most notable was shuttle mission STS-88 in December 1998, for which the SVS was used in the first assembly stage of the ISS (see photo on p. 24).

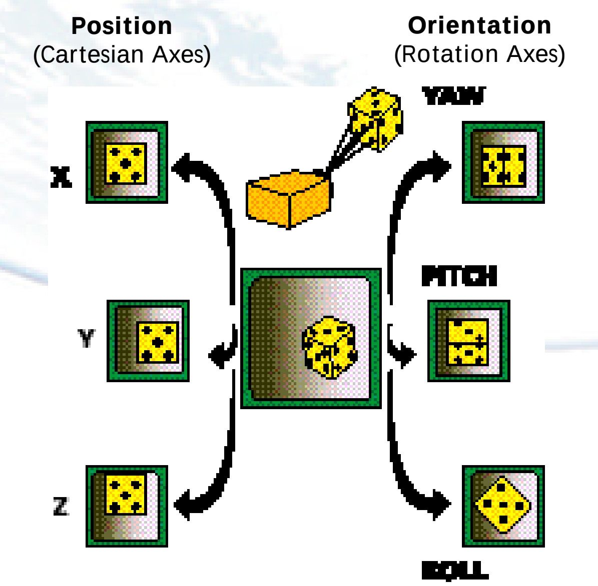
During the assembly, the shuttle attitude control was disabled. The entire assembly rolled out toward the sun, resulting in some extreme lighting conditions. The SVS temporarily lost track of some of the targets during these operational conditions, until most of the targets had uniform lighting.

Neptec is currently researching this problem and prototyping an algorithm to deal with harsh shadows crossing the targets.

### Following the dots

In many ways, using the SVS is as simple as "following the dots" on the payload–at least as far as the human operator is concerned. The system operates on the principle of "cooperative targets." Prior to flight, an array of circular targets is rigidly attached to each of the payloads that are to be mated. NASA surveys the targets, while CSA requests the placement targets on the payloads. Another NASA contractor actually places them on the payloads.

**Figure 1. Photogrammetric principles**




To prepare for a mission, the position of each target in the array must be accurately surveyed with respect to a berthing coordinate system. The targets and their backgrounds have a high contrast, either black on white or white on black. This enables the targets to be reliably detected in the video image. The targets tracked by the SVS on the shuttle have typically been 10 to 15 pixels in diameter.

The SVS measures the geometric centres of the targets or "centroids." The measurements are conducted in real time, 30 times a second, to an accuracy of less than 1/10 of a pixel. Two cameras can be processed simultaneously by the system, producing centroid measurements for up to 20 targets. A correction is then applied to the centroids to account for optical errors within the camera.

Intuitively, as the payload is moved and rotated, the pattern of target centroids on the camera images will change. Six degrees of freedom (three for position and three for orientation) are used to align payloads. From Figure 1 (which uses dice to represent a payload), it can be seen that each degree of freedom of the payload's position/orientation can be interpreted by specific changes in the centroid pattern. By using the centroids and the surveyed target positions as inputs, the SVS software determines from the two-dimensional image where the payload must be in three-dimensional space. This information is used to generate a graphical or "steering display," which the astronaut uses as a cue to guide the payload to its desired berthing point.

The SVS is capable of measuring the position and orientation of two payloads simultaneously. The target arrays on the payloads can be viewed by one or both cameras to provide measurements for the SVS. The two payloads' position/orientation measurements can be combined to provide a relative measurement between the payloads.

### Preventing system failures

Operating a vision system in space requires a fault tolerant design to help prevent system failures in the hostile environment of space. Neptec has completed an extensive failure mode error analysis (FMEA) on the system, to identify its failure modes. Neptec's FMEA was reviewed by the safety committee at NASA—a very rigorous process in the human space flight program. The results of the analysis were used to identify and compensate for various failure modes in the hardware and software, wherever possible.

For example, the random access memory (RAM) in all hardware in the SVS is protected by error detection and correction (EDAC) circuitry, which allows for automatic correction of single bit errors and detection of multiple bit errors in the RAM. Such errors are often caused by high-energy particles passing through the shuttle. Previous shuttle experiments have shown that RAM errors can occur up to nine times per hour, often causing the computing system to lock up. The SVS was designed to be able to react to these errors. Single bit errors are written to an error log whenever they occur, and the system shuts down gracefully upon detection of any multiple bit error. EDAC circuitry has been built into all processing boards in the SVS, to protect RAM.

### Seeing the light

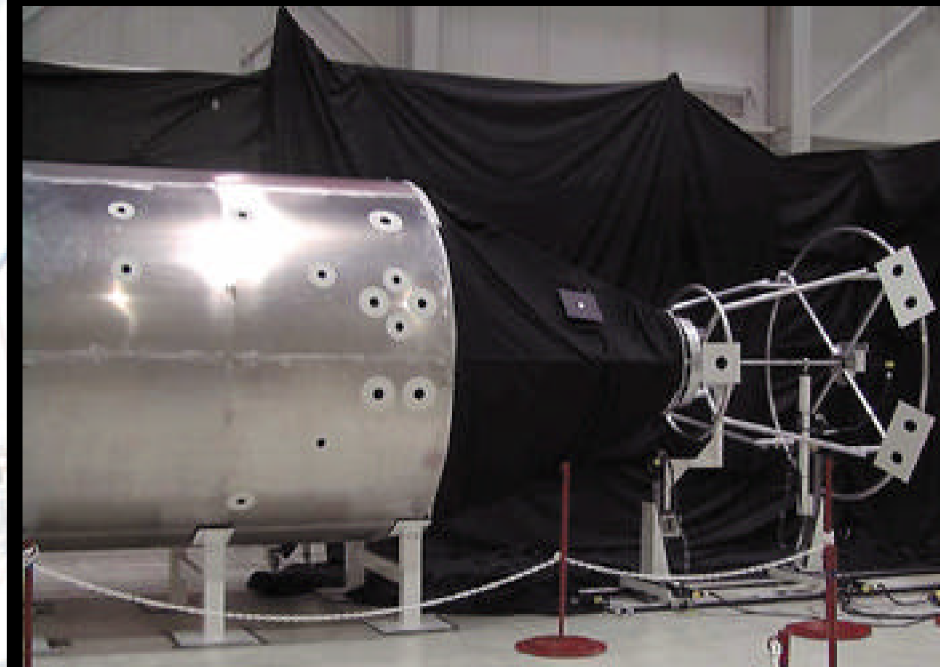
Often there is little control over the lighting outside of the shuttle. It can vary from blinding sunlight, to the darkness of night—all in the span of 94 minutes for one orbit of the shuttle around the earth. The video processing system must take these dynamic lighting conditions into account. SVS software will adaptively adjust the centroid measurement process for each target, to provide the best measurements possible under current lighting conditions. If a centroid measurement is flawed by poor lighting or an obstructed view, the software will discard the measurement and attempt to reacquire the target on subsequent video images. This mode of operation is called "target degradation with recovery."

To correct for poor or excessive lighting conditions, SVS software uses an image enhancement feature. When enabled, image enhancement will send appropriate commands to the shuttle cameras to control their irises, shutters, gain (brightness) and/or gamma (contrast) corrections. The image enhancement software monitors the contrast between the target and background for all centroid measurements. If the contrast is insufficient or too great, a command is sent to the camera until a desirable contrast is obtained.

### All systems go...

To fly the SVS on space shuttle missions, Neptec must ensure that all units produced are space qualified for flight. This rigorous process involves testing and qualifying the entire integrated system of hardware and software. The hardware in the system is a combination of both Neptec manufactured products (mechanical enclosures and multi-processor printed circuit boards) and commercial off-the-shelf products, such as power supplies and hard drives.





**Getting ready for space flight: One of several half-scale models of International Space Station payloads used to verify space operations at Neptec's Vision Systems Certification Lab. Mounted on platforms, the models stimulate the movement of payloads in space, making preflight testing as realistic as possible.**

The qualification tests performed on SVS hardware involve simulating thermal conditions (-11 C to 45 C), air pressure (to simulate cabin pressure loss), humidity, EMI/EMC (electromagnetic interference/electromagnetic compatibility) vibration and shock. Functional testing of the system (hardware and software combined) is performed between tests to verify its operability. In addition, each release of SVS software must be verified with a formal qualification test, which is designed to exercise and test each of the software's specified requirements. Requirements that cannot be proven through testing are verified through analysis.

For the SVS used on the orbiter shuttle, a final integrated test is conducted at the Shuttle Avionics Integration Laboratory, located at the Johnson Space Center in Houston, Texas. The laboratory is a full-scale replica of the shuttle avionics system. Final software verification and communication testing is completed on areas that cannot be completely verified, such as camera control and telemetry.

Integration of the SVS into the avionics for the ISS is currently being completed by Neptec with CSA observers, as part of requirements for the space station program. The SVS has already been integrated with the United States Laboratory module for the space station and the Space Station Remote Manipulator System. The testing took place at Kennedy Space Center at Cape Canaveral Florida. Several tests were performed including:

**The Canadarm and space vision system will play important roles in construction of the space station–the most ambitious project in space history.**

- ◆ tests of SVS photogrammetry, using space station video;
- ◆ camera control tests;
- ◆ data download tests, involving a real-time update of the artificial vision unit database; and
- ◆ tests of the space station fault summary and telemetry handling systems.

Quality assurance personnel, who act as representatives to the customer, monitor all qualification/integration testing. All tests have a clearly defined plan and procedures that identify all pass/fail criteria. All failures identified during qualification testing are recorded, monitored and resolved through a configuration control software package. Likewise, all documentation for the program is controlled with the same software package.

### Putting it all together

Before shuttle missions, Neptec's Operations and Test Group acts as a liaison with mission planning staff at NASA. Much planning takes place before payloads are lifted into orbit. Cameras must be calibrated. Target arrays must be chosen from the targets available on the payload, and then surveyed and analyzed for their effective "strength" on the photogrammetric solution.

The Operations and Test Group often uses computer simulations of a mission to identify which cameras and fields of view to use during the mission, and to test different operational scenarios. However, even the most realistic computer simulation can never completely account for all subtleties, such as lighting gradients, optical distortions and varying mechanical tolerances.

Neptec has built its Vision System Certification Lab to provide a controlled lab environment to verify different space operations on the ground. Several half-scale models of the ISS payloads have been constructed and mounted on mobile platforms. The platforms allow the ISS to move along three Cartesian axes (X,Y, Z) and rotate about three rotation axes (yaw, pitch and roll). An operator can control the ISS' movement, while attempting to mate two model payloads using the SVS (see photo, above).

### A future in space

Neptec has developed a flight qualified vision system for use in the shuttle orbiter and the International Space Station, which has been successfully used by astronauts to position and align payloads in space. Along with the Canadarm, it will play an important role in construction of the space station–the most ambitious project in space history. Expected to be completed by the year 2004, it will be as large as two football fields and require 45 space flights and over 140 space walks to assemble.

With a continued improvement and testing program guided by ISO 9000 procedures, Neptec expects to adapt the SVS to meet future requirements, as the space program encounters new and challenging problems. ◆

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