RAVEN: AN ON-ORBIT RELATIVE NAVIGATION DEMONSTRATION USING INTERNATIONAL SPACE STATION VISITING VEHICLES

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Since the last Hubble Servicing Mission five years ago, the Satellite Servicing Capabilities Office (SSCO) at the NASA Goddard Space Flight Center (GSFC) has been focusing on maturing the technologies necessary to robotically service orbiting legacy assets–spacecraft not necessarily designed for in-flight service. Raven, SSCO's next orbital experiment to the International Space Station (ISS), is a real-time autonomous relative navigation system that will mature the estimation algorithms required for rendezvous and proximity operations for a satellite-servicing mission. Raven will fly as a hosted payload as part of the Space Test Program's STP-H5 mission, which will be mounted on an external ExPRESS Logistics Carrier (ELC) and will image the many visiting vehicles arriving and departing from the ISS as targets for observation. Raven will host multiple sensors: a visible camera with a variable field of view lens, a long-wave infrared camera, and a short-wave flash lidar. This sensor suite can be pointed via a two-axis gimbal to provide a wide field of regard to track the visiting vehicles as they make their approach. Various real-time vision processing algorithms will produce range, bearing, and six degree of freedom pose measurements that will be processed in a relative navigation filter to produce an optimal relative state estimate. In this overview paper, we will cover top-level requirements, experimental concept of operations, system design, and the status of Raven integration and test activities.

INTRODUCTION

The next generation of missions undertaken by National Aeronautics and Space Administration (NASA) will require the ability to autonomously rendezvous and mate space vehicles in a variety of Earth orbits and interplanetary locations. These future missions will be focused on exploring beyond Earth orbit with humans, building large-scale science observatories, returning samples from ancient asteroid or comets, and rescuing aging and ailing satellites. As such, NASA continues to invest in both commercial- and government-owned Autonomous Rendezvous and Capture (AR&C) technologies that will enable rendezvous and capture across a wide spectrum of applications: from capturing man-made objects to landing on primitive bodies; from navigating to cooperative targets to tracking natural features; from operating under ground control supervision to reacting autonomously to the dynamically changing environment.

Raven is NASA's newest flight experiment to develop and validate these new AR&C technologies. Specifically, Raven will demonstrate the necessary components—next-generation sensors; vision processing algorithms; and high-speed, space-rated avionics—of an autonomous navigation system. Over its two-year mission on the ISS, Raven will estimate in realtime the relative navigation state of the various visiting vehicles (VVs) that come and go from the station each year: the Progress and Suyoz vehicles from Russia, the H-II Transfer Vehicle (HTV) from Japan, and the Cygnus and Dragon spacecraft from the United States. Over the course of Raven's nominal on-orbit lifespan, we expect to monitor approximately 50 individual rendezvous or departure trajectories.

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Raven is a subsystem of the ISS SpaceCube Experiment–Mini (ISEM) experiment which is being developed by the GSFC. ISEM and Raven will fly aboard the Department of Defense (DoD) Space Test Program-Houston 5 (STP-H5), an ISS hosted payload, along with many other experiments from various agencies, universities, and NASA centers. The STP-H5 payload will be delivered to ISS from Kennedy Space Center (KSC) in a Dragon capsule during the launch of the SpaceX Commercial Resupply Service 10 (SpX-10). STP-H5 will be placed on the Nadir-Inboard-Wake node of ELC-1 for its two year mission. Figure 1 shows the Raven experiment and the full STP-H5 payload. Figure 2 shows the location of ELC-1 on ISS.
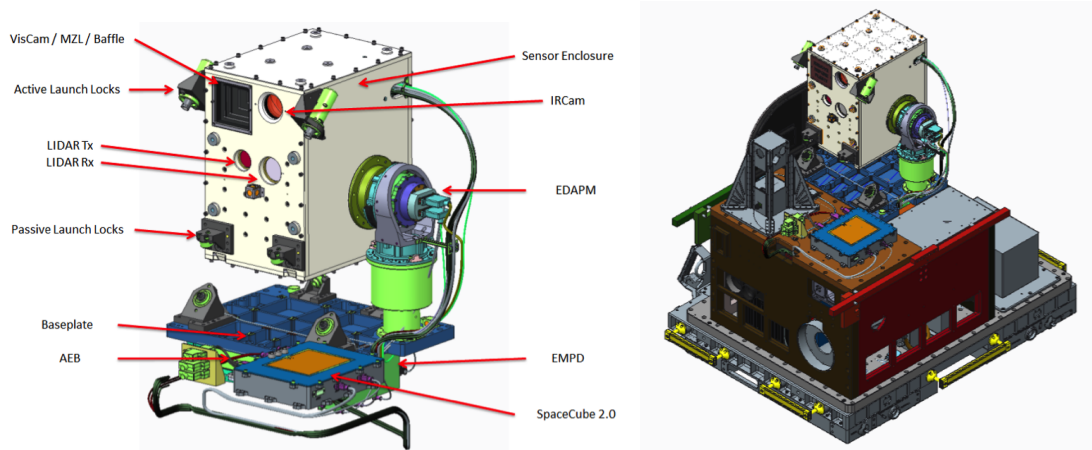
Figure 1. Computer-Aided Design (CAD) models of Raven (left) and Space Test Program-Houston 5 (STP-H5) (right). The Raven assembly is comprised of two main parts: the Raven core and the SpaceCube 2.0 electronics, which are mounted separately to STP-H5 payload.
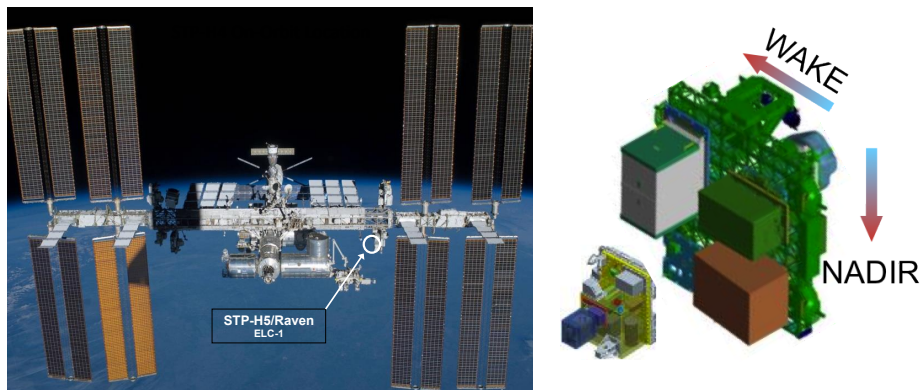
Figure 2. ELC-1 location on ISS (left) and Space Test Program-Houston 5 (STP-H5) and Raven location and orientation on ELC-1 (right)

Raven Extensibility

NASA's recent focus and investment in the AR&C arena has been in developing a common sensor specification that can support the variety of planned AR&C-related missions. In 2014, NASA completed an assessment of the various concept of operations for multiple upcoming missions including the crewed and robotic segments of the Asteroid Redirect Mission (ARM), as well as deep-space sample return; satellite servicing; and entry, descent, and landing missions. The results of this assessment were that a suite of sensors consisting of varying numbers of visible cameras, infrared cameras, and 3D imaging lidars—each built to a common specification—could meet these missions's challenging requirements, without the expense of each

mission developing unique hardware. Such an *à la carte* capability will allow the Agency to realize reduced non-recurring engineering costs on a per-sensor basis, while allowing for a multitude of different mission scenarios through a multitude of different sensor combinations. NASA acted on these findings through the 2014 Asteroid Redirect Mission Broad Agency Announcement (BAA),[1] which is funding industry to build the aforementioned sensor components to the common specification goals laid out in Appendix B of the BAA.

In addition to using it to mature critical AR&C technologies for a satellite servicing mission concept, NASA is also planing to utilize the flexibility of Raven to verify the AR&C Common Sensor Specification paradigm. Raven uses the same sensor methodology as specified in the Common Specification as well as high-performing space-rated reprogrammable processors that can host the myriad algorithms that are needed for these demanding future missions. By using Raven's reprogrammable platform, visiting researchers from the United States Government, universities, research development centers, and commercial companies can host their own algorithms on Raven and demonstrate the flexibility of the Common Sensor Specification.

The remainder of the paper will cover the Raven experiment in more detail including discussions on key mission objectives, the concept of operations, sensing and avionics hardware, and the baseline flight software to support satellite servicing.

MISSION OBJECTIVES

Raven's technology demonstration objectives are three-fold:

1. *Provide an orbital testbed for satellite-servicing related relative navigation algorithms and software.* The role of the SSCO is to develop and mature through on-orbit and ground demonstrations the technologies required to robotically service legacy satellites in orbit. By flying the baseline servicing algorithm suite, Raven will provide on-orbit experience to the SSCO Guidance, Navigation, and Control (GN&C) team. Raven continues the technology maturation effort that was started with the Dextre Pointing Package (DPP) effort[2] and the Argon ground demonstrations.[3]

2. *Demonstrate multiple rendezvous paradigms can be accomplished with a similar hardware suite.* NASA is interested in using similar hardware to perform cooperative docking tasks as well as landing on a non-uniform asteroid. By utilizing sensors within the NASA common sensor suite and flying multiple algorithms, Raven will demonstrate relative navigation to a defined cooperative target and natural feature tracking of a non-cooperative vehicle.

3. *Demonstrate an independent VV monitoring capability.* For each rendezvous by a VV to ISS, the crew and ground operators get different amounts of information concerning to accuracy of the VV in following its nominal flight path. All of this information is provided to the crew and ground operators from the VV: there is no relative navigation solution that is independently sensed and computed by NASA. Additionally, if the necessary sensors for VV rendezvous are located on the station, the Agency can reduce cost by reusing hardware over multiple missions instead of having duplicate hardware on each vehicle which may be disposed of after the resupply mission.

From these high-level objectives, NASA developed the following minimum success criteria for Raven:

1. *Collect sensor data (raw visible, infrared, and lidar images) at distances within 100 meters at rates up to 1 Hz.* These images, along with multiple ISS GN&C telemetry points, will allow engineers to compute a VV best-estimated relative trajectory on the ground. This trajectory will be the truth against which the realtime Raven navigation solution will be compared against.

2. *Collect rendezvous imagery for four different vehicles.* By collecting imagery of multiple vehicles, ground operators can understand the sensitivity of the flight software to variations in the size and shape of servicing clients. One specific algorithm of interest builds a simplified math models of the client vehicle to be serviced; such a capability will allow a servicer to update an *a priori* model of the client vehicle with on-orbit data showing its current configuration.

3. *Collect rendezvous imagery for at least five different approaches per vehicle.* Engineers can use the VV trajectory dispersions, and the corresponding varying Raven navigation solution, to develop statistics

on the how well Raven will perform against similarly sized and shaped servicing clients. Additionally, even thought Raven will operate during both approaches and departures, approaches are far more relevant to satellite servicing. The small corrective burns performed by the VV more accurately represent our servicing clients, as opposed to a departing VV freely drifting away from station.

4. *Demonstrate realtime vision processing solutions within 85 meters for three different vehicles.* The vision processing algorithms are the work horses of the relative navigation system being tested on Raven; they also are the most critical part of a non-cooperative navigation system that uses a natural-feature approach to determine relative position and attitude. By accomplishing this criteria, SSCO can validate that the hardware and software components in Raven are flexible enough to navigate to multiple vehicles without new hardware or software, something that has not been demonstrated before.

5. *Demonstrate gimbal tracking of two different vehicles using navigation filter feedback.* Unlike the others, demonstrating gimbal tracking will require a fully operational system including sensors, vision processing software, navigation filter, and closed-loop control logic for the gimbal. Demonstrating an end-to-end closed-loop, multi-sensor AR&C system is a significant improvement in the state-of-the-art. Current systems can do some of these items, but not all.

CONCEPT OF OPERATIONS
Launch, Installation, and Checkout

After delivery to and check-out at Kennedy Space Center (KSC), Raven will be delivered to the ISS on SpX-10, along with the rest of STP-H5. SpaceX will install STP-H5 into the unpressurized trunk of the its Dragon spacecraft, which will be sent to orbit via the SpaceX Falcon 9 launch vehicle. After the Dragon spacecraft autonomously rendezvouses with the ISS and the Space Station Remote Manipulator System (SSRMS) berths the vehicle to a port, the two-armed Special Purpose Dexterous Manipulator (SPDM) will remove STP-H5 from the Dragon trunk. Figure 3 shows both STP-H5 in the Dragon trunk and the robotic infrastructure present on ISS. STP-H5 will be attached to ELC-1 at the Flight Releasable Attachment Mechanism (FRAM)-8 site, after which the ELC will be providing its full complement of services[4] to the STP-H5.
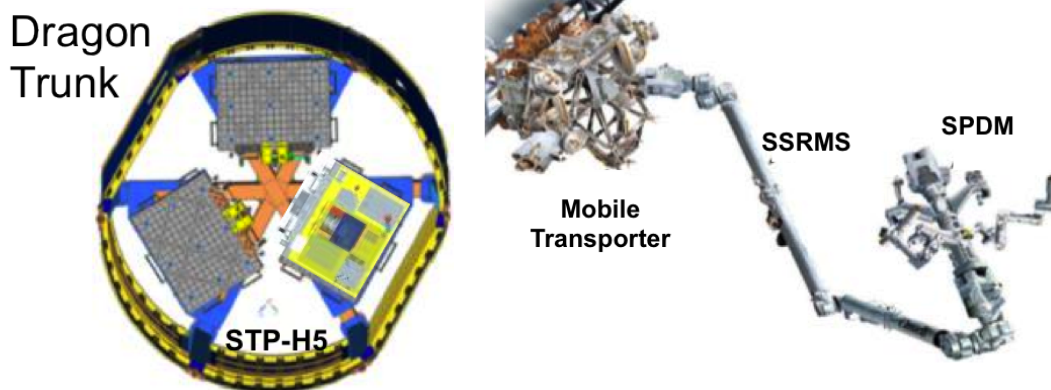
Figure 3.   Raven launch and installation activities: Space Test Program-Houston 5 (STP-H5) shown installed in the Dragon trunk (left) and Robotic infrastructure of the International Space Station (ISS).

Approximately 1 week after STP-H5 installation on the ELC, during which the STP-H5 operations team will check out the payload's command and data handling system, Raven operators will perform a complete check-out of the flight hardware. The avionics will be checked out to verify that all command, telemetry, and data paths are working. Next, ground operators will send the command to release the launch locks, which will allow the gimbal to move the sensors to where they can see the Earth, ISS structure, already docked or berthed visiting vehicles, and a cooperative target placed on STP-H5. Operators will uses these scenes to perform a

functional checkout of the sensors, measure the inter-sensor alignment, and calibrate feedback potentiometers in the gimbal, all in preparation for Raven science operations.

Science Operations

Having an AR&C demonstration on the ISS offers a unique opportunity to view the many VV coming to the station every year. Given it's location underneath the station (on the nadir side), Raven can observe all of the ISS VVs starting at 1 km away all the way to docking or berthing at a separation distance of approximately 20 meters. The list of the different VV flying to ISS during Raven's two-year mission is shown in Table 1. The ISS docking/undocking attitudes are parameterized by which ISS body axis is aligned with the velocity vector: for example, +XVV reads as "+X velocity Vector" denotes a configuration where the positive X axis and velocity vectors are aligned. These different docking attitudes are important to Raven because the effective field of regard in the Local Vertical, Local Horizontal (LVLH) coordinate system will change as shown in Figure 4. Table 1 also shows whether the approach trajectory is from the ISS radial (R-bar) or velocity (V-bar) directions, as well as the ISS port locations a VV is compatible with. From the ELC-1 vantage point, the distance between Raven and the different port locations listed in Table 1 is between 20 and 30 meters.

Vehicle	ISS Docking Attitude	ISS Undocking Attitude	Trajectory	Port Locations	Expected # During 2yr Raven Lifetime
Dragon	+XVV +Z-Nadir	+XVV +Z-Nadir	R-bar	N2 Nadir	2
Cygnus	+XVV +Z-Nadir	+XVV +Z-Nadir	R-bar	N2 Nadir	2
Soyuz	-XVV +Z-Nadir (+XVV +Z-Nadir sometimes)	+/-ZVV –X-Nadir for zenith & nadir ports	V-bar	MLM/RS Node/SM Nadir or MRM1/FGB Nadir	7
Progress	-XVV +Z-Nadir (+XVV +Z-Nadir sometimes)	+/-ZVV –X-Nadir for zenith & nadir ports	V-bar	MRM2/SM Zenith or SM Aft	8
HTV	+XVV +Z-Nadir	+XVV +Z-Nadir	R-bar	N2 Nadir	1
USCV	TBD	TBD	TBD	N2 Fwd/PMA2	1
USTV	TBD	TBD	TBD	N2 Nadir or N1 Nadir	8
TV	TBD	TBD	TBD	N2 Nadir	1

Table 1. Visiting vehicle table during Raven operations. Shows ISS docking attitude, approach vector, docking port locations, and expected number of visits.
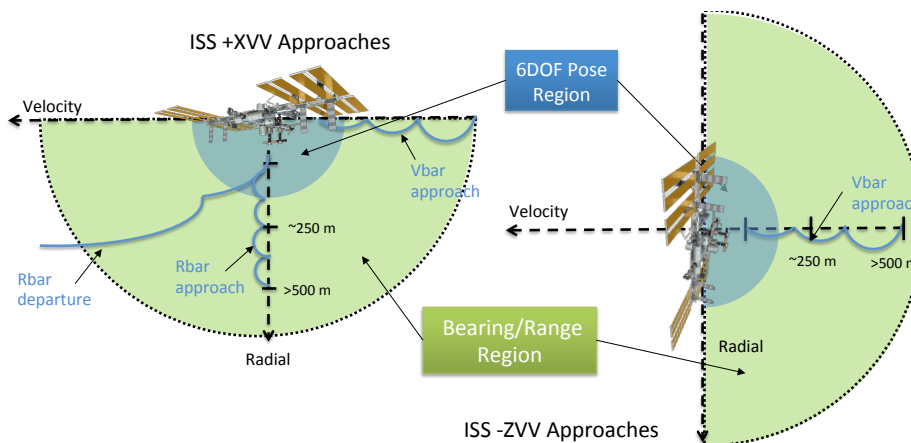
Figure 4. Different ISS attitude and visiting vehicle (VV) approach vectors overlaid with Raven's operational field of regard.

Raven science operations typically start a day prior to the actual arrival of the VV to ISS. The operations team will power up the Raven processor and perform a standard checkout of the system approximately T-

27 hours before a VV berthing takes place. Immediately following power up, operators will upload new software or firmware to the system. These updates provide two main functions: incorporating lessons learned from previous approaches and changing VV model and trajectory files. At T-3 hours, the two-axis gimbal is powered up and verified. Shortly afterward,the three rendezvous sensors are powered up and calibrated. Part of this rendezvous sensor calibration uses ISS structure and dedicated targets placed on STP-H5 to verify inter-sensor alignments. At T-1 hour, the Inertial Measurement Unit (IMU) is calibrated through a scripted sequence of gimbal commands and the sensors are open loop pointed in the general direction from which the VV will approach the ISS. At this point, Raven is ready for science operations.

Acquisition

Once the sensors are oriented toward the VV, the vision processing algorithms can acquire the vehicle. Nominally, VV acquisition will occur once the vehicle is within 1 km of the ISS. Image telemetry will be evaluated in realtime to determine if the target is in the optical sensors Field of View (FOV), if not, the gimbal pointing can be adjusted from the ground if necessary. For target locations that are uncertain, a raster scan of a wide field of regard can be used to acquire the target. If necessary, ground operators can intervene to keep the target in the FOV until it is acquired by the vision processing algorithms using different range and bearing methods.

Tracking

Once the vehicle has been acquired, Raven will nominally track a vehicle—keeping the sensors pointed at the vehicle—until the vehicle berths or docks with the ISS. There are several approaches that Raven can use to track a vehicle, each more autonomous than the next. Over numerous rendezvous, Raven will progress through each, starting with a hands-on approach and finishing with an autonomous one. The most basic uses the *Teleop* mode where Raven receives desired joint angle commands from the Raven ground terminal, where the operator is determining desired pointing from realtime image telemetry. Next is *Path Tracking* mode, which uses scripted pointing commands uploaded before the science interval to change desired optical sensor pointing. An onboard IMU can be either enabled or disabled to make this mode closed or open loop, respectively. Raven also has an autonomous mode, *Visual Tracking* mode, which is used in concert with the relative navigation solution to automatically control the optical sensors pointing relative to the target.

Transition

At the farther ranges, the onboard vision processing algorithms provide only relative position measurement to the VV. For the cameras, two degree of freedom bearing measurements are provided; for the lidar, both a range and a bearing measurement are provided. At closer ranges, the algorithms calculate a full relative position and attitude vector (pose) to the VV. The transition between range/bearing-only mode to full pose mode usually occurs when the subtended angle of the vehicle is ≥ 30 % the sensor's FOV. Raven's onboard relative navigation filter will automatically incorporate these pose solutions into the estimate as they become available.

Characterization

During intervals where VVs are not conducting proximity operations, Raven will still be conducting limited operations. Ground operators can point the sensors to predetermined locations on the ISS and, if present, a berthed VV, to collect imagery and continue testing the vision processing algorithms. Additionally, the ISS and other externally attached payloads are interested in IMU measurements of the ELC environment. The disturbance environment is a large contributor to complexity of eternal payloads, which often require secondary pointing mechanisms to provide stable science platforms. Currently, ISS has externally mounted accelerometers along the truss to measure position disturbances, but not the attitude disturbances. The Raven IMU will be able to provide these correlated attitude and position disturbance measurements to the community. There will be dedicated intervals during characterization and throughout the Raven mission to collect IMU data and correlate against ISS crew activities.

HARDWARE DESCRIPTION

At its core, Raven is comprised of two main hardware groups: the Sensor Enclosure and the Gimbal Baseplate Assembly. Given the tight volume constraints of accommodating the many payloads on STP-H5, the

Raven SpaceCube electronics are not co-located with Raven's core and are instead mounted to the bunker lid next to rest of Raven. Figure 5 shows the Raven CAD model and the fight assembly.
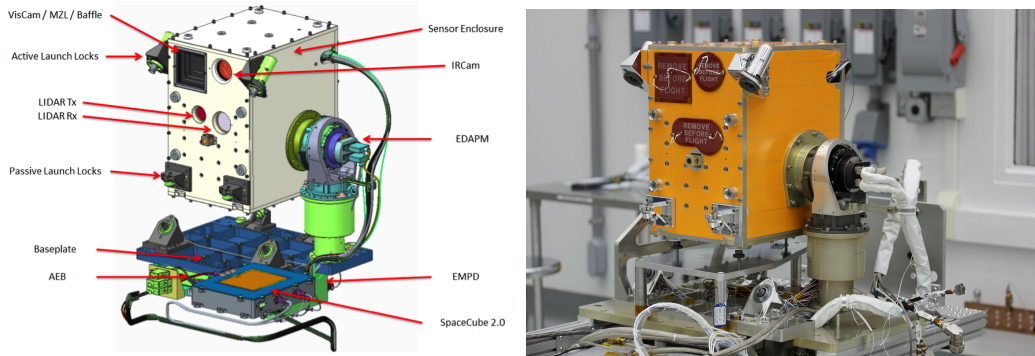
Figure 5. Raven Computer-Aided Design (CAD) model (left) with hardware callouts and flight hardware (right) with ground support equipment (GSE) support stand under the Sensor Enclosure.

The Sensor Enclosure is a light-weight mechanical structure that contains the Raven sensors. The basic structure is six panels attached at the edges. Inside the Sensor Enclosure, the Raven Optical Bench, shown in Figure 6, sits on two side ledges built into the two side panels. This optical bench holds the Visible and infrared cameras, along with an IMU, and provides a rigid surface to constrain inter-sensor alignment shifts during launch and on-orbit operations. The optical bench also provides thermal accommodations—heaters, thermostats, and thermistors—and volume to house connectors, connector brackets, and harnessing to support sensor operations. The Raven flash lidar is not mounted directly to the optical bench but instead to the front panel of the Sensor Enclosure. Alignment between the lidar and the optical bench is controlled through multiple alignment pins between the front panel, the two side panels, and the Optical Bench.
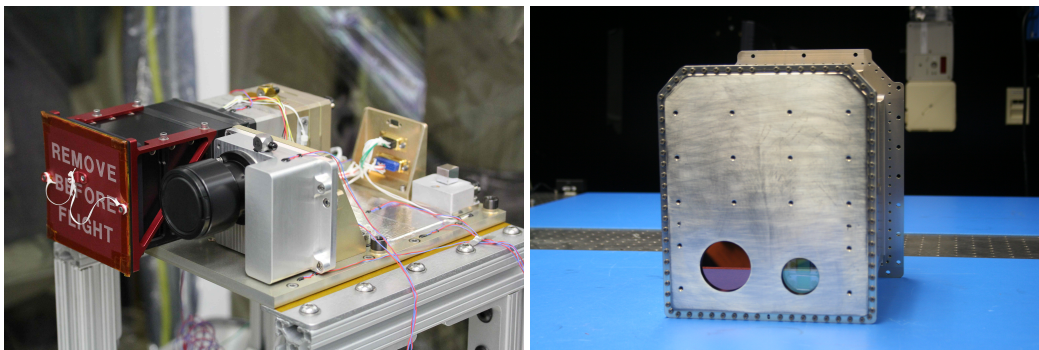
Figure 6. (Left) Picture of the flight Raven optical bench supported by mechanical ground support equipment. Three of the four Raven sensors can be seen: the VisCam (left w. black stray light baffle and red remove before flight hardware), the IRCam (center with black lens and brushed aluminum body), and the Inertial Measurement Unit (IMU) (right in brushed aluminum with alignment cube installed on the top). (Right) Raven flash lidar showing both transmit and receive optics. The mechanical interface is through the 16 fasteners shown on the front face.

The Raven VisCam is a Visible wavelength camera that was originally manufactured for the Hubble Space Telescope (HST) Servicing Mission 4 (SM4) on STS-109. The camera saw operation during SM4 on the Space Shuttle Atlantis as part of GSFC's Relative Navigation Sensor (RNS) Demonstration Test Objective (DTO) in May, 2009.[5,6] The 28 Volt camera contains a Cypress Semiconductor IBIS5-B-1300 focal plane array that outputs a 1000 x 1000 pixel monochrome image over a dual data-strobed Low Voltage Differential Signaling (LVDS) physical interface. For Raven, this camera has been paired with a commercially available,

radiation tolerant 8-24mm zoom lens that has been ruggedized for spaceflight by GSFC. This Motorized Zoom Lens (MZL) provides zoom and focus capabilities via two, one-half inch stepper motors. The adjustable iris on the commercial version of the lens has been replaced with a fixed f/4.0 aperture. The Viscam provides a 45° x 45° FOV when at the 8 mm lens setting and a 16° x 16° FOV while at the 24 mm lens setting. The combination of the fixed aperture and variable focal length and focus adjustments in the lens yield a depth of field of approximately four inches from the lens out to infinity. The VisCam assembly includes a stray light baffle coated with N-Science's ultra-black Deep Space Black coating. The stray light baffle protects the VisCam from unwanted optical artifacts that arise from the dynamic lighting conditions in Low Earth Orbit (LEO).

The Raven IRCam is a Long Wave Infrared (LWIR) camera sensitive in the 8-14 μm wavelength range and is a build-to-print version of the LWIR camera used in the TriDAR DTOs.[7,8] It contains a DRS Technologies U6010 Vanadium Oxide (VOx) 640 x 480 pixel micro-bolometer array. The IRCam includes an internal shutter for on-oribit camera calibration and flat field correction. The camera operates via a Universal Serial Bus (USB) 2.0 interface that handles all power, video, command, and telemetry functions. The camera includes an athermalized, 50 mm f/1.0 lens that yields a 18° x 14° FOV.

The Raven Inertial Measurement Unit (IMU) is a commercially available STIM300 that has been screened for spaceflight by GSFC. It contains three Micro-Electric Mechanical System (MEMS) gyroscopes, three MEMS accelerometers and three (unused for Raven) inclinometers. The IMU also contains internal temperature sensors (one for each gyro, one for each accelerometer, and one for each inclinometer) which are used with calibration data from thermal chamber testing to compensate for temperature effects while in operation.

The Raven flash lidar, shown unintegrated in Figure 6, collects data by first illuminating the relative scene with a wide-beam 1572 nm laser pulse and then collecting the reflected light through a set of receive optics, which funnel the light on to a 256 x 256 focal plane array. By clocking the time between transmission and reception, the focal plane array can accurately measure the distance to the reflected surface, as well as the return intensity, at a rate of up to 30 Hz. Additionally, the lidar utilizes a Liquid Crystal Variable Retarder (LCVR) which acts as an optical switch to provide either a 20° or 12° transmit FOV: this ability to toggle between two FOVs allows operators to maximize the receive signal to noise ratio across large separation distances. The lidar uses a variety of interfaces such as 28 Volt power input, RS-422 command and telemetry links, and a set of LVDS data link pairs. The flash LIDAR is functionally similar to a unit that flew as part of the Sensor Test for Orion Rel-Nav Risk Mitigation (STORRM) DTO on STS-134 in May, 2011.[9]

The second main subassembly in Raven is the Gimbal Baseplate Assembly, which is comprised of the baseplate, gimbal tower assembly, active/passive launch locks, and secondary support electronics. The baseplate serves as Raven's interface to STP-H5 and provides mounting accommodations for most of the Raven flight hardware. The gimbal tower assembly located on the top of the baseplate is actually two pieces: the Enhanced Deployment and Positioning Mechanism (EDAPM)—a Commercial Off-The-Shelf (COTS) azimuth-over-elevation gimbal which points the Sensor Enclosure over a wide field of regard—and the gimbal tower—a mechanical interface adapter between the gimbal and the baseplate. Also on the top of the baseplate are launch lock tie downs—used to secure the gimbal and Sensor Enclosure during launch—and thermal accommodations to protect the secondary hardware mounted to the bottom of the baseplate. Mounted underneath the baseplate are the Enhanced Motor Power Drive (EMPD) and the Auxiliary Electronics Box (AEB). The EMPD will control both the azimuth and elevation motors on the EDAPM as well as the zoom and focus motors on the VisCam MZL. The AEB is a catch-all electronics box that ties together the various electrical systems of Raven: it contains voltage converters for the various pieces of hardware, current inrush limiters, and launch lock power and control services.

Raven uses a SpaceCube 2.0[10] Engineering Model as its primary command and data handling processor. The same processor design flew aboard Space Test Program-Houston 4 (STP-H4) as part of the ISS Space-Cube 2.0 experiment. Figure 7 shows the top and bottom sides of the board with the three Xilinx Virtex-5 Field Programmable Gate Arrays (FPGAs) used in the Engineering Model architecture. One FPGA is the main board controller, providing interfaces to radiation hardened static random-access memory (SRAM), double data rate (DDR) Synchronous Dynamic Random Access Memory (SDRAM), a custom 16-channel analog to digital convertor (ADC), two flash memory modules, and 10/100 Ethernet. The other two FPGAs host application-specific code and are where the Raven flight software and VHSIC hardware description lan-

guage (VHDL) will run. Each of these FPGAs has two DDR memory modules, one flash modules, and a variety of external interfaces. The SpaceCube 2.0 architecture includes the ability to reprogram the two application-specific FPGAs;[11] Raven developers plan to use this capability to implement a variety of new software and VHDL over the life of the experiment.
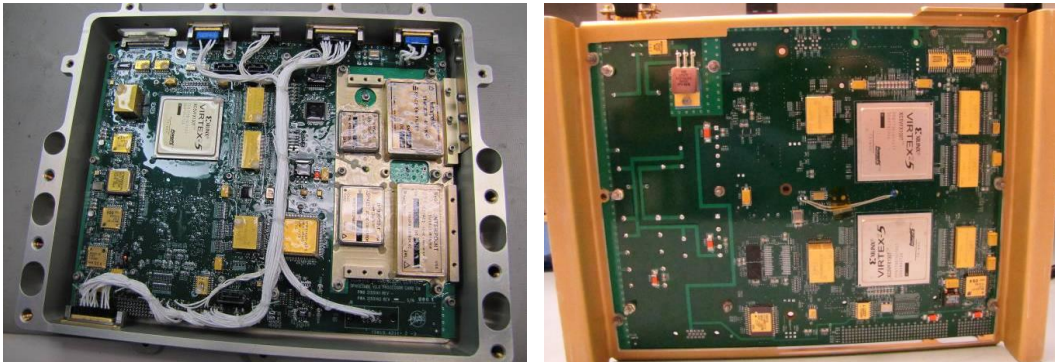
Figure 7. Raven flight science data processor: based on the SpaceCube 2.0 architecture.

BASELINE PROCESSING DESCRIPTION

The Raven hybrid computing system features a mix of hardware-accelerated firmware cores and embedded software libraries that are each designed to run optimally on SpaceCube's multi-FPGA architecture. The basic building blocks are VHDL cores that perform all of the interfacing to the flight hardware components—gimbal, sensors, auxiliary electronics, etc. Flight software is executed on multiple MicroBlaze™soft core processors, each with running a custom realtime Linux operating system. Device drivers bridge the gap between the hard realtime operations of the VHDL cores and the soft realtime processing in software. A software message bus provides inter-processor communication, which allows software processes to synchronize operations across multiple hardware processors.

Raven's GN&C processing utilizes a mix of firmware and software components to maximize overall system throughput. The high-speed vision processing algorithms are implemented in firmware to leverage the massively parallel processing capable with FPGAs. More mathematically intense algorithms, such as the navigation filter, run as software processes on the soft core processors. Figure 8 shows the end-to-end data path for Raven's GN&C architecture.

Each vision processing algorithm will generate either a bearing measurement or a full six-state pose measurement depending on the range to the vehicle. The lidar algorithm will additionally provide a direct range measurement during bearing mode operations. Raven's GN&C-related sensors—the IMU and gimbal potentiometers—are processed using the Sensor Processing (SP) application. Using raw potentiometer data, the SP application produces position and rate estimates for both the azimuth and elevation joints. Additionally, the SP application generates the field of view and focus estimates for the optical zoom lens and forwards IMU data to the other GN&C applications.

Goddard Natural Feature Image Recognition (GNFIR)

GNFIR is a natural feature image recognition application developed initially for the RNS experiment on HST SM4.[5,6] It requires no fiducials on the target vehicle and utilizes an edge model of prominent features to track. The algorithm first reduces the imagery to edges through standard edge detection, then projects the model into the image plane using the previous pose measurement, searches for nearby edges and then performs a least squares minimization of the search results to arrive at a pose measurement.[12] Figure 9 shows a simulated image of a Dragon rendezvous overlaid with the GNFIR algorithm's tracking detail. Figure 10 shows GNFIR working with infrared camera imagery. The figure also highlights recent updates to GNFIR to track objects in images with cluttered backgrounds.
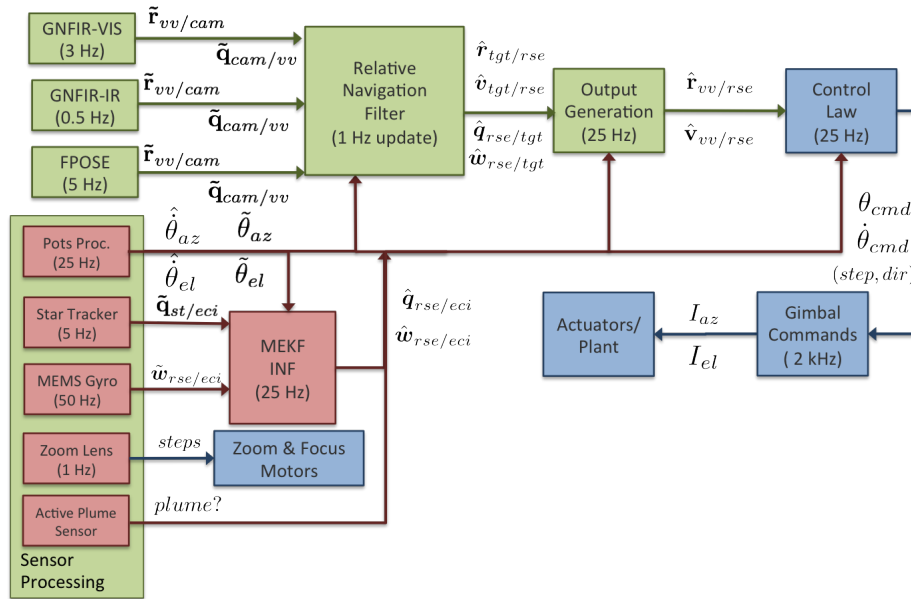
Figure 8. Raven's Guidance, Navigation, and Control (GN&C) software architecture

FlashPose (FPose)

FPose utilizes the flash lidar range and intensity point clouds to develop a pose measurement at close range and a range and bearing measurement at farther distances. The algorithm leverages standard Iterative Closest Point (ICP) methods to match a model to the point cloud data[13] and then converts the least squares minimization result to a pose measurement using the Horn algorithm.[14] Figure 11 shows simulated lidar imagery of a Dragon rendezvous and the Fpose algorithm tracking the vehicle.

Navigation Filter

The next step in the processing pipeline is to fuse the bearing and pose measurements from GNFIR-Vis, GNFIR-IR, and FPose, along with measurements of the Raven joint angles and rates, into a state estimate of the vehicle. The Raven navigation filter architecture is built off the standard extended Kalman filter architecture.[15] The filter performs the state and measurement updates at 1 Hz, while an output processing loop generates input for gimbal at a higher 25 Hz while propagating in between measurement updates. Two different dynamic formulations are implemented in the filter—a simple kinematic force model and a Clohessy-Wiltshire dynamic model—and ground operators can choose based on the current information available. Initially, operators will use the simpler kinematic force model because it does not rely on external, imprecise information, such as its location relative to the ISS center-of-mass. The filter solution is exclusively used onboard to provide the desired pointing vector for the *Visual Tracking* mode and is transmitted to the ground operators for evaluation. To increase processing speed, the Raven filter also implements a UDU formulation—where the covariance matrix is factored into unit upper triangular and diagonal matrices—given the large number of pose bias states included in the filter state vector.[16] The filter also incorporates measurement editing using underweighting techniques and features consider states using the Schmidt-Kalman consider covariance.[17]

PROGRAM STATUS

As of January 2015, most of the Raven flight hardware has been integrated. The Sensor Enclosure and Gimbal Baseplate Assembly have been mechanically integrated and successfully passed both azimuth and elevation range of motions tests. The Sensor Enclosure is completely electrically integrated with all safe-to-mates between the sensors and the processing and power electronics complete. The flight SpaceCube electronics box is undergoing environmental testing in parallel to Raven core vibration testing. Figure 12 shows the remaining Raven testing activities and the ship date to STP-H5.
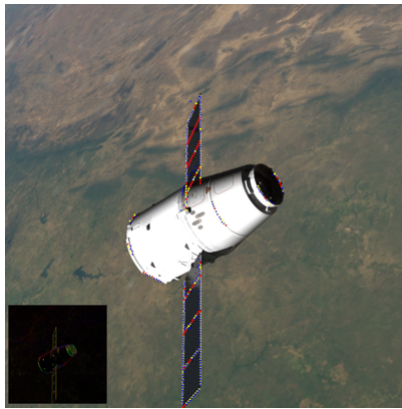
Figure 9. Goddard Natural Feature Image Recognition (GNFIR) tracking synthetically generated image of a Dragon vehicle. Dots represent tracked points used in the solution; dot color corresponds to whether or not the point is successfully being tracked. Inset image shows processed edge image.
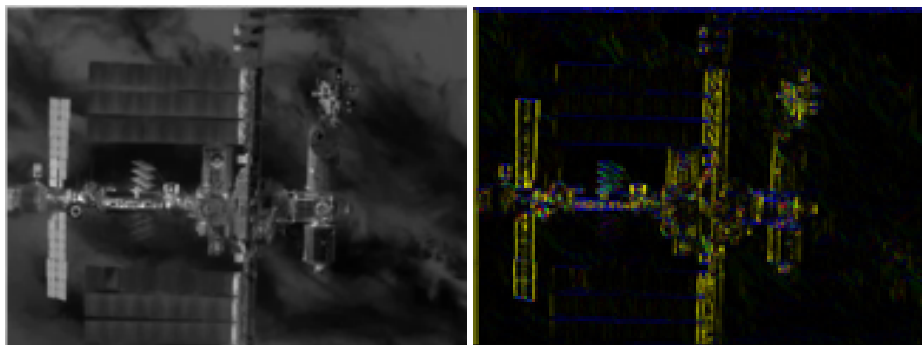
Figure 10. Raw infrared image of the ISS (left) and Goddard Natural Feature Image Recognition (GNFIR) edge tracking image (right).

NASA had to overcome many risks in order to be successful with Raven. By far the biggest hurdle has been verifying that the Raven lidar does not interfere with any GN&C sensors aboard the approaching or departing VV. GSFC, Space Test Program (STP), and the ISS Program Office worked together to resolve this potential issue by chartering the NASA Engineering and Safety Center (NESC) to conduct an independent assessment of Raven and its effect on VVs. The assessment team found no credible fault could result in a catastrophic hazard; as of this writing, the ISS program office is still working the VV providers to concur with the assessment of the NESC by fully analyzing the possibility of any type of interference between Raven and their vehicles.

One of the other major risks faced by the project was the use of COTS and preexisting hardware on Raven in order to meet mission objectives within a reasonable budget and schedule while still meeting ISS safety and mission assurance requirements. The 18-month development schedule forced the project to use a "capabilities-driven engineering approach" that resulted in using flight or flight-spare hardware from previous missions—the VisCamera and flash lidar—and commercially available hardware—the IRCamera, gimbal and associated electronics—with no modifications. Additional analysis not included with the standard COTS products, or missing from legacy hardware, needed to be completed by the NASA team. In some cases, the mission objectives were adjusted to accommodate less expensive and more readily available hardware.
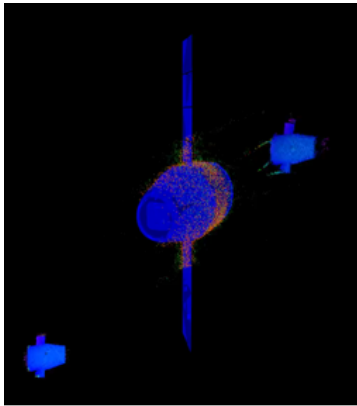
Figure 11. FlashPose (FPose) registering an internal model—shown in blue—with synthetically generated point cloud. The two small inset images show the variations in the raw lidar range images at different points in the scenario.
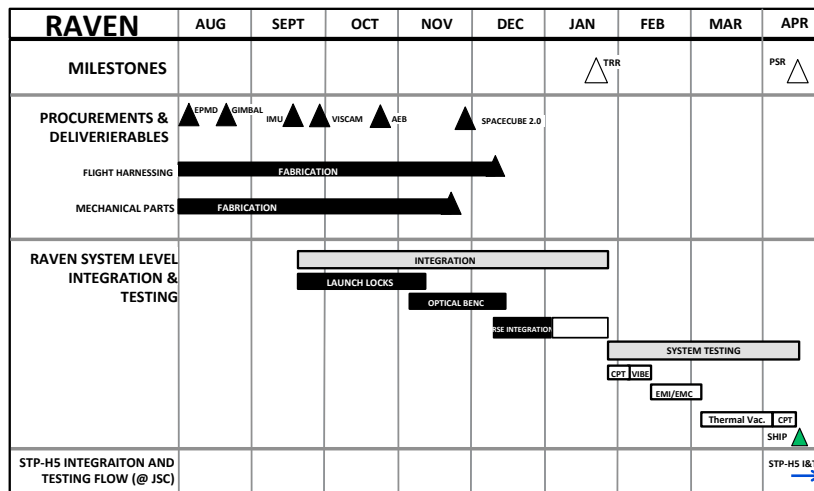
RAVEN SUMMARY SCHEDULE

Figure 12. Raven summary schedule as of Janurary 2015

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ACRONYMS AND ABBREVIATIONS

ADC	analog to digital convertor
AEB	Auxiliary Electronics Box
AR&C	Autonomous Rendezvous and Capture
ARM	Asteroid Redirect Mission
BAA	Broad Agency Announcement
CAD	Computer-Aided Design
COTS	Commercial Off-The-Shelf
DDR	double data rate
DoD	Department of Defense
DPP	Dextre Pointing Package
DTO	Demonstration Test Objective
EDAPM	Enhanced Deployment and Positioning Mechanism
ELC	ExPRESS Logistics Carrier
EMPD	Enhanced Motor Power Drive
FOV	Field of View
FPGA	Field Programmable Gate Array
FPose	FlashPose
FRAM	Flight Releasable Attachment Mechanism
GN&C	Guidance, Navigation, and Control
GNFIR	Goddard Natural Feature Image Recognition
GSE	ground support equipment
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
HTV	H-II Transfer Vehicle
ICP	Iterative Closest Point
IMU	Inertial Measurement Unit

ISEM	ISS SpaceCube Experiment–Mini
ISS	International Space Station
KSC	Kennedy Space Center
LCVR	Liquid Crystal Variable Retarder
LEO	Low Earth Orbit
LVDS	Low Voltage Differential Signaling
LVLH	Local Vertical, Local Horizontal
LWIR	Long Wave Infrared
MZL	Motorized Zoom Lens
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
RNS	Relative Navigation Sensor
SDRAM	Synchronous Dynamic Random Access Memory
SM4	Servicing Mission 4
SPDM	Special Purpose Dexterous Manipulator
SRAM	static random-access memory
SSCO	Satellite Servicing Capabilities Office
SSRMS	Space Station Remote Manipulator System
STORRM	Sensor Test for Orion Rel-Nav Risk Mitigation
STP	Space Test Program
STP-H4	Space Test Program-Houston 4
STP-H5	Space Test Program-Houston 5
USB	Universal Serial Bus
VHDL	VHSIC hardware description language
VOx	Vanadium Oxide
VV	visiting vehicle