INSPECT Sensor Suite for On-Orbit Inspection and Characterization with Extravehicular Activity Spacecraft

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Most inspection and maintenance operations at the International Space Station (ISS) rely on astronaut extravehicular activities (EVAs). Autonomous or radio-controlled spacecraft that work in conjunction with astronauts could improve diagnostic and imaging capability during EVA missions. The Integrated Navigation Sensor Platform for EVA Control and Testing (INSPECT) system is a proposed testbed for EVA systems that builds off of the Synchronized Position Hold Engage Reorient Satellites (SPHERES) facility at MIT and the International Space Station (ISS). INSPECT’s imaging payload includes a stereo-vision optical camera, an optical range finder (ORF) and a thermal infrared (IR) imager. A configuration of four miniature control moment gyroscopes (CMGs) acquired from Honeybee Robotics work alongside SPHERES CO2 thrusters to provide enhanced pointing precision and slew control for the imaging payload. Results from laboratory testing and microgravity experimentation aboard a NASA reduced gravity aircraft have validated sensor fusion algorithms and have demonstrated the torque capability of INSPECT CMGs. Torques of 120mN-m have been demonstrated with the CMGs, as compared to individual thruster pairs capable of providing torques of 20mN-m from 0.1N thrust for each thruster at a moment arm of 10 cm. Offsets of the center of mass from the system’s geometric center were computed to be: 4.4cm in x, -1.5cm in y, and 4.6cm in z. Additionally, the moment of inertia about the z-axis was computed to be -0.398 kg·m².

Nomenclature

\( a_{pulse} \) = acceleration induced with a thruster pulse \([\text{m/sec}^2]\)
\( a_{x,y,z} \) = acceleration in the x-axis, y-axis or z-axis measured by an accelerometer in the SPHERES’ body frame \([\text{m/sec}^2]\)
\( F_{pulse} \) = nominal thruster force for a pulse \([\text{N}]\)
\( F_{x,y,z} \) = reaction force in the x-axis, y-axis or z-axis in the SPHERES’ body frame \([\text{N}]\)
\( I_{x,y,z} \) = mass moment of inertia of INSPECT about the SPHERES x-axis, y-axis or z-axis \([\text{kg-m}^2]\)
\( m \) = system mass \([\text{kg}]\)
\( r_{x,y,z} \) = moment arm from INSPECT center of mass to SPHERES accelerometer location \([\text{m}]\)
\( \tau \) = torque on SPHERES INSPECT system \([\text{N-m}]\)

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I. Motivation

Free-flying semi to fully autonomous systems that can operate at stand-off locations in close proximity to a host vehicle or astronaut can reduce overall risk and provide additional valuable functions and resources to mission planners, such as inspection, navigation, characterization, and health monitoring capabilities. The use of multiple free-flyers for redundancy would reduce risk and could help increase task completion speed. The free-flying systems could lessen the need for manned extravehicular activities and decrease crew member risks, while potentially increasing the duration of robotic missions, since crews could remain within their spacecraft and avoid performing inspections of potentially hazardous areas.

For example, a free-flying system such as INSPECT could be used to examine a reported leak aboard the ISS. Astronauts would remain in a safe location while the free-flyer could enter the restricted space on either the interior or exterior of the station to determine the specific location, flow rate, and type of leak. An INSPECT system, for example, could have identified that the supposed ammonia leak in January, 2014, was a false alarm without requiring astronauts to investigate themselves. Similar applications include inspection of devices that have experienced electrical faults, thermal insulation deterioration, and micrometeoroid impacts. Functionality provided by INSPECT would have been for the damage assessment of the Mir space station after the 1997 Progress vehicle collision; lacking such a vehicle, engineers were unable to make an assessment until an extravehicular activity (EVA) was performed by the Mir crew and an inspection by a Space Shuttle three months later.

Increasing reliance on autonomous and robotic systems for in-space operations (both for complete spacecraft and for spacecraft subsystems) has led to the growing demand for preliminary testing research platforms. For example, the NASA Human Exploration and Operations Mission Directorate (HEOMD) has specified a need for free-flying robotic systems like the kind mentioned above for extravehicular inspection and characterization. There are large risks associated with such a mission that stand in the way of development, especially those related to collisions between spacecraft or losing free-flying spacecraft entirely because of either hardware or software failures. A risk-reducing, retrievable testbed that can perform technology maturation aboard the International Space Station (ISS) is an attractive option for technology verification and validation. An ISS testbed provides this risk reduction for both inspectors within and outside spacecraft, since many enabling technologies are common to both environments.

The ISS provides an environment where we plan to test the technologies required for these robotic systems. Such technologies include staged estimation, sensor fusion, and adaptive control schemes that can incorporate multiple types of actuators, primarily thrusters and CMGs. Because the ISS constitutes a habitable environment in Low Earth Orbit, new hardware and software may be sent to the station with comparative ease to take advantage of the long duration microgravity and risk tolerant operation that is possible. The ISS is the only long duration microgravity environment available for testing new spacecraft technologies, offering researchers using the SPHERES satellites the ability to conduct full six degree-of-freedom motion experiments in microgravity for durations lasting five to ten minutes. These microgravity tests would not be possible on any other location. While the ISS environment cannot perfectly replicate the space environment, the microgravity dynamics are the most crucial in developing the INSPECT technologies, since the relative motions between inspector and target satellites are most dependent on the long duration microgravity provided by the ISS.

The MIT and ISS SPHERES facility provides a base platform for testing new hardware and software. SPHERES satellites have been tested extensively for almost a decade aboard the ISS in more than seventy test sessions. Three SPHERES satellites remain aboard the ISS to conduct test sessions, and an identical set of three satellites is at MIT for conducting ground testing and research. Each of the SPHERES satellites is a complete satellite bus with all necessary subsystems for operation within the space station environment, allowing efficient testing of new software and expansion with new hardware additions via an expansion port.

Modifications to the SPHERES facility are required, however, to fully address the HEOMD mission. Figure 1 shows SPHERES satellites operating aboard the ISS in the left image, as well as a potential extension of SPHERES for use outside the ISS environment in the right image. This sequence must expand upon the SPHERES satellite (a computer aided design rendering of which is shown in the center image of Figure 1) with the sensing capabilities required for operation in the EVA environment in close proximity to other space objects. The INSPECT system addresses the HEOMD mission by advancing the SPHERES facility aboard the ISS with sensors and actuators for a prototype system that is capable of maturing inspection, navigation, and characterization technologies.
II. INSPECT Design Overview

We have designed and prototyped the INSPECT system to be later extendable towards an EVA-capable system that meets the inspection, navigation, and characterization needs exemplified by HEOMD. INSPECT is an extension of the SPHERES facility through its use of several added hardware components. The backbone of INSPECT is the “toolbelt” Halo structure which attaches to a SPHERES satellite and enables up to six peripheral devices to be controlled by a central SPHERES satellite. Halo serves as an electromechanical extension to a SPHERES satellite by functioning as a rigid attachment for peripherals to attach to the satellite, while data is transferred via Universal Serial Bus (USB) hubs and a gigabit Ethernet switch within the Halo itself. Attaching a Halo to a satellite requires the use of an added processor, provided by the Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) Avionics Stack, which is the computer that saves incoming data and provides processing well above the capabilities of the SPHERES satellite itself. VERTIGO is comprised of both an Optics Mount containing two black and white Universal Serial Bus (USB) cameras and an Avionics Stack, which may be separated so that the Avionics Stack can function as a computer for other peripherals. Two VERTIGO systems are aboard the ISS. Figure 2 shows a labeled Halo structure without the VERTIGO Avionics Stack.

The INSPECT peripherals constitute a sensor and actuator suite that mounts to the Halo. The Halo structure was designed specifically to enable up to six peripheral devices to be attached to the SPHERES satellite for a given test. These may be operated simultaneously, since Halo provides its own batteries for power and both Ethernet and USB communication to each Halo port. These ports are labeled “HP 1” through “HP 5”, in addition to a port with direct communication to the SPHERES satellite labeled “HPG”, which is so named for the VERTIGO Goggles system, which nominally is mounted to that port. The INSPECT system is fundamentally a set of peripheral devices; any combination of sensors and actuators may be mounted to a Halo at any given time depending on a particular test’s objectives. The baseline suite for INSPECT is configured so that the resulting control and data acquisition software
need not change between tests. The specific implementation that has been tested is comprised of a Mesa (Switzerland) SR4000 optical range-finder (ORF), stereo camera system named VERTIGO Optics Mount, and a FLIR (United States) A5 thermographic camera (ThermoCam), as well as four 120 Nm control moment gyroscopes (CMGs) purchased from Honeybee Robotics. These components are mounted onto five of the six Halo ports. The complete INSPECT system therefore consists of a SPHERES satellite, Halo, ORF, VERTIGO Optics Mount, ThermoCam, and four CMGs. The total mass is approximately 17.4 kg, with the INSPECT sensors and actuators accounting for approximately 8.1 kg and the central satellite accounting for 4.2 kg. Table 1 presents a summary of the INSPECT peripherals that are attached via the Halo structure. Any combination of sensors and actuators can be mounted at a given time, however, because of the modularity enabled by the Halo port system.

<table>
<thead>
<tr>
<th>INSPECT Peripheral</th>
<th>Number</th>
<th>Type</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermographic Camera</td>
<td>1</td>
<td>FLIR A5</td>
<td>Sensor</td>
</tr>
<tr>
<td>Optical Stereo Cameras</td>
<td>1, pair</td>
<td>VERTIGO Optics Mount: two IDS-Imaging uEye LE 1225-M-HQ cameras</td>
<td>Sensor</td>
</tr>
<tr>
<td>Optical Rangefinder (ORF)</td>
<td>1</td>
<td>MESA SR4000</td>
<td>Sensor</td>
</tr>
<tr>
<td>Control Moment Gyroscope (CMG)</td>
<td>4</td>
<td>Honeybee Project FS1019</td>
<td>Actuator</td>
</tr>
</tbody>
</table>

Figure 3 is the INSPECT system model (Solidworks Computer Aided Design file), while the fully assembled system as tested is shown Figure 4. In both figures, the CMGs are depicted in their mounted orientation on the aft Halo ports (left three ports in Figure 2), while all of the sensors are mounted to the forward Halo ports such that they share parallel boresight axes. In the left image, the target satellite (without the INSPECT system attached) is shown. This target maintains its position relative to the sensors on the INSPECT satellite using its onboard thrusters. The ORF and ThermoCam sensors each are mounted into their own mounts which are electromechanically identical to one another, a design choice that enables rapid development without the need for multiple highly specific components, while reducing the time required to build and test all of the INSPECT elements fully. These sensors are able to receive power and commands, as well as save images, through circuit boards that provide an added measure of current overdraw protection for the safety of the entire system. All three sensors save their data to the VERTIGO Avionics Stack using the Ethernet and USB lines within the Halo structure: the VERTIGO cameras utilize the USB lines, while the ORF and ThermoCam use the Ethernet lines.

The four CMGs require additional processing in order to maintain constant flywheel rates and to compute and execute gimbal rates that correspond to torque commands issued by the SPHERES control law. This added computation as well as housekeeping functions specific to the CMGs is performed by a dedicated control board provided by Honeybee Robotics, which is mounted in a protective box on one of the Halo ports underneath one of the two pairs of CMGs. To maintain symmetry in the system’s mass properties as well as an option for future CMG electronics redundancy, an empty box is mounted underneath the other pair of CMGs as well. The single controller board is responsible for all four CMGs, but because the commercial board is not designed to take advantage of the Halo communication channels, external data wires are needed. These wires are secured to the Halo structure to prevent snagging, twisting, or damage to the cables or end connectors during operation.
The INSPECT sensors and actuators are controlled as part of the SPHERES control cycle, which operates at 1 Hz. The actuation for INSPECT is performed by a combination of pulse-width modulated thrusters on the satellite and CMGs on the INSPECT system. Each SPHERES satellite maneuvers using 12 CO₂ cold gas thrusters, but the CMGs afford significantly higher rotational control capabilities. Each SPHERES thruster can provide only 0.1N of thrust, mounted approximately 10cm from the satellite center of mass without any attached peripherals, whereas the CMGs can provide torques of approximately 120mN-m. To take advantage of this increased performance, the commands for translations and rotations are split: translations are actuated by thruster firings, while rotations are actuated by the CMGs. This approach is a more fuel-efficient way to use the available actuators in the complete INSPECT system, since electricity from Halo batteries is used to control the satellite’s attitude instead of the onboard CO₂. Required torque commands are sent to the CMGs at the same 1 Hz rate as the required force commands that are sent to the thrusters. The SPHERES mixer determines which thrusters to fire and the durations of each thruster firing, which is a directly analogous process to how the CMG controller board determines the gimbal rates to provide the required torques to the system.

The INSPECT sensors are also tied to the 1 Hz SPHERES control frequency. Images from each sensor are acquired once per control cycle, resulting in the acquisition of six images per second: each VERTIGO camera takes one image, the ThermoCam takes one image, and the ORF takes a depth map, confidence map, and visual image. These images are taken at the native resolutions for each sensor, but are resized to 80 × 64 pixels for the ThermoCam and 640 × 480 pixels for the VERTIGO cameras and ORF to allow comparison of point cloud depth data from the ORF and VERTIGO system during post processing. All images are saved in the VERTIGO Avionics Stack, which includes a 64 GB storage drive.
III. Laboratory and Reduced Gravity Experiments

The INSPECT sensor and actuator suite was developed for use in MIT Space Systems Laboratory ground laboratory environments with planned traceability for future flight testing aboard the International Space Station. The parabolic flight campaign in August, 2014, was necessary in order to provide system characterization data to the team. In particular, the flights were required in order to obtain image sets from all sensors while operating in microgravity for post-processing and to observe the effect of commanded CMG torques on the satellite’s motion for system center of mass and principle moment of inertia determination. Laboratory experiments before the flight were used to build and test INSPECT system functionality, as well as to provide a baseline for sensor and actuator performance in the presence of gravity. In order to accomplish these goals, an air-bearing table and flat floor for translation and single-axis rotation were used for laboratory testing. In addition to these flat surfaces, a stationary single-axis rotation mount and a limited 3-axis rotation mount were used to validate control moment gyroscope control algorithms.

A. Laboratory Experiments

Testing Environment

Existing flat surfaces and air-bearing fixtures in MIT’s Space Systems Laboratory served as the primary testing surfaces for the INSPECT system. With free planar translation and single-axis rotation, the flat surfaces provide INSPECT with three directions of freedom (3DOF). In order to support individual sensor integration and optical payload sensor fusion operations on the ground, a visual and thermal landscape was constructed to serve as a target field for the INSPECT system during ground tests. This landscape was designed to simulate depth, thermal, and visual stimuli, and a broad range of stimuli was included to ensure the greatest flexibility for INSPECT testing objectives. In the figure below, black and white structures represent visual and depth targets and red squares represent thermal targets with adjustable temperatures.

![Figure 5. The Inspection Landscape, initial model (above) and actual construct (below). Thermal pads are black in the lower image.](image)

INSPECT Sensor Configuration

The combined field of view created from individual sensor specifications as well as sensor placement is 33.55° (H) x 35.56° (V). From a distance of 1 meter this is equivalent to 59.53 cm (H) x 64.14 cm (V). Limiting factors for
horizontal field of view include both individual sensor field of view and sensor placement. The center of the horizontal field of view is located 14.37 cm from the center of the system. Figure 6 and Figure 7 show the corresponding fields of view for each sensor in their appropriate mounting locations. All sensors are located on the same horizontal plane. This leads to only sensor field of view to be the limiting factor. The FLIR A5 has the smallest vertical field of view and thus is the limiting factor.

Figure 6. Horizontal field of view viewing sensors top-down; units are degrees and centimeters

Figure 7. Vertical field of view viewing sensors right to left; units are degrees and centimeters

INSPECT Sensor Fusion Testing

One of the most important enabling functions of the INSPECT system is to support sensor fusion testing. The goals of the sensor fusion testing enable users to determine more effectively the state of the targets under inspection in the laboratory environment both on the ground, aboard the reduced gravity aircraft, and eventually aboard the ISS prior to implementation on a flight mission. Additionally, it is planned to improve upon the initial fusion algorithms to enable the inspector satellite to navigate around its operational environment using the fusion images. An initial fusion algorithm was created for the initial ground and reduced gravity testing. Figure 8 shows how the fusion algorithms are designed to fit into the overall INSPECT control process, where the acquisition of images from each sensor helps to provide state estimation for position and attitude control of the satellite. Currently, the fusion algorithm combines the 3D point cloud of the ORF with the 3D VERTIGO data to create a new 3D point cloud with both depth and visual information available.
For the RGA campaign, the algorithms in the pink boxes were tested in the MIT Space Systems Laboratory, with the Real-Time Fusion Algorithms occurring in real time, but with previously acquired images. This testing process revealed several important results regarding the operation of the sensors individually and the fusion of multiple sensor datasets. Laboratory experiments highlighted the following phenomenon: ORF confidence decreases as infrared illumination time diminishes. This result is important to the fusion algorithm’s implementation within the SPHERES architecture since the use of IR illumination for the ORF payload interferes with SPHERES metrology beacons that are necessary for SPHERES’s estimation algorithms. It was necessary to time the infrared pulses of the ORF such that the infrared pulses avoided interference with SPHERES estimation processes. Further details will be discussed in Section 3B.

**Figure 8. Control and Sensor Processes of INSPECT.** Light green represents existing VERTIGO Avionics Stack software, dark green represents existing SPHERES software, and red represents newly developed fusion algorithm software from Urbain, 2014.  

**Control Moment Gyroscope Testing**

The majority of laboratory testing with the suite of four 120 Nm (maximum torque) and 120 mNm-s (angular momentum capacity) Honeybee Robotics control moment gyroscopes (CMGs) occurred on a fixed, single-axis rotation stand and on the flat surface facilities at the MIT Space Systems Laboratory. Ground tests focused on verifying new C++ software written to control the CMGs run on the SPHERES avionics stack. Single-axis slews using a box-90 configuration were successfully conducted and demonstrated CMG subsystem functionality. These tests focused on commanding set torque values about each body axis on a mass mockup of the INSPECT system atop a rotary air bearing. This box-90 configuration was chosen because of its ready applicability for mounting to orthogonally aligned Halo ports. Other configurations have been explored by Gersh et al and a review of singularity-robust steering laws is provided by Kurokawa.

Future planned developments of the INSPECT system include modification of the CMG mounting structures to support a pyramid configuration as well as the originally implemented box-90 configuration for additional control research aligned with assessing the utility and performance gains associated with a combined control concept that relies on combining CMG and thruster actuation.

While a single-axis rotation stand provided a solution for verifying communication protocols and command methods, the restriction of motion to only one rotational axis was unable to provide information about any additional torques introduced with our control algorithms. In order to discover the three-axis nature of torques executed by CMGs, follow-up experiments conducted on a three-axis rotational stand were also conducted in the Space Systems Laboratory at MIT.

Preliminary results indicated successful isolation of torques to the axes of rotation commanded in software, though detailed analysis and accurate measurements of torque were not possible in the ground set-up. The difficulty of characterizing CMGs on the ground in three axes of rotational freedom provided motivation for microgravity testing.
aboard NASA’s reduced gravity aircraft as a proxy of extended microgravity testing aboard the International Space Station.

B. RGA Test Results

While the laboratory tests described in Section 3A provided confidence to the team that the system could operate in a 1-g environment, experimentation aboard NASA’s reduced gravity aircraft allowed unrestricted, full six degree of freedom (6DOF) testing that is necessary to characterize CMG actuation and validate payload operation in a relevant environment toward eventual operation of the INSPECT system aboard the International Space Station (ISS). The specific objectives for the 138-P flight campaign were to:

1. Perform INSPECT system identification to identify the center of mass and principle moment of inertia by acquiring dynamic response data for actuation and maneuvering;
2. Provide a preliminary evaluation and 6DOF data for INSPECT sensor performance and interoperability;
3. Demonstrate basic controllability of the CMGs;

The underlying theme of these objectives is to assess the difference in system performance under the effects of microgravity compared with 1-g ground testing. The ability to test in microgravity for (list duration of microgravity periods during flights) seconds allowed measurements to be taken without the influence of gravity and limitations on testable degrees of freedom.

Table 2 summarizes the daily activities during the RGA experiments. VERTIGO, ORF, ThermoCam and the CMGs were tested in microgravity. The set of operating peripherals for each day is indicated in the “Operating Peripherals” column. The results from the RGA test flights align with the test flight objectives and incrementally advance the team’s technology in preparation for ISS flight testing. These include:

1. Utilize a set of four CMGs to accentuate the attitude control capabilities of the SPHERES cold-gas thrusters
2. Demonstrate the ability to command the CMGs in concert with the SPHERES thrusters
3. Determine that a negligible amount of thruster impingement is created through the addition of the INSPECT suite to the Halo structure
4. Gather IMU data from the INSPECT-equipped satellite during both sensor operation and CMG movement in the relevant operational environment of microgravity
5. Conduct post-processing to create a preliminary assessment of the performance of the sensors and confirm that they can operate in concert
6. Conduct post-processing of the sensor data to create 3D maps demonstrating 6DOF motion in microgravity for future use in autonomous mapping, navigation, and characterization.

<table>
<thead>
<tr>
<th>Flight Day (2014)</th>
<th>Operating Peripherals</th>
<th>Experiments Conducted</th>
</tr>
</thead>
</table>
| Aug 19           | VERTIGO, ORF, TC     | • Integrated sensor collection for post-processing of sensor fusion  

Sensor Fusion

The INSPECT data processing software focused on the fusion of the images acquired at each imaging step from the three different sensors in order to recreate a dense 3D cloud of the target. Importantly, however, while the ORF
and VERTIGO can provide 3D imagery data for the fusion algorithm, the ThermoCam cannot, and thus it is not incorporated currently into the fusion process. This software can run either online using live capture from the sensors, or offline to test new fusion algorithms on previously collected data. Additional information regarding the software architecture and implementation on the SPHERES satellites can be found in Gabriel Urbain’s Master’s thesis.10

The RGA campaign provided thousands of images (collection at 1Hz over nearly 1.5 hours of testing per flight), of which only a few hundred were selected based on their quality and content to develop and test a series of new sensor fusion algorithms. For each of the four flights, the sensors were powered on and collecting data throughout the entirety of the time when the RGA was at altitude. Doing so allowed the sensors to acquire as many images as possible, though the vast majority correspondingly were not during periods of microgravity. Image pruning occurred on the ground post-flight in order to select only those from microgravity tests. Microgravity periods were identified by observing the absence of gravitational pull in the accelerometer data.

Figure 9 shows an example of the saved images from (top left to bottom right) the VERTIGO Left Camera, VERTIGO Right Camera, ThermoCam, ORF Confidency Map, ORF Depth Map, and ORF Visual Image. These images were taken nearly simultaneously and thus could be fed through the newly developed algorithms.

While features are present across the images, the entirety of the target satellite is not visible across all three images simultaneously. This result is expected owing to the separation spacing of the sensors, the fact that the sensors share a common boresight axis, and the short separation distance between the sensors and the target (on the order of 1 m). Consequently, only a portion of the forward facing environment is visible in all three sensor fields of view at a given instant. This operational result underlines the importance of feature tracking across images, and all future testing and reflight opportunities will be conducted with increased separation between the inspector and target satellites.

To improve the accuracy of the fusion algorithm is the challenge of on-line calibration of all fusion sensors. The calibration process determines the relative pose of each camera with respect to each other, providing the linear and angular separations from the other sensors that allow the fusion algorithm to determine the linear and angular separations from a target. The calibration process aims to compute the relative pose of the sensors against a known, stationary target location. With the calibration matrices, the sensor fusion algorithm is able to determine the position of either stationary or moving targets accurately. Further INSPECT calibration information has been discussed in Urbain, 2014.10

The reconstructed 3D points using the only the ORF data from Figure 9 are shown in Figure 10, where thermal and scattering noise around the object edges (particularly around the target satellite) is evident. The fusion image
formed out of the data from the ORF and VERTIGO is shown in Figure 11. With the current version of the algorithm, accuracy is not enhanced as expected due to hardware and calibration maximal precision. Additionally, the fusion output shows objects in the common field of view, cutting the woman out of the resultant fusion output despite being present in one sensor’s images. Further information regarding the fusion algorithm can be found in Urbain, 2014.¹⁰

Figure 10. ORF Point Cloud, viewed forward (left) and top-down (right), showing how the INSPECT sensors can obtain 3D point clouds with shadow areas (visible in the right image) behind objects nearer to the sensor.

Figure 11. Fusion Image of VERTIGO and ORF Data, viewed forward.

Based on the individual sensor images, several performance factors of the sensors related to the quality of the resulting sensor images for use in post-processing and fusion algorithms can be assessed in order to optimize the design of a fusion algorithm, as discussed in Table 3.
Table 3. Performance Metrics for INSPECT Sensors

<table>
<thead>
<tr>
<th>Performance</th>
<th>ORF</th>
<th>VERTIGO</th>
<th>ThermoCam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>Omnipresent noise</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Linearity</td>
<td>Non-linear with object speed and distance</td>
<td>Non-linear with object textures</td>
<td>Linear</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Sensible to luminous noise, saturation and movement</td>
<td>Sensible to the lack of texture in the environment</td>
<td>Low sensibility</td>
</tr>
<tr>
<td>Resolution</td>
<td>Medium spatial resolution and good temporal resolution</td>
<td>Good spatial resolution and bad temporal resolution (computation)</td>
<td>Bad spatial resolution and very good temporal resolution</td>
</tr>
<tr>
<td>Reliability</td>
<td>Result guaranteed (but quality can be poor)</td>
<td>Result not always guaranteed</td>
<td>Result guaranteed</td>
</tr>
<tr>
<td>Range</td>
<td>Very limited</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

The RGA campaign revealed several limitations of the sensors concerning image acquisition. Four principle limitations will be discussed here. First, the short duration of active sensing by the ORF to avoid interference with the SPHERES metrology system decreases the resultant depth accuracy. This phenomenon subsequently was investigated on the ground as shown in Figure 10. Future testing will be conducted taking into account the lower confidency of the ORF sensor data resulting from operating the sensor at less-than-peak infrared illuminations owing to the constraints imposed on account of SPHERES satellite-based operations.

Figure 12. Effect of Infrared Illumination on ORF Confidency: Low Illumination (Left) and High Illumination (Right). A good confidency in depth measurements corresponds to light pixels whereas dark pixels stand for bad confidency

The RGA campaign also illustrated limitations regarding range and auto-exposure when the target is in close proximity to the ORF. When the target satellite is less than approximately 0.75m from the ORF, the confidence
decreases on the depth value computed for each point on the target. The team plans to improve performance by accounting for this effect during the fusion and by finding a balance between auto-exposure time and depth accuracy.

A third limitation is based on relative sensor/target motion. Excessive motion during sensor integration produces errors in depth estimation. The speed of the motion during the RGA campaign because of difficulties with initial placement owing to the short duration of microgravity per parabola and the acquisition delay between cameras of approximately 100 ms leads to objects moving between image acquisitions across all three sensors, an effect seen in Figure 13. This delay is difficult to remove through software, since the delay is processing speed dependent. Should the processor need to perform more or less functions, then the delay period can vary accordingly. The images in this figure were captured as synchronously as possible but given the 146ms of software acquisition, the INSPECT system had rotated too much to perform fusion. Using calibration parameters to match points from VERTIGO and the ORF becomes then impossible to do. Possible means to reduce the motion effect are to either adapt the fusion algorithm to account for the rotation when performing the data fusion step or to investigate ways to make the image capture be completely synchronous across all sensors. Both of these options are feasible but add complexity.

Figure 13. Sample Images Showing Too Rapid Relative Movement between Target and INSPECT Satellites (left to right: ORF visual image, VERTIGO left image, VERTIGO right image)

Finally, field-of-view constraints have also been observed: the full target satellite is visible to all three sensors for a comparatively short duration across the campaign. To mitigate this issue, the team plans to carefully develop controllers and test plans, as well as adapt the fusion algorithm to incorporate non-fused points into the output points cloud.

Summary of RGA Testing Results
The post-flight data analysis supported the following conclusions regarding sensor and fusion algorithm performance.

- The precision of the calibration conducted on the ground prior to the campaign tests to obtain precise relative locations of each sensor led to less-than-desired accuracy upon conducting sensor fusion with the current version of the algorithm.
- Certainty is affected by the depth errors provided by the ORF, which are generally affected by relative movement, exposure, and range to target.
- A trade between depth point cloud completeness and processing time must be performed.
- The fusion should include points beyond the subspace framed by all cameras in order to avoid constraints on the fusion image’s field-of-view.

INSPECT System Identification
Control algorithms for INSPECT system operations in microgravity require knowledge of mass properties including center of mass (CM) and moment of inertia. Both properties can be estimated by observing the effects of known thruster impulse forces on SPHERES Inertial Measurement Unit (IMU) accelerometers and gyroscopes during microgravity parabolas of the flight campaign.

During the first and second flights of the campaign the INSPECT system was commanded to perform a series of thruster actuations. Each actuation consisted of a fixed-time firing of a pair of thrusters oriented either along the same direction or in opposite directions separated by a moment arm. In the first case, the pair of thrusters together apply a force vector to the system, while the second case applies a torque to the system. Another way of describing the thruster
actuations used for the system identification is that if the INSPECT system had a center of mass at the SPHERES coordinate system origin with a spherically symmetric moment of inertia, then thruster actuations would result in either linear acceleration of the system along the SPHERES x, y, or z axis, or angular acceleration of the system along the x, y, or z axis.

Center of mass was estimated in the following manner: first, all accelerometer and gyroscope data was filtered and the average acceleration amplitude response (linear and angular) was measured for each thruster firing pulse; next, the average force of the thrusters were calculated from the system mass and average acceleration of each thruster pulse (see Equation 1 below); subsequently, a least squares approximation for the distances from each single-axis accelerometer to the center of mass was conducted using a decomposition of thruster forces as shown in Equations 2-4 below; finally, the known locations of the accelerometers with respect to the SPHERES coordinate frame were used to measure the INSPECT system’s center of mass.

Key equations governing the center of mass and moment of inertia calculations are listed below.

1. Thruster force

\[ F_{\text{pulse}} = m_{\text{system}} a_{\text{pulse}} \]  

(1)

Where \( F_{\text{pulse}} \) is the nominal thruster force per pulse, \( m_{\text{system}} \) is the INSPECT system mass, and \( a_{\text{pulse}} \) is the response acceleration from a thruster pulse.

2. Decomposition of INSPECT system linear forces

\[
\begin{align*}
F_x/m &= a_x + a_x r_y - a_y r_x \\
F_y/m &= a_y + a_x r_z - a_z r_x \\
F_z/m &= a_z + a_y r_z - a_x r_y
\end{align*}
\]  

(2-4)

Where \( F \) is reaction force, \( m \) is the system mass, \( a \) is linear acceleration measured at one of SPHERES’ accelerometers, \( r \) is the moment arm from the system’s center of mass to the location of accelerometer considered, and subscripts refer to SPHERES coordinate frame axes (x, y, and z). Solving for the moment arm distances can thus be performed using a least squares analysis to determine the INSPECT center of mass.

The moment of inertia of the INSPECT system was measured by using known thruster locations and measurements for average thruster force (Equations 5 and 6). Since the INSPECT system is operated predominantly by executing CMG-induced rotations about the z CMG axis (see Figure 3), determining the z direction moment of inertia is of primary importance.

3. Torque computation

\[ \tau = 2 F_{\text{pulse}} d \]  

(5)

Where \( \tau \) is the torque applied to INSPECT system, \( F_{\text{pulse}} \) is the average thrust of a single thruster pulse, and \( d \) is the moment arm between actuated thruster pair.

4. Moment of inertia computation

\[ I_z = \tau_z a_z \]  

(6)

In this equation, \( I_z \) is the mass moment of inertia of INSPECT about the SPHERES z-axis, \( \tau_z \) is the z-axis torque response of the system, and \( a_z \) is the z-axis angular acceleration response of the system.

With these equations, the offsets from the system’s geometric center were computed to be: 4.4cm in x, -1.5cm in y, and 4.6cm in z. Additionally, the moment of inertia about the z-axis was computed to be -0.398 kg-m². These values were determined entirely based off least squares estimation of the data acquired from the SPHERES onboard accelerometers and gyroscopes, and further testing will improve the precision and accuracy of these calculations.

**CMG Validation**

Open-loop commands were sent to the CMGs during the last flight of the campaign in order to validate the capability of the CMG subsystem to provide torques to the INSPECT system that would adequately enable INSPECT to maneuver during inspection operations. Angular rates between 0.1-1.5 rad/s (3 deg/s – 43 deg/s) were observed in microgravity for the CMGs, which demonstrates that the selected actuators are capable of quickly changing the attitude.
of the INSPECT system. The continuous control inherent to CMG operation as compared with the fixed-bandwidth actuation control available with thrusters was also demonstrated using open-loop torque maneuvers.

Unfortunately, technical progress was impeded during the flight campaign by unforeseen hardware complications. The result was a severe restriction to the duration and type of CMG testing that could be afforded in a reduced gravity environment.

C. Proposed Future Reduced Gravity and ISS Testing and Expected Results

Second RGA Campaign

A second INSPECT RGA campaign is planned for summer 2015. This campaign is planned to expand upon the research conducted both on the ground and aboard the first campaign, with the following priorities, listed in order of importance: 1) CMG characterization, 2) system identification with and without CMGs, 3) sensor operation with thrusters, CMGs, and combined thrusters and CMGs. As in the last RGA, a sensor target satellite will accompany the SPHERES-INSPECT system. CMG characterization will focus on the use of the box-90 configuration CMGs in order to determine the precise nature of torques that can be induced and how those torques compare with expected torque values. These torques will be measured by analyzing the gyroscope data from the SPHERES IMU and computing the induced torques using experimentally derived moment of inertia values, which themselves will be obtained from thruster firing sequences designed to cause specific rotations about each axis.

During the second INSPECT RGA we will also test gimbal homing and saturation limitations imposed on the control system. Additionally, the campaign will enable the experimental determination of corresponding disturbance torque rejection requirements for the thruster subsystem of SPHERES. During this process, the team will assess differences in propellant consumption by running two systems, one INSPECT system with CMGs and one INSPECT system with mass mock-ups instead of CMGs and collect reduced gravity, 6DOF data. System identification will use the CMGs and thrusters to induce torques and forces to continue the system identification from the first RGA and obtain more accurate center of mass location data as well as the moments of inertia characteristics for the remaining two axes. The last objective will test the entire INSPECT system operating in concert to determine interface characteristics between the sensors and actuators, with particular focus on motion blur and target framing, thereby characterizing the effect of slew and tumbling of the inspection and target satellites and sensor integration times on image quality.

ISS Testing

Following the ground and RGA2 testing, a testing sequence aboard the ISS will enable INSPECT to operate in an environment with the most direct traceability to space operations: long duration microgravity enabling full 6DOF motion. This testing will be planned to continue the technology maturation of the INSPECT system and the associated software and algorithms through incremental and iterative testing that capitalizes upon the ISS environment. The focus of the ISS testing phase will be on the use of the CMGs to maneuver the INSPECT system in close proximity to other satellites and to the boundaries of the test volume in order to conduct tests that are directly traceable to EVA inspection, characterization, and navigation missions. Testing will begin with validation of ground and RGA tests before proceeding to more complicated mission scenarios.

Because the ground and RGA testing focuses on gathering sensor data and demonstrating that the CMGs could be commanded, the first ISS testing will use build upon these technological capabilities and demonstrate that the entirety of the INSPECT system can function as an integrated system with all peripherals operating in concert. Once this basic functionality is demonstrated, the MIT team will use the long duration microgravity to perform vision navigation maneuvers utilizing the CMGs to reduce the amount of required propellant, thereby extending the potential duration of individual tests. Additionally, these tests will demonstrate the ability of the INSPECT system to safely maneuver without the need for the SPHERES ultrasound-based metrology system that is used for position and attitude determination. By maturing highly capable sensor fusion algorithms, the INSPECT system will be able to efficiently maneuver with a combination of thruster and CMG actuation while using multi-spectral imaging for navigation and mapping. These techniques will enable full mission scenario demonstrations.

Mission scenarios for INSPECT aboard the ISS focus on meeting the demands of the HEOMD future autonomous inspection and characterization system requirements. In order to demonstrate technologies required for these missions, INSPECT will perform its own inspection and characterization missions with the target ranging from another SPHERES, an astronaut, the interior wall of the ISS module, or any other object that may be placed within the SPHERES operational volume. These targets can vary in their size, color, thermal properties, motion, or depth complexity. Increasingly challenging targets can be provided to demonstrate the robustness of several algorithm classes, ranging from those required for testing target tracking during inspector movements, identification of elements.

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on the surface of the target, or comparing the images it acquires with a pre-defined map to characterize discrepancies and consequently determine failures of the target object, among others. These mission scenarios, by being prototypical for future EVA missions, can be performed within the risk tolerant ISS test volume using the INSPECT system, thereby allowing algorithms to be matured using flight data from the relevant space environment of extended microgravity.

IV. Conclusions and Future Work

The August 2014 flight campaign for SPHERES extended the capabilities of the satellites by validating a new sensor and actuator suite configuration that had not yet been tested in a microgravity environment. The test allowed the SPHERES facility to advance a modular approach to satellite sensing and actuation, since the use of each sensor or actuator may be operated independently of the others. Additionally, the integration of all data across each component allows for detailed analysis of sensor fusion for mapping and navigation in a full 6DOF microgravity environment. Several hundred image sets were obtained from all three sensor systems operating in the relevant environment of microgravity with 6DOF motion, and the system center of mass and principle moment of inertia were determined.

Additionally, using the data from the flight testing, the team has been able to determine areas for improvement of the entire INSPECT system in advance of ISS operations. For example, while the sensors themselves may be considered commercial off the shelf (COTS) components for the INSPECT system, their mounts are custom designed. These will need modifications to allow improved access to control switches and cable access. Additionally, while the CMG hardware is nearly complete, extensive software development is required prior to final implementation with the SPHERES satellites on orbit.

Because of the RGA testing, the INSPECT system has been able to mature several technologies associated with robotic servicing and assembly, system identification, robotic assistants, and attitude control, among others. These technologies can be applied directly to a multitude of future missions in Low Earth Orbit both inside and outside the ISS, Geostationary Orbit, and beyond. Examples of such missions include autonomous astronaut assistants, asteroid characterization for sample retrieval, leak detection and repair, and sensing systems for close inspection during multi-satellite operations with close proximity operations. The reduced gravity flight campaign was an invaluable tool for laying the foundation for these exciting future developments.

INSPECT testing will continue to provide risk reduction to ensure that a similarly sized and equipped EVA satellite will be able to navigate safely around the ISS. The CMGs of the INSPECT suite, however, are only capable of providing rotational motion; translational capabilities are provided strictly by the carbon dioxide thrusters on the SPHERES satellite. An INSPECT-derived EVA system will likely exhibit a similar actuator topology to maximize the traceability from testbed to flight system. One of the most critical concerns, however, is that of the safety of the ISS should an unintended actuation by the thrusters lead to an impact between the ISS and the EVA system. A detailed hazard analysis will need to be conducted to ensure the safety of the ISS should such an error arise; the analysis would incorporate the inspector thrusting capabilities, structural rigidity, operational envelope, and safeguards, as well as the ISS structure surrounding the operational zone. Such studies can only be effectively performed with knowledge of proposed concepts of operation and EVA satellite systems, as was performed with the INSPECT system itself for operation aboard the RGA and the SPHERES facility aboard the ISS. Regardless of these factors, the INSPECT sensor and actuator suite will provide IVA testing to reduce these and other risks associated with EVA operations.

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