THE SPHERES VERTIGO GOGGLES: VISION BASED MAPPING AND LOCALIZATION ONBOARD THE INTERNATIONAL SPACE STATION

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ABSTRACT

The Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) are an experimental testbed for guidance, navigation and control algorithms that has been operated, by astronauts, inside the crew volume of the International Space Station (ISS) since 2006. In October 2012, the MIT Space Systems Laboratory and Aurora Flight Sciences will launch a vision based navigation upgrade to the SPHERES satellites that will perform visual mapping and localization inside the ISS.

1. INTRODUCTION

This paper will present the design and status of the Goggles developed under the Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) Program. It will also present the details of a set of algorithms designed for location and mapping of an unknown, uncooperative and possibly moving and tumbling target object. Additionally, it will present preliminary ground based experimental results that will be used ahead of ISS experiments to validate the algorithms and their implementation.

2. SPHERES

The Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES[8, 9, 11], shown in Figure 1) are a set of volleyball sized micro-satellites that have been operating inside the International Space Station (ISS) since 2006. The SPHERES satellites are considered a research and development testbed for guidance, navigation and control algorithms for formation flying satellites. In the past 6 years, MIT has held 32 test sessions onboard the ISS covering research topics such as rendezvous and docking, formation flight, decentralized control, satellite reconfiguration, inertial navigation and other research areas. Additionally, the SPHERES satellites have been used for national and international STEM programming competitions where middle and high school students have programmed the SPHERES satellites that are on-orbit[12].

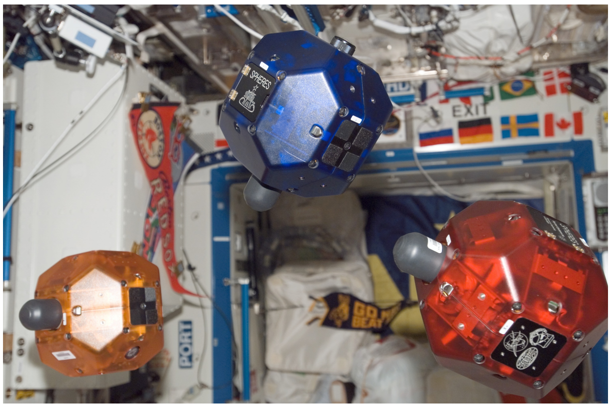

Figure 1. The SPHERES Satellites inside the ISS

The SPHERES satellites are designed as a small satellite bus. Some of the detailed features are shown in Figure 2. They weigh 4.16 kg and are 21.3 cm in diameter. They utilize a carbon dioxide (CO2) cold gas propulsion system to produce both forces and torques. A "pseudo-GPS" ultrasonic time-of-flight sensing system is use with onboard gyroscopes to estimate the position, orientation, linear and angular velocity with respect to the interior of the ISS. A Texas Instruments C6701 Digital Signal Processor is used to perform onboard computations and a 900 MHz low bandwidth modem is used for communication with the laptop that is used by the ISS astronaut. The entire SPHERES satellite is powered by 16 AA non-rechargeable batteries.

3. LIIVE GOGGLES

In 2008, the MIT Space Systems Laboratory began a program to develop an upgrade to the SPHERES satellites that would allow it to perform vision based navigation experiments onboard the ISS. This was the Low Impact Inspection Vehicle (LIIVe) program that was sponsored by the Office of Naval Research and the Naval Research

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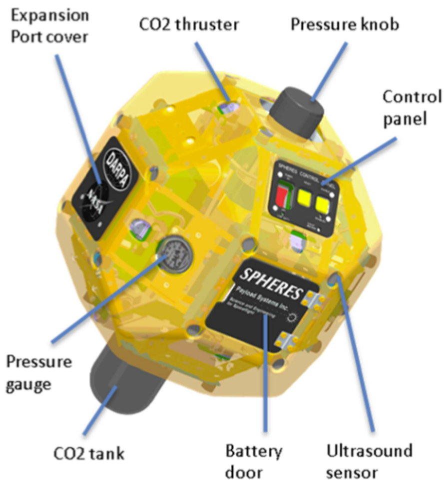

Figure 2. Details of the SPHERES Satellite

Laboratory. This program's intent was to develop a high-fidelity prototype of the hardware that could be launched to the ISS under a future program. This program resulted in the design and fabrication of the LIIVe Goggles, shown in Figure 3.

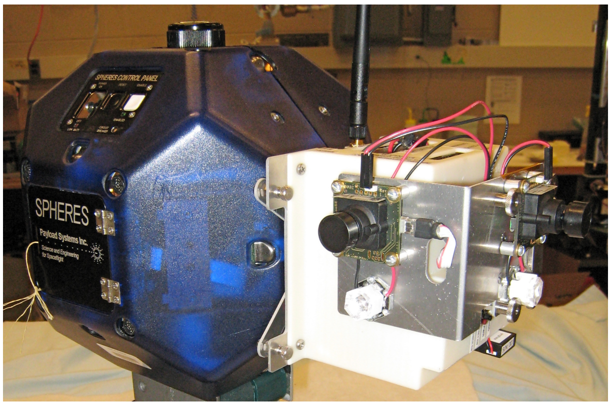

Figure 3. The LIIVe Goggles

The LIIVe Goggles add two grayscale cameras (in either stereo or right angle configurations), a 1.0 GHz Via C7 x86 microprocessor, a 16GB flash drive, illuminating LED lights, an 802.11g network card and lithium polymer batteries to power the Goggles[15, 14]. Under the LIIVe program a number of vision based navigation experiments were performed for both cooperative and non-cooperative target inspection[3, 13].

4. VERTIGO GOGGLES

In 2010, the MIT Space Systems Laboratory and Aurora Flight Sciences began a DARPA sponsored Visual Estimation and Relative Tracking for Inspection of Generic Objects (VERTIGO) program. This program was to refine and launch the Goggles developed under the LIIVe program as well as perform additional research on inspection of unknown, non-cooperative targets that are possibly moving and tumbling. The Goggles received a number of minor tweaks and upgrades. The final ISS-flight version of the Goggles are shown attached to a SPHERES satellite at the MIT Space Systems Laboratory in Figure 4.

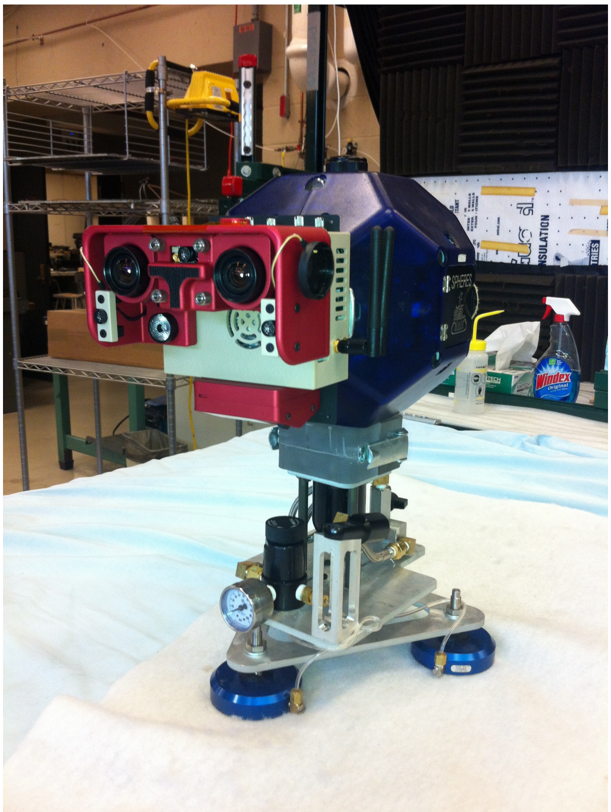

Figure 4. The VERTIGO Goggles attached to the SPHERES Satellite

The processor was upgraded to a Via 1.2 GHz Via Nano, the network card was upgraded to 802.11n, the battery was changed to a unit that was already onboard the ISS, and the optics were upgraded to a larger aperture lens that was in a synchronized stereo configuration. An additional flash drive was added to create a total of 128 GB of storage space. The mechanical design was refined to meet the requirements of operations inside the ISS. Figures 5 and 6 show different components of the Goggles in their CAD model.

The schematics for the Goggles electronics system and the overall integrated layout is shown in Figure 7 and 8. The average power consumption of the Goggles is approximately 24 Watts, but can vary between 14 and 30 Watts depending on the system load.

One of the main design features of the Goggles is future upgradeability. The design incorporates two methods for upgrading future systems. The first is a detachable Optics Mount (the red block containing the cameras and LEDs in Figure 5 and 6). The Optics Mount contains the CMOS

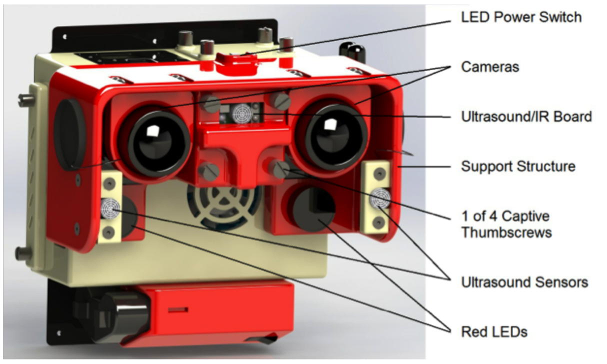

Figure 5. Illustrated Front View: CAD Model of VERTIGO Goggles

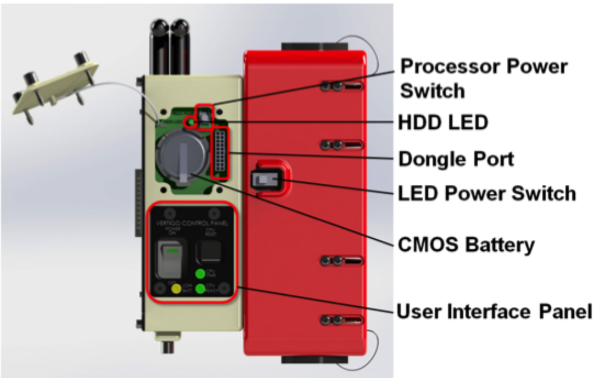

Figure 6. Illustrated Top View: CAD Model of VERTIGO Goggles

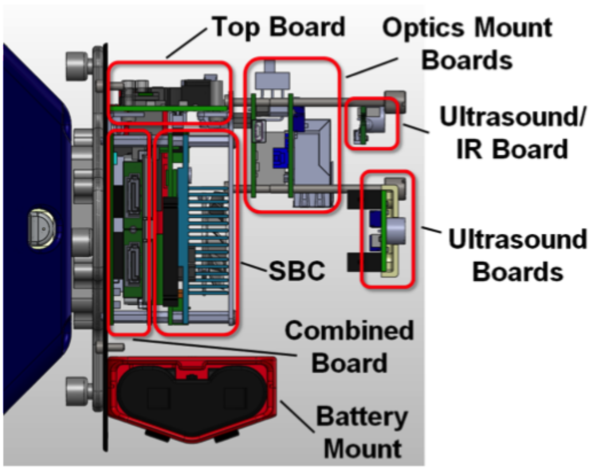

Figure 7. Cutaway Diagram of Integrated VERTIGO Goggles

camera sensors, lenses, illuminating LEDs and additional circuitry. The interface between the Goggles Avionics Stack and the Optics Mount is an electro-mechanical connection. The mechanical connection consists of four captive thumbscrews which can be removed to detach the optics mount. The electrical connection provides 12 Volt power, USB, ethernet and RS232 data to interface with

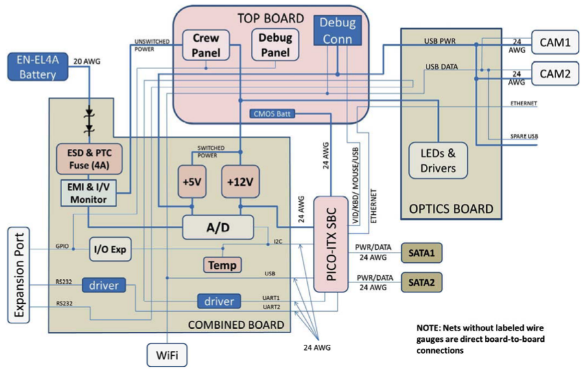

Figure 8. Electronics System Diagram of VERTIGO Goggles

the SPHERES and Goggles. The Optics Mount could be replaced by another piece of hardware that has different sensors or other capabilities. Example upgrades could include cameras in a different configuration or different model, or could even contain a different sensor system entirely (i.e. a LIDAR system). The second method for upgrading the Goggles is via the 802.11n connection. Off-board processing systems could be added that process the images that are captured by the Goggles and streamed over the wireless network.

5. VERTIGO GRAPHICAL USER INTERFACE

One of the most important aspects of the SPHERES satellites as a research testbed is that they are operated by the astronauts that are onboard the International Space Station. This allows them to supervise and monitor tests and algorithms that are being run on the SPHERES satellites. If a test should fail, the astronaut has the ability to abort and rerun the same or a different test. One of the challenges and successes of the SPHERES program is to provide a user interface and training for the astronauts (who are unlikely to have a detailed background in spacecraft robotics), that allows them to operate the SPHERES satellites effectively.

The VERTIGO program will mirror the operational model that has been successfully utilized by the SPHERES program. The main component of this is that an upgrade for the SPHERES GUI has been developed to operate the VERTIGO Goggles. This upgraded Graphical User Interface (GUI) is shown in Figure 9.

In addition to monitoring a number of status and state of health variables, the VERTIGO GUI adds the ability to stream video from the Goggles to the SPHERES GUI either via ethernet or 802.11. This allows the astronaut to monitor what the Goggles are seeing in real-time. This is implemented as a TCP server on the astronaut's laptop that can receive a stream of OpenCV images. These images are programmable by the Goggles so that they can either be the raw images from the cameras, or an inter-

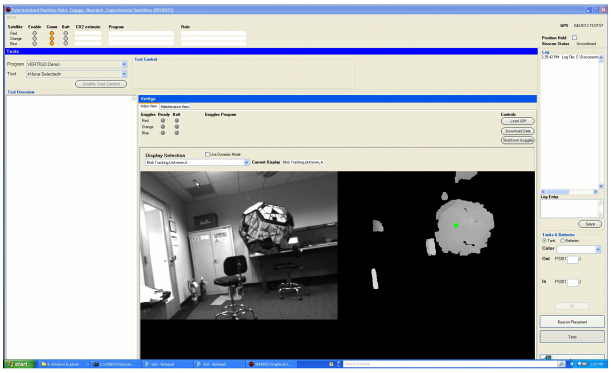

Figure 9. SPHERES GUI with VERTIGO Plugin

mediate processing stage (Figure 9 shows a raw image on the left and an processed depth map on the right). The astronaut can select from a number of different streaming modes that are provided by each individual test program.

The GUI also allows the astronaut to run a set of maintenance mode scripts. These scripts are shell scripts that can be executed in the linux environment, which are prepared by the researcher or payload developer approximately 2 weeks prior to being run by the astronaut on the ISS. These scripts can be as simple as checking network configurations or removing old data files, or as complicated as running a camera calibration routine that streams video to the GUI.

6. VERTIGO PROGRAM STATUS

The VERTIGO Goggles flight hardware was built and passed internal functional testing on July 3, 2012. It will be delivered to the Department of Defense's Space Test Program on August 2, 2012 to be prepared, shipped and launched on a Soyuz spacecraft from the Baikonur Cosmodrome in Kazakstan. It will be launched on TMA-06M which is currently scheduled for October 15, 2012. TMA-06M will also carry Oleg Novitskiy, Evgeny Tarelkin and Kevin Ford to the ISS. VERTIGO is scheduled to be operated by NASA astronauts Kevin Ford, Karen Nyberg, Thomas Marshburn and Christopher Cassidy during Expeditions 33-36.

7. VERTIGO RESEARCH PROBLEM: LOCALIZATION AND MAPPING OF AN UNKNOWN, UNCOOPERATIVE TARGET

The first research problem that will be experimentally tested with the VERITGO Goggles is how to map and navigate with respect to an unknown, uncooperative, moving and possibly spinning target. In many cases these target objects may be in a configuration that is unknown and unexpected. This means that a priori models of appearance and geometry may not be valid. To further compound the problem, the target object may be tumbling or spinning at an unknown, and possibly variable, rate.

A notional concept of operations is shown in Figure 10, where one SPHERE with Goggles is inspecting another SPHERE. It is important to note that the target SPHERE has a set of textured stickers applied to it to increase the visual texture, however the visual pattern is not preprogrammed into the algorithms. This allows the Goggles cameras and image processing algorithms to better pick up the target object. Initial testing will begin with these textured stickers and later move to completely unknown objects. This is considered acceptable, since the interior of the ISS is not a photo-realistic representation of on-orbit visual lighting and texture conditions.

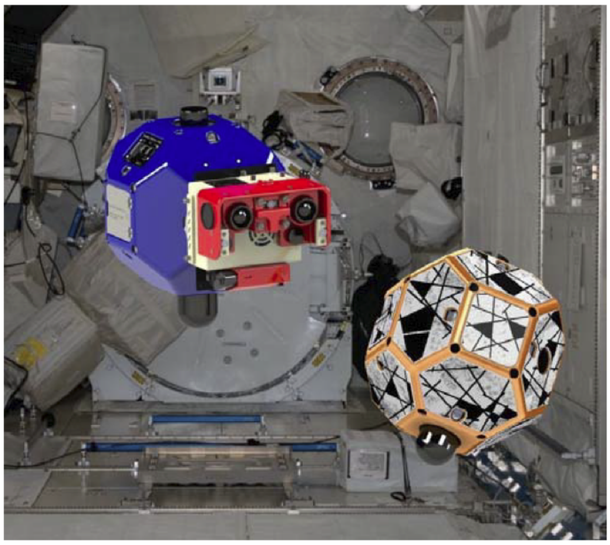

Figure 10. CAD Visualization of Inspection of Target Object Onboard ISSS

In order to demonstrate vision-based navigation with respect to a non-cooperative target, the authors are planning to use a three-phase approach, which is illustrated in Figure 11. In the first phase, the SPHERES satellites will use a simple image-processing algorithm (stereo centroiding) combined with rate gyroscopes to traverse an inspection path around the target object with a safe keep-out zone. This algorithm has already been demonstrated onboard the ISS using simulated vision data [10].

In the second phase, the VERGTIGO Goggles will post-process the images that were captured in the first inspection phase to build a three-dimensional map of the target object. We have developed a set of algorithms that uses custom designed algorithms as well as open source libraries to build a map of a target object and estimate the trajectory of the inspector. It is assumed that this target object is static and a trajectory of the inspector is estimated in a reference frame that is relative to this target object. This approach is illustrated in Figure 12. The system primarily makes use of OpenCV[2], Fovis[5] and iSAM[6, 7].

The first stage of this second phase is to perform a visual

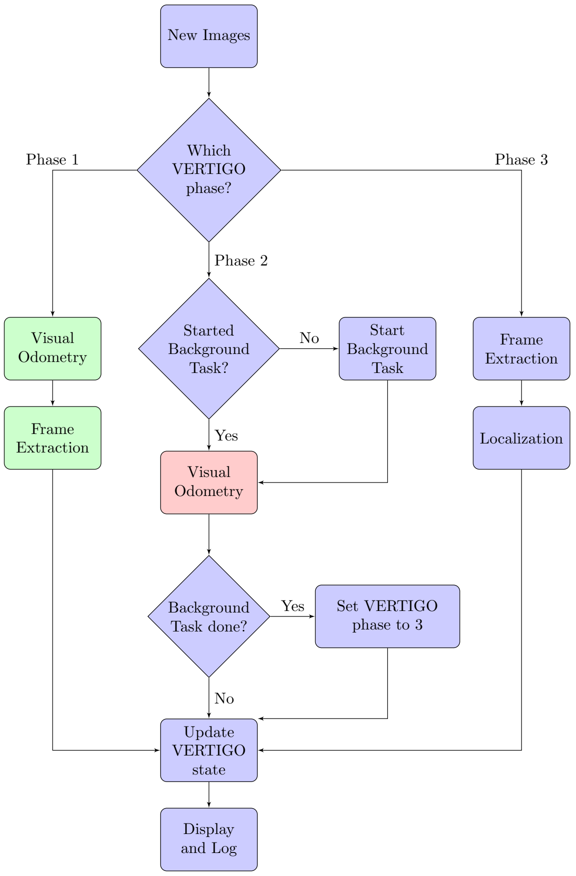

Figure 11. Uncooperative Spacecraft Inspection: 3 Phase Flowchart

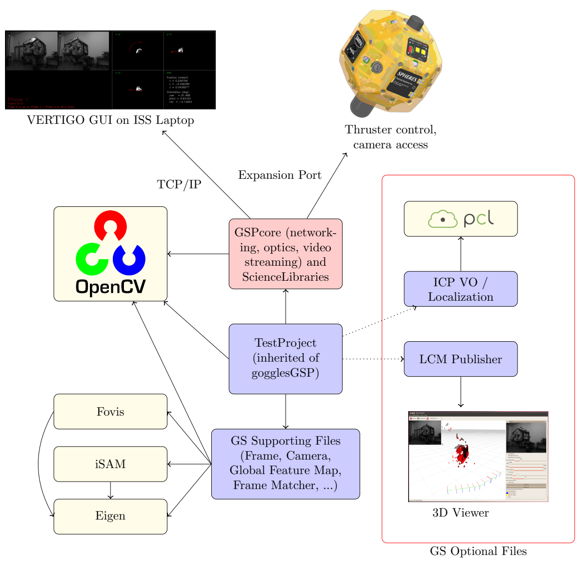

Figure 12. Uncooperative Spacecraft Inspection: Software Architecture and Libraries

odometery processing step using Fovis to estimate a trajectory for the inspector vehicle in a relative frame. Next a set of feature points (i.e. SURF features) are mapped in three dimensions using a loop closure step. This loop closure step builds a pose-graph network using constraints obtained from a RANSAC based Absolute Orientation[4] solution. This pose-graph network is then optimized using iSAM. The last step is to develop a factor graph that models the landmarks and poses so that the map can be built and finally optimized in a bundle adjustment step (using iSAM again as the optimization framework). The final step is to reproject the dense stereo depth map and the image colors into the three dimensional space so that a photo-realistic reconstruction can be made. The results of this process is shown in Figure 13.

Once the second phase of the algorithm has constructed a map, the third phase uses this map to perform relative navigation and control of the inspecting satellite. This step has been developed to use either a feature based Absolute Orientation solution or the Iterative Closest Point algorithm[1] to estimate the pose of the inspector relative to the target object. Once this is complete, the inspector will use this estimate for closed loop control and possibly path planning and/or docking.

8. CONCLUSIONS AND FUTURE WORK

In terms of the Goggles hardware and operational procedures, at the time of writing (July 2012) the VERTIGO team is currently finishing up testing the flight hardware and refining the operational software for launch delivery in early August 2012.

Since the research algorithms can be uploaded a few weeks prior to ISS operations, the VERTIGO team will continue to be developing, testing and refining a number of the research algorithms. The first major shortcoming of the current implementation of the research algorithms is the inability to handle fast moving and spinning objects. The current approach works well if it can be assumed that the target object is an inertial reference frame. However, there are a number of cases where the target object may be moving or spinning at high rates. The authors are currently researching new methods to accommodate these types of situations and estimate dynamic properties such as linear and angular velocities of both the target and the inspector as well as the inertial properties of the target object.

The second major shortcoming of the current implementation is the inability to handle more realistic visual conditions, such as low-texture and specular materials. The team is currently looking into global registration methods to attempt to solve these problems.

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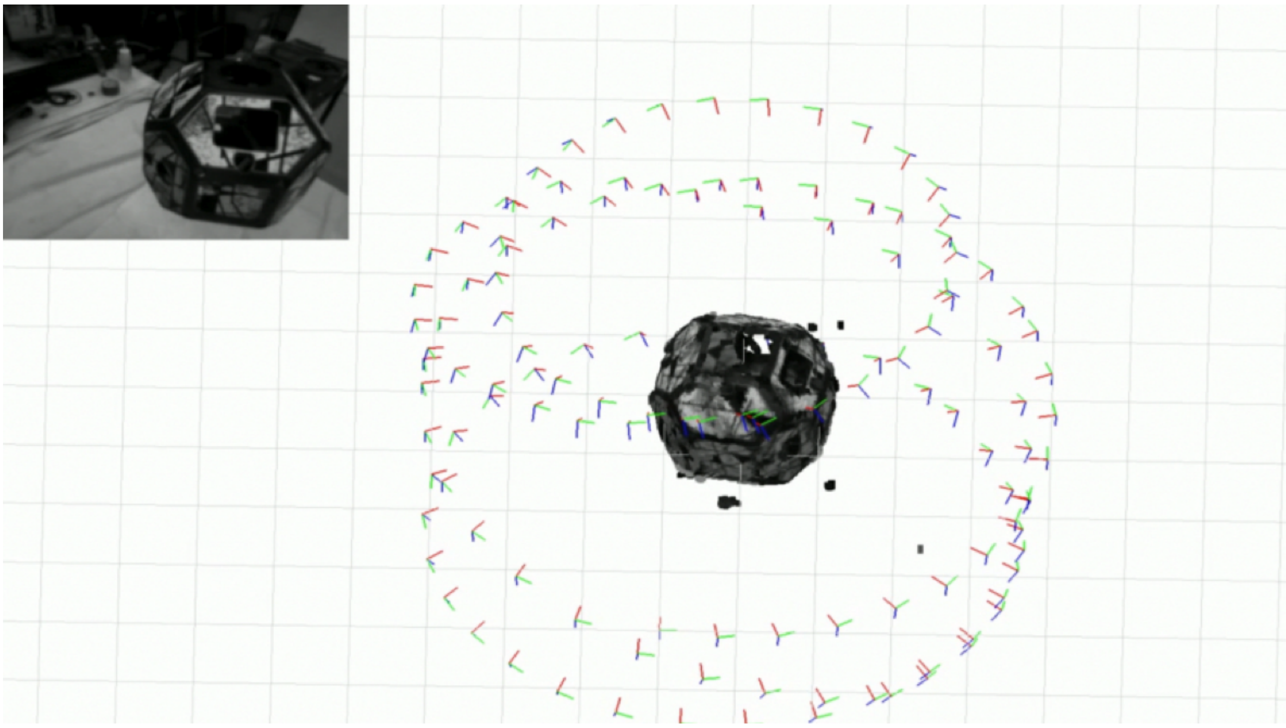

Figure 13. Inspector Trajectory and Dense Target Map

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