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COTS 3D CAMERA FOR ON-ORBIT PROXIMITY OPERATIONS DEMONSTRATION

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ABSTRACT

Space exploration and utilization trends demand efficient, reliable and autonomous on-orbit rendezvous and docking processes. Current rendezvous systems use heavy, power intensive scanning radar, or rely on transmitters/beacons from the host spacecraft. A possible alternative to these bulky legacy systems presents itself with the advent of highly efficient 3D cameras. These cameras, used as an input device for consumer electronics, provide an instantaneous 3D picture of a target without a complex mechanical scanning system. They are exceptionally compact and require little power—ideal for space operations.

Researchers at the United States Naval Academy are utilizing a 3D camera as an active ranging solution for on-orbit rendezvous and docking with targets that have not been embedded with retro-reflectors or similar visual aid devices. As the accuracy requirements of relative attitude knowledge do not change based on the size of the platform, tests can be completed using low-cost cube satellites. The research has two stages: 1) terrestrial testing, involving systematic parameterization of camera performance; and 2) on-orbit demonstration, expected in Spring 2018. A representative commercial, off-the-shelf camera, the Intel R200 was selected to serve as a demonstration unit. In the first phase, the camera's detection capability was tested on a variety of representative objects in a space like environment including eclipse, direct simulated sunlight, and in "off axis" sunlight. Test results are being used to develop an on-orbit demonstration plan. Two CubeSats will launch together, connected by a variable length tether. To test in situ performance, the R200 will be installed on one spacecraft, looking at the other. Terrestrial simulations will be compared to the on-orbit data to validate the testing method for future sensors. This paper will detail both the method and results from terrestrial testing and the concept of operations for the demonstration spacecraft launching in 2018.

INTRODUCTION

As the costs of launch, as well as the time between launches, continue to diminish, more and more national governments and commercial interests are exploiting space to enhance the human experience with respect to everything from communications to pharmaceutical applications. In what has become widely recognized as a crowded environment, the development and enhancement of autonomous proximity operations, specifically rendezvous and docking procedures, supports a number of exceedingly important functions:

1) the ability to monitor, inspect and even repair another spacecraft on-orbit, either by replacing failed components or fixing mechanical issues
2) the capacity to reposition satellites so they do not expend their own fuel for routine station-keeping maneuvers
3) the possibility of installing new capabilities on-orbit and thus upgrading existing buses with new technologies
4) the opportunity to interact with space debris, either with a view to modifying the orbit of, deorbiting or otherwise reusing or recycling the debris.

These functions would serve to extend the life of on-orbit satellites. They also provide the added benefit of maximizing launch operations and efficiencies, as component replacement or repair would provide a significantly lighter payload than an entirely new satellite.

Maximizing these efficiencies and providing the broadest reach for these capabilities requires an active ranging solution for utilization in on-orbit rendezvous and docking with so-called “non-cooperative” targets – targets that have not been embedded with retro-reflectors or similar devices.

Current Space Solutions

Many individuals and organizations have worked to take advantage of machine vision to assist in autonomous on-orbit rendezvous and docking operations. After all, if machine vision can control a drone in formation flight, track an Xbox player or drive a car, it should be able to locate an object in space. However, machine vision is not a “silver bullet” for rendezvous and docking. Machine vision in space faces challenges in respect of lighting, as well as standard small satellite platform limitations. Lighting on the target spacecraft will be incomplete; at most only half the spacecraft will be illuminated. Moreover, components will be shadowed – and those shadows will change rapidly, varying between extremely dim and bright in a matter of minutes. At times, the target may even be totally eclipsed. Similarly, background lighting will be variable: the camera will occasionally point directly at the sun and the target will be distorted by ambient light from heavenly bodies. Finally, in space, machine vision is constrained by standard spacecraft limitations including volume, mass and power.

However, there are significant “terrestrial” machine vision limitations that have no corollary in the space environment. First, terrestrial machine vision does a lot of work to determine which objects in field of vision are the target and which are not. And secondly, terrestrial applications are time-sensitive, something not usually as critical in space operations. Thus far, space application has been successful.

The August 2009 launch of the Space Shuttle Discovery, STS-128, marked the first flight of the “TriDAR Model-Based Tracking Vision System for On-Orbit Servicing.” The system was the first to focus on “non-cooperative” docking, eliminating the need to have retro-reflectors installed on the target spacecraft. Using a pair of laser-based 3D sensors, a thermal imager, and tracking software, TriDAR is capable of providing a relative vector to non-cooperative targets at ranges exceeding 30 km. The combination triangulation + LIDAR elements of the sensor functioned within 2.6 km. The system also proved tolerant to day-night transitions and functioned without human intervention. Tests on the final Space Shuttle flight, STS-135, successfully confirmed TriDAR’s ability to autonomously rendezvous and dock with non-cooperative targets in orbit. [1]

Nevertheless, active sensors based on LIDAR have been discounted due to their large weight and power consumption.[2] This has begun to change with the advent of “flash LIDAR” also known as a “3D Camera” which provides an instantaneous 3D picture of the target without a complex mechanical scanning system.[3] Thus, building on the proof of concept embodied in TriDAR, NASA Goddard has proposed a “non-scanning flash lidar 3D imaging system.”[4]

Similarly, Advanced Scientific Concepts has developed a 3D imaging Flash LIDAR camera that captures “Time of Flight” (ToF) information to provide range distance for each pixel in its sensor. This generates a real-time 3D representation of the scene without the need to scan or pan. The system has been demonstrated on SpaceX’s Dragon spacecraft, where it was used to rendezvous with the International Space Station.[5]

Recently, efforts have been made to reduce the scale of these sensors. Terrestrially, pmd technologies offers the first commercially available 3D CMOS image sensor. Designed to be incorporated into laptops and cell phones, the sensor is already extremely compact and optimized for low power consumption. Driven by a LED, the system is intended for extremely short ranges. Additionally, ToF cameras exist for automotive applications. Melexis (Microelectronic Integrated Systems) has a 320x240 pixel optical Time-of-Flight sensor that merely requires a light source between 800 and 900 nm.[6] Finally, Intel has developed a “RealSense” camera, designed as an input device for computers and tablets. Thus far, the limiting factor on this camera’s range is background detection and mitigation.

United States Naval Academy Solution

Researchers at the United States Naval Academy (USNA) seek to descope and compact the machine vision capabilities currently being demonstrated and utilized for space operations. Focusing solely on rendezvous and docking in a single target situational space environment, the goal is to create a 3D machine vision system that is descaled for a small satellite platform and optimized for single target capture. The ultimate objective is to provide accessible autonomous rendezvous and docking resources at the CubeSat level, without monopolizing either cost or functionality.

The sensor system was designed around typical CubeSat requirements which generally have tight mass, volume and power constraints. Representative notional constraints for the navigation subsystem are:

Size: Components shall occupy a volume of no more than 0.25U (250 cm^3)
Mass: The navigation system shall have a mass less than 500 grams.
Power: When active, the navigation system shall have an average orbital power consumption of less than 2 watts.

DESIGN OVERVIEW

Component Selection

USNA surveyed numerous commercially available 3D cameras to determine which would best serve as the basis for the proposed navigation system. The cameras were placed in three general categories:

Stereoscopic Imagers

Stereoscopic imagers use two cameras that are spaced a known distance apart. Stereoscopic vision works by taking two images at the same time from different perspectives. By determining the relative position of an object in each photo, and calculating the shift between perspectives, it is possible to determine the distance from the cameras to the objects. Objects that are closer to the camera have a larger shift, objects that are farther away have a smaller shift. The farther apart the cameras, the longer the effective range, at the cost of minimum distance. Typical maximum ranges are between two and five meters, and minimum ranges are between 0.2 and 0.5 m.

Stereoscopic imagery is best suited for complex objects with numerous features available for comparison. Without feature sets, there is no defined shift between perspectives, and therefore no way to calculate depth. Stereoscopic imagery accuracy is dependent on the fixed distance and mounting of the cameras. In the varying temperatures seen on orbit, this accuracy will most likely be degraded as the camera mount expands and contracts due to thermal loading. These cameras are relatively inexpensive and are very prevalent in terrestrial robotics. They have a low power draw.

ToF Cameras

A ToF camera is similar in operation to RADAR or LIDAR. It can be described as a “non-scanning flash LIDAR 3D imaging system” where a flash is used to illuminate the target, and a start pulse from the laser triggers the timer on a camera. The time it takes the light to travel from the emitter to the target and reflect back to a conventional camera will be measured and used to establish ranging information. The system is focused on applications in complex, obstacle-ridden environments. It works equally well on large flat objects and on complex ones. It is not affected by dark environments. Range is limited by the flash intensity.

ToF cameras use more power than stereoscopic imagers and are more susceptible to interference from outside lighting sources.

Hybrid Cameras

Hybrid cameras utilize both ToF and stereoscopic properties. They pair a fixed projector with stereo cameras. For complex, well-lit objects, the stereoscopic cameras operate normally. In the dark or with featureless objects, a projector projects a pattern to add features to the objects in view. These features are used by the stereoscopic cameras to determine range. Generally, a combination of distance data from both sources is used to determine object location.

Overall system range is limited by both the separation of the cameras and the power of the projector. Increasing either or both will increase range. Hybrid cameras share the larger power draw with ToF cameras but are also equally capable of operating in the dark.

USNA Selection

USNA elected to use a hybrid camera in its navigation system because of the camera's ability to interact with large featureless flat planes (solar panels, side walls, etc.) in dark lighting conditions while maintaining the high-intensity lighting benefits of stereoscopic imagery. The hybrid camera is also the most promising for range extension without compromising close-in performance by merely upgrading the projector.

Exhibit 1: Internal view of Intel R200 3D Camera.[7]

The USNA 3D camera system is based on the Intel R200 RealSense 3D camera. A cross section of the Intel R200 is shown in Exhibit 1. The Intel R200 has three cameras on it: Two infrared or IR cameras spaced approximately 8 cm apart for stereoscopic vision, and one RGB camera for image recognition. These cameras are paired with an IR laser. The IR laser emits a fixed pattern recognizable by the cameras. This adds detail to items that otherwise would not be suitable for stereographic imagery. A depth stream contains depth information for every pixel in the array. The R200 generates this data using its two IR cameras paired with the IR laser. The primary depth calculation is completed using stereoscopic vision. To ensure the ability to gather depth from a wide variety of objects, the R200 also uses an IR laser projector. [7]

PERFORMANCE VERIFICATION

The R200 was designed to be embedded in a consumer laptop or tablet and used for basic computer interactions. It was certainly not designed for the space environment. USNA's small satellite program has extensive experience flying non-space parts in CubeSats and focuses on three areas when determining a part's space suitability.

1. *Temperature Suitability:* Beyond the harsh temperatures in LEO (nominally -20 ^{o}C to 70 ^{o}C), components are not able to remove heat convectively in the vacuum of space. In this environment, it is very likely that non space-grade components will overheat.
2. *Vibration Suitability*: Launch is the most challenging mechanical environment for systems. Items must be able to survive the trip to space.
3. *Space Environment*: The space environment is a challenging area to operate. Without the earth's protective atmosphere, sensors are subjected to radiation, 33% more sunlight, and various vacuum effects.

The sensors ability to perform in under these conditions must be validated prior to flight to ensure that the component will survive in space. The thermal performance of the sensor was evaluated based on the manufacturer's specification. The camera is rated to operate between 0 and 50 ^{o}C and can be stored in temperatures ranging from

-40 to 70 ^{o}C. Using relatively short operating times, there is little concern about thermal overload in normal LEO conditions. [7]

As the camera is monolithic, and has no moving or removed parts, its vibration suitability is already high. It is built for an active lifecycle in devices that typically see a lot of damage (tablets/laptops), and as such is not considered a risk for launch.

The radiation environment in LEO is benign enough that CubeSats routinely used COTS equipment without major impact to the mission. The adverse lighting conditions are of concern, however. Testing was conducted to determine the sensors efficacy.

TEST RESULTS

R200 Testing

In the first phase, the camera’s detection capability was tested on a variety of representative objects in a space like environment including eclipse, direct simulated sunlight, and in “off axis” sunlight.

Initial test

The objective of the initial test was to create a “worst case”' baseline test to establish the sensor's suitability for the orbital environment. Testing was conducted at night outdoors to minimize reflected/ambient light, as shown in **Error! Reference source not found.**2. The test object was a “plus” shaped solar panel. Three 500W halogen lights were used to simulate solar flux.

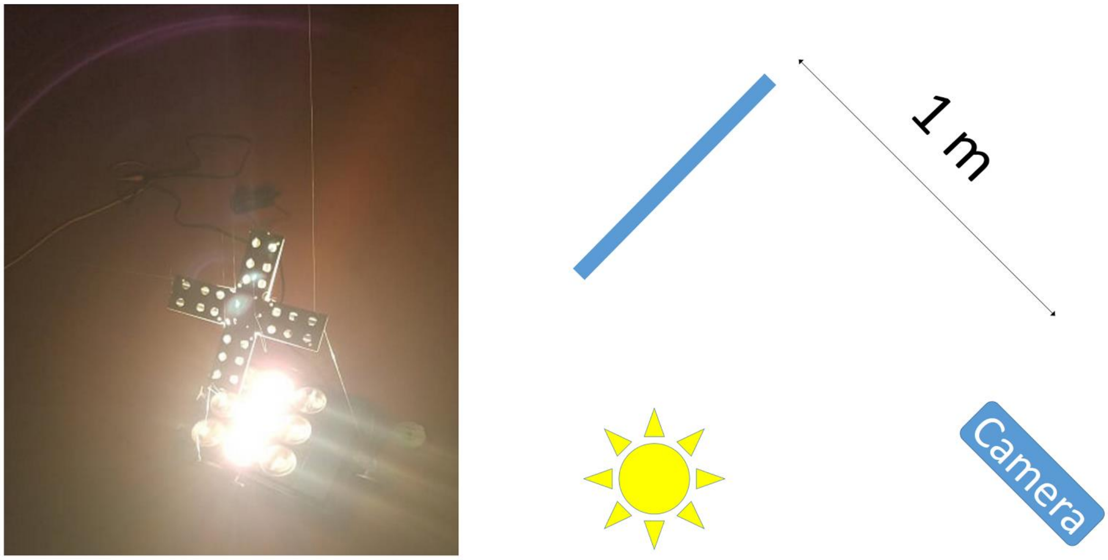

Exhibit 2: R200 Camera Test Setup

This configuration produced the following results, shown in Exhibit 3. The solar panel is easily visible in no-light conditions. As the light increases, it becomes increasingly difficult to see the target object. The conclusion of this testing was that the sensor was not ready to operate in an orbital environment without better characterization.

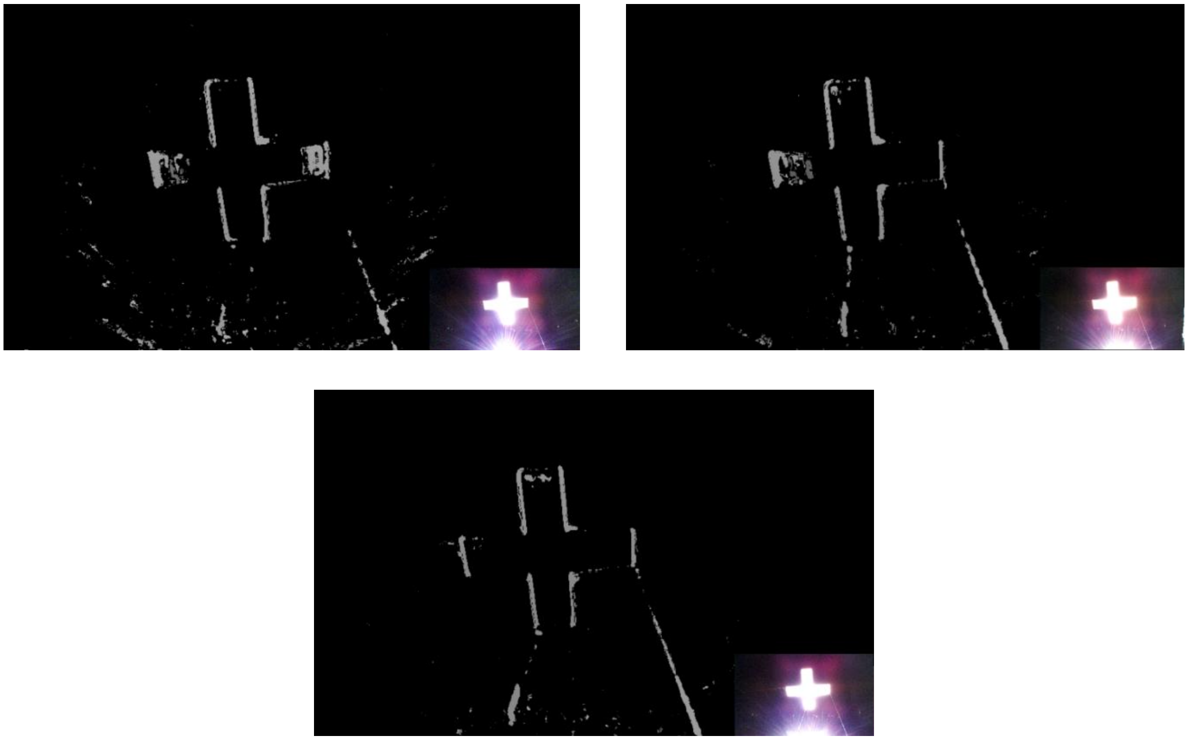

Exhibit 31: Outdoor R200 Test Data

Angle testing

The next set of tests performed looked at the angle of light incident to determine what approach angles a spacecraft could use. Testing was conducted at night outdoors to minimize reflected/ambient light. The test object was a "plus" shaped solar panel. Three 500W halogen lights were used to simulate solar flux. The configuration was similar to **Error! Reference source not found.**3, except the object was then rotated through 180 degrees. The object was visible between 20 and 70-degree incident light. During the testing, the relationship between sensor overload and incident light was determined. This prompted additional testing.

Flux testing

The objective of the "Flux Testing" was to determine the magnitude of incident light required to overwhelm the sensor. Testing was indoors. Ambient light was accounted for in the incident light detection. Three 500W halogen lights were used to simulate solar flux.

The camera was positioned in an indoor hallway, sitting underneath a solar simulator. The test object was moved an arbitrary distance down the hallway to start. A light sensor was positioned immediately next to the camera to determine incident light. A computer was setup to display the output from the camera and to determine when loss of signal occurred. The results indicate that a flux in excess of 3,300 lux overwhelms the camera.

THEORETICAL ANALYSIS

The results of the practical testing were used to conduct theoretical analysis on the camera operations. The primary focus of this analysis was in areas where the R200 range-finding camera functioned. Additional analysis was conducted to determine what the maximum non-3D range of the camera would be.

R200 Operating Areas

It is possible to look up the reflective properties of basic spacecraft components. These values can be used in conjunction with the incident light results to determine what on-orbit conditions are acceptable, and where they occur on orbit. These values are used to determine the distance at which the reflected light overwhelms the sensor.

An analysis was conducted to determine the operational regions of the spacecraft based on the maximum light restriction on the camera. The analysis was conducted in STK and was used to determine the magnitude of reflected light at different locations in an orbit, shown in Exhibit **4**4. A representative ISS type orbit and a "V-bar" approach path to a nadir pointing spacecraft with sun tracking solar panels was chosen as the test case. The test orbit was a 500 km circular orbit at a 27-degree inclination.

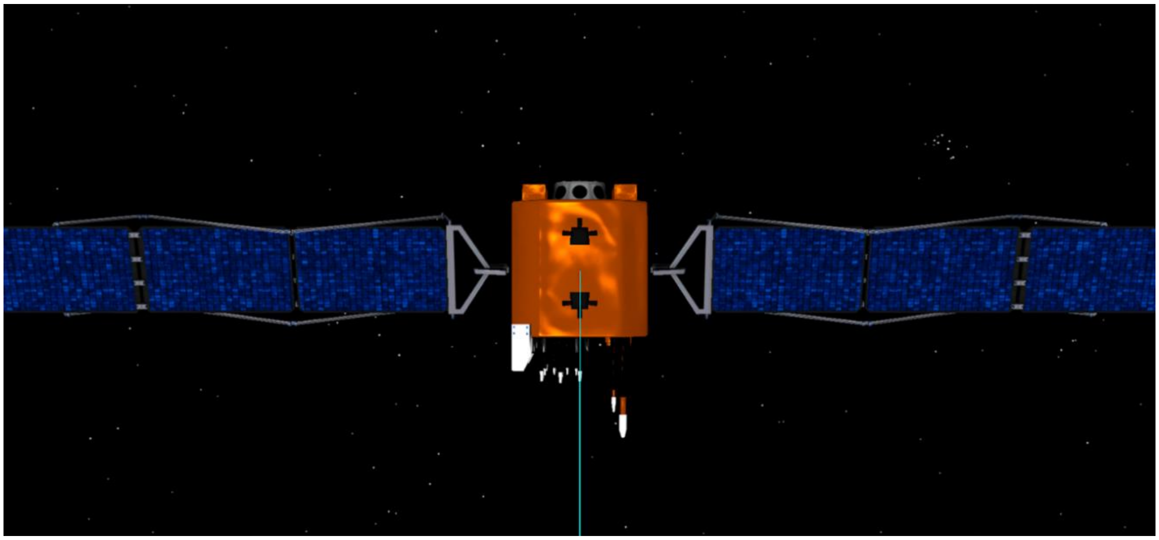

Exhibit 4: STK Analysis (Sample Spacecraft)

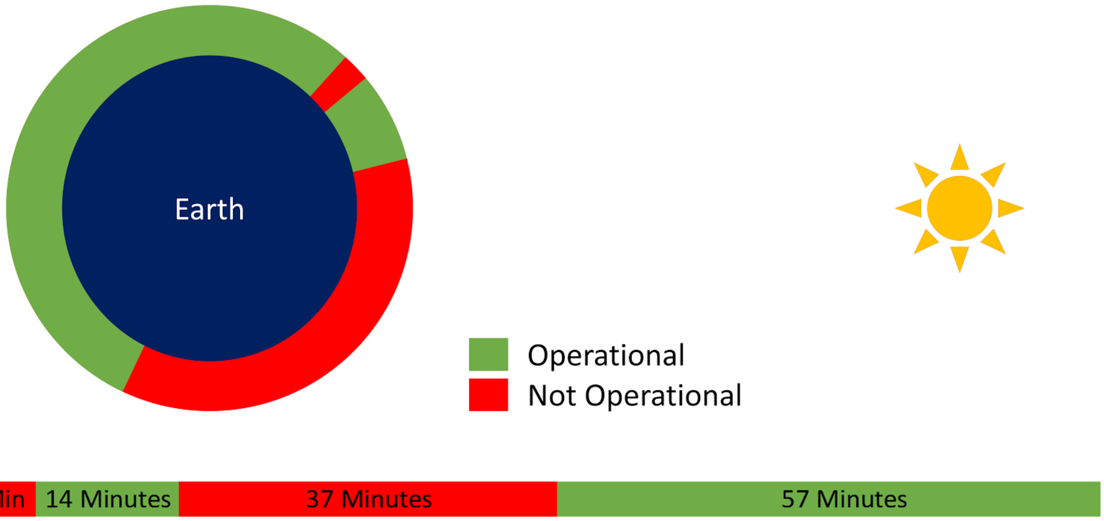

Exhibit 5: Operational Areas of R200 Camera

Using the results from the terrestrial testing, each location was evaluated to determine if the camera would function correctly. The results of this analysis are shown in **Error! Reference source not found.**. This indicates that there are two periods of operation--one when the sun is eclipsed by earth lasting 57 minutes, and one when the sun is eclipsed by the spacecraft lasting 14 minutes. The other periods of the orbit do not allow for proximity maneuvers.

Departure Simulation

The goal of the departure simulation was to verify if it is possible to detect the host spacecraft/other space objects at range in real world conditions. Footage showing the departure of the Cygnus Spacecraft from the ISS was screen grabbed from YouTube, at a variety of ranges. While we may launch into any LEO, the ISS orbit is extremely common for CubeSats and these lighting conditions can be assumed to be extremely similar to what is expected. The image quality is on par, if not below, what we would expect from our onboard camera system.

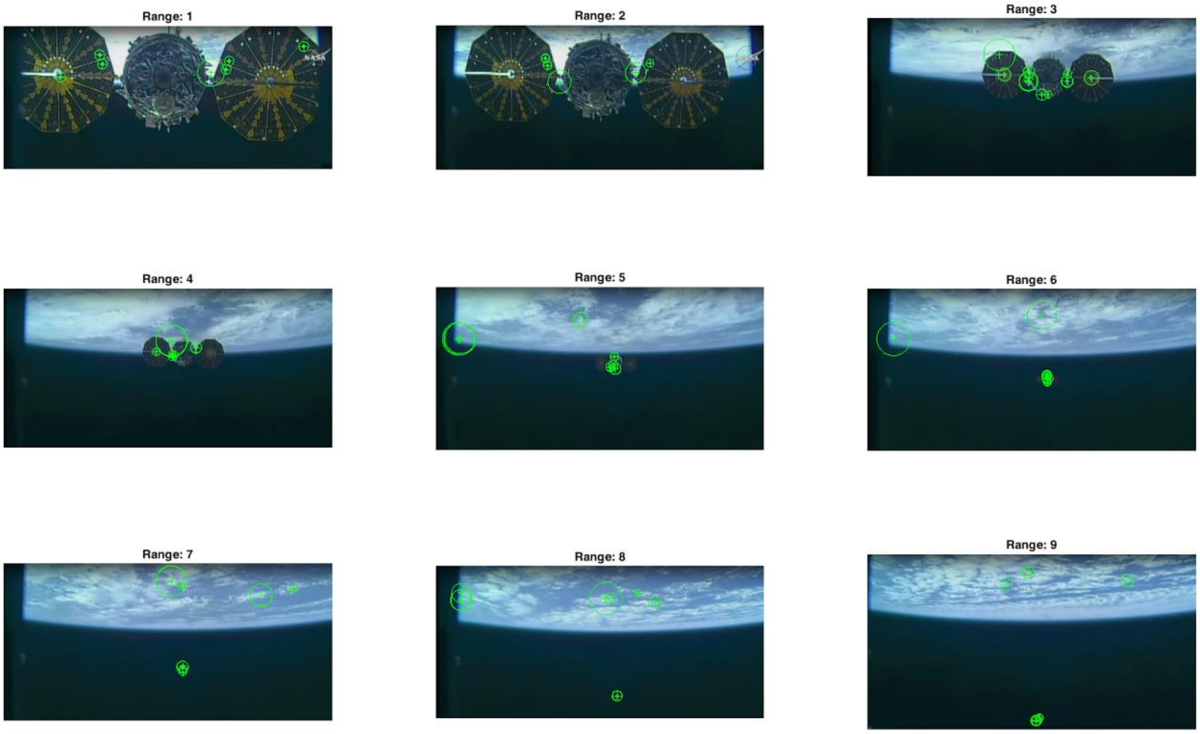

Exhibit 6: ISS Test Result

Screen grabs were read into MATLAB, where the “significant object detection” filter was run across them. This produced the result shown in Exhibit 6. The filter could detect the spacecraft all the way to 500 m (range based on astronaut commentary in the video.) This capability will allow the spacecraft to orient itself relative to its target spacecraft and begin the docking sequence, even when out of range of the 3D camera.

FLIGHT TEST

This technology is intended to be tested on-orbit. It will be tested using CubeSats. Two 3U CubeSats: TUGSat and its partner, USNA Sat will launch linked by 1m long tethers. The 3D Camera will be on one spacecraft, positioned to image the other spacecraft. The camera will be turned on in a variety of lighting conditions. This will verify terrestrial testing and models with on-orbit data. After this point, the spacecraft will conduct separation operation. The whole mission is intended to launch in 2018.

Systems

There are three primary systems on the TUGSat spacecraft. These systems are required to demonstrate basic 3D camera operation.

1. *Locking System*: The locking system ensures the two spacecraft remain connected for launch. It is required to be able to easily withstand launch forces while still separating the spacecraft when commanded.
2. *Tether System*: Two tethers will keep the spacecraft positioned 1 m apart. These tethers will provide enough stability to keep the spacecraft stable relative to each other, but must not significantly interfere visually.
3. *3D Camera*: The Intel R200 will be paired with an ``upboard'' processor to function as the navigation system for the flight. It is positioned to look at USNA Sat.

Concept of Operations

There are three primary mission phases: Initialization, Camera Test, and Separation. These steps will serve to demonstrate basic 3D camera operation, while also testing other USNA payloads. This mission is intended to launch as a single 6U spacecraft and conduct joint operations for the first 2 months of the mission.

Initialization

After achieving orbit, the spacecraft will be initialized. The spacecraft will start as two 3U spacecraft linked to form a 6U spacecraft. The initialization phase begins at launch and will end with the separation of the two spacecraft.

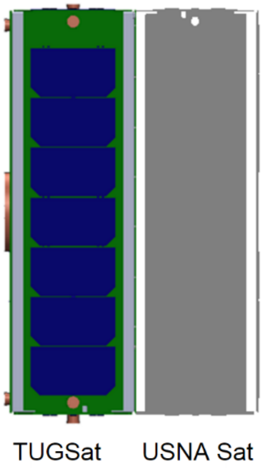

Exhibit 7: Initialization phase. In the initialization phase, TUGSat and USNA Sat will be linked together using the locking system. They will launch as a single 6U spacecraft.

Camera Test

After the initialization phase, the two spacecraft will separate. After separation, the two spacecraft will be joined by two 1 mm diameter 1 m long tethers. The camera will be positioned to look between the spacecraft and will be turned on in a variety of lighting conditions. Light sensors on both spacecraft will measure incident light to compare to ground-based testing.

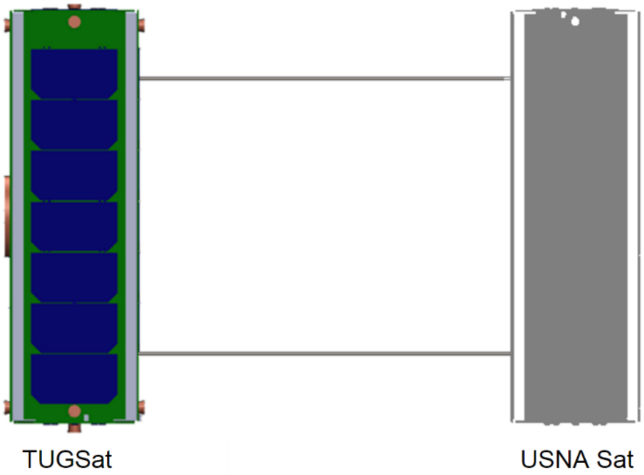

Exhibit 8: Camera Test Phase. For the camera test phase, TUGSat and USNA Sat are linked by two fixed 1 m long tethers. This keeps their relative attitude and range constant for imaging demonstrations.

Separation

After the camera characterization is validated, it will be used for an operational mission. The two spacecraft will conduct a slow separation, using the R200 camera to track relative positioning.

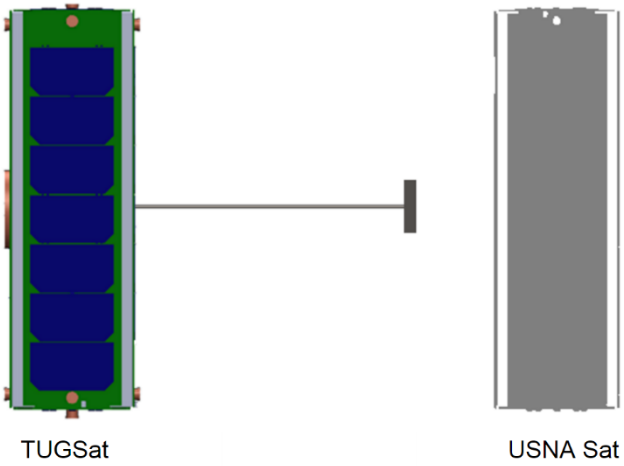

Exhibit 9: Separation Phase. In the separation phase, the two spacecraft are separated and TUGSat uses its 3D camera to maintain its relative attitude.

CONCLUSION

Systematic ground testing concluded that a COTS 3D camera sensor is capable of operating in certain orbital conditions. Results will be validated in the flight of the TUGSat spacecraft in 2018. This research offers a twofold purpose. First, the test results can be scaled to conventional satellite purpose and structure to offer further insight and innovation for rendezvous and docking processes. Secondly, it has the potential to widely broaden the flexibility and utility of the small satellite platform even as use of the smaller platform burgeons over multiple industries and applications. The value of a compact rendezvous navigation system cannot be overstated. A reliable and autonomous on-orbit rendezvous and docking process – both conventional and as proposed here on the CubeSat platform – will be instrumental if not vital to the maximization of efficiencies in space exploration and utilization, significantly reducing costs and waste.

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