Intelligent Space Assembly Robot (ISAR)

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ABSTRACT

On orbit assembly of spacecraft has historically involved human intensive robotic operations. To facilitate this construction process the U.S. Naval Academy is augmenting its current robotic arm capabilities with the Intelligent Space Assembly Robot (ISAR) program. This research is aimed to identify key requirements and select a 3D camera for use in ISAR's robotic operations. The research has three stages: 1) requirements identification, 2) ground testing and 3) an on orbit demonstration. The camera requirements were identified based on the current robotic arm capacity of the previous version of the arms, and three cameras (Intel R200, DuoM, and Tara) were chosen for further testing. Terrestrial testing consisted of demonstrating capabilities of each camera by taking and processing photos of a test satellite that represented common spacecraft features. The second phase of testing was a comparison of real and measured depth data using CloudCompare software. This paper also details the design modifications required to incorporate the updated sensors as well as an outline for ground testing of the system. The on orbit demonstration of the system's capabilities is planned to occur in 2019 with the launch of ISAR to the interior of the International Space Station as a payload science experiment.

INTRODUCTION

Satellite and spacecraft size is greatly limited due to the size and weight that rockets can lift on launch. Only two modular spacecraft, the International Space Station (ISS) and the Russian Mir station, have ever orbited around earth. Other large objects in orbit include the Hubble Space Telescope and ESA's Envisat.[1]

The International Space Station is currently the largest artificial satellite in orbit around the earth. It stretches out at 108 m by 73 m and weighs 408233 kg. It was constructed over a series of launches in a modular fashion starting in 1998 and ending in 2011. This long process took numerous Shuttle flights and extensive astronaut training.[1]

The launch of large spacecraft into orbit is a complex process which is why it has only been done a few times in history. Satellite size is not only governed by launch parameters but is also limited by the current on-orbit assembly capabilities.

As the construction of the ISS showed, the spacecraft assembly process can take decades. Human driven assembly in space is a time and monetary drain. There are massive costs associated with launching both a human and a spacecraft into space as well as associated risks with potentially putting human lives in danger. Human assembly processes are best augmented with robotic manipulators which can negate the need for an astronaut's spacewalk.

Current Solutions

Terrestrial assembly is often done with robotic and autonomous operations. This technology has been available for years in the automotive industry. Robots are in charge of everything from welding the joints on a car to painting and polishing. This adaptive automation increases accuracy and efficiency in the assembly process.[2]

Robotic operations are not unheard of in the space environment; the Canadian Space Agency has used the Canadarm in shuttle and ISS missions. It provides the capability to visually inspect the station, and to support astronauts during spacewalks. It is controlled through a human operator in a console inside the ISS.[3] This makes this technology very slow to operate as it requires feedback from the controller as well as costly due to the time and training of an astronaut as well as the cost to launch the astronaut into space.

Human-in-the-loop robotics also pose more complex problems when the communications time delay from space is taken into account. Currently the Mars rovers like Curiosity receive a string of commands every day and then execute them before waiting for more instructions from the ground. This interaction is slowed down by the 40 min time delay in the communications.

One of the solutions to this problem as proposed by the Jet Propulsion Laboratory is to build a model of the terrain around the rover so that operators can better predict how it is going to move.[4] However the technology that would enable the rover to work a few steps ahead of itself is still in development and will not be tested until the next launch of a Mars rover.

Proposed Solution

The U.S. Naval Academy (USNA) is looking to supplement robotic arm capabilities with autonomous functions such that it can operate independently with minimal feedback from the ground. Humans are always kept very firmly in the loop in robotic operations in space. This is mostly due to the sensitivity of the equipment being handled and the cost and difficulty of relaunching a part should something break.

The ISAR program looks to demonstrate the reliability of robotic operations in space by launching a small scale robotic arm into the space environment. Through this demonstration the program aims to expand the use of autonomous robotic arms in the assembly process.

ISAR SYSTEM OVERVIEW

ISAR is comprised of two key subsystems. The first is the robotic arm platform which is called RSat and the other is the new hardware and software capabilities that are being developed as part of the ISAR mission.

RSat

RSat was initially developed at the Academy for the purposes of on orbit diagnosis of failed satellites. It is comprised of two 7 degree of freedom robotic arms that fit into a 3U CubeSat form factor. The robotic arms were developed such that they could maneuver around the exterior of any satellite to access every surface for the purpose of diagnostic imaging. Each arm is 60 cm long for a total wingspan of 1.5 m. The CubeSat platform was chosen due to the high availability of launches, their small size, and low cost. Each joint is controlled with a 10 mm zero backlash stepper motor with a magnetic encoder. The arm components are 3D printed using Windform XT and the initial ground prototypes were printed in house using ABS plastic.[5] The overview of RSat is shown in Figure 1.

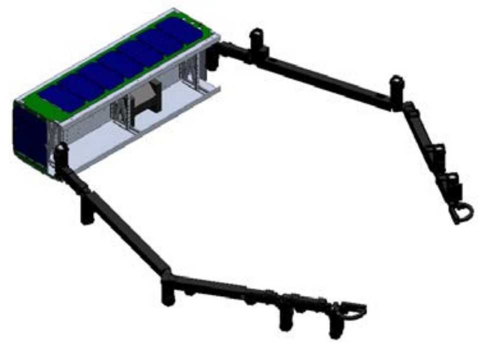

Figure 1: RSat System Overview

The first prototype of the spacecraft is manifest for launch onboard the ELaNa XIX launch in fall 2017 onboard the Rocket Labs Electron Rocket.

The robotic arms for the ISAR program will be derived from the RSat arm design. This is because they will be tested on orbit and demonstrated to operate in the space environment. The CubeSat form factor will continue to be used so that the program can continue to be tested over multiple launches which is easier using a standard size such as the 3U CubeSat.

New Hardware and Software Capabilities

RSat is completely controlled through commands from the ground. This is because it was best for the initial demonstration that a human operator respond to the environment around the robotic arms. The goal is to take the more basic robotic functionality of RSat and augment it with a more autonomous capacity. The key step is that process is the robot's ability to use sensors to build an awareness of its surrounding workspace. This is achieved through the use of a 3D camera onboard which can detect the position of the arms as well as the spacecraft it is assembling and its features.

This machine vision is achieved through the incorporation of both the 3D camera but also the relevant software which processes and interprets the images in the Robotic Operating System (ROS). Not only does that include the cameras but also the use of contact sensors and proximity detectors so as to minimize the risk of collision with parts of the spacecraft to be assembled. The robots awareness is also increase using strain gages in the major sections of the arm which detect vibrations from collision. This will all work to allow the ISAR system to autonomously assemble demonstration parts of a spacecraft on orbit as can be seen in Figure 2. However the 3D camera is still the main source of the robot's awareness as is one of the most crucial of ISAR's systems.

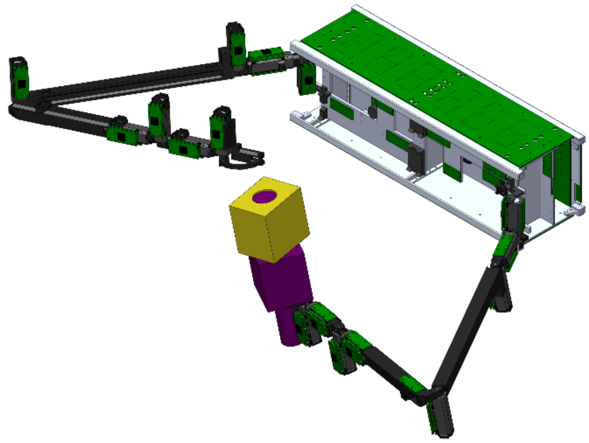

Figure 2: ISAR Performing an Assembly Demonstration

3D CAMERA SELECTION

The use of 3D cameras in the space environment is still in development. Most of the current research suggests that time of flight cameras are ideal for the space environment. Their applications include inspection and rendezvous. However 2D cameras are still the norm in spacecraft operations.[6]

Requirements for the 3D Camera

Requirements were derived from several factors. The foremost is the limited space available on the spacecraft. The camera must be able to fit into the arm housing and not protrude too far back into the interface board which houses the central processors of the robotic arms. The camera also needed to be suitable for the space environment and able to operate with as little power draw as possible due to the limitations of the solar panels.

1. Geometry of RSat

Each arm on RSat is 60 cm long and will be operating around parts to be assembled approximately 1 m away to 20 cm from the spacecraft body. It must be able to have a 170 degree field of view in order to monitor the entirety of the arm's working area so as to avoid collisions with the spacecraft parts it is assembling.

2. Integration with C&DH System

It is critical that the camera be USB 2.0 compatible. This is due to a Raspberry Pi being the computer that will receive the camera output and process it in the Robotic Operating System. The camera must also be able to output a 3D point cloud that can then be processed or output a mesh that can be sampled into a point cloud.

3. Space Environment

All of the hardware selected must be compatible with the space environment. Some of these requirements include a need for the camera to survive the vibrations of launch which will be tested on the vibration table along with the arms. The camera must also be able to adjust the exposure of the cameras due to the dynamic nature of light in space as it orbits around the Earth, ranging from direct sunlight to complete darkness. This is especially difficult for stereo vision because it does not have the ability to operate in full darkness. This is not a tight constraint because LEDs can be added to the spacecraft body to illuminate the area of construction when the satellite is in eclipse. The last important requirement is the average power draw which cannot exceed 2 W. Any greater average power draw will drain the batteries of the satellite due to the size of the solar panels, the amount of power they can produce and the amount of power the EPS system can store.

4. Other Requirements

Other requirements look at the long term mission of ISAR which is to be able to use this technology in future on orbit demonstrations. This requires the camera to be easy to use and understand, and have ample hardware and software support. By choosing an accurate off-the-shelf camera solution, other developers can easily program it to be used to test other robotic operating systems using the available software. This will enable ISAR to be used as a platform for future space missions exploring the use of robotics on orbit.

INITIAL RESULTS

The four criteria listed above were used to comb through many of the options for a suitable 3D camera. There were approximately 10 initial options. One of the factors that was the most limiting was the size and power requirements. These parameters meant that there were only a few suitable selections available from commercial vendors. The three cameras that passed the initial criteria and were studied further in depth were the Intel R200, the DUO M, and the Tara Vision camera. A summary of the basic camera parameters is shown in Table 1.

Table 1: Page Margins for Letter and A4 Submissions

Parameter	Intel R200	DUO M	Tara
Maximum Range	10 m	2 m	8.5 m
Resolution	640x480	752x480	752x480
Frame Rate	30 fps	45 fps	60 fps
Size	130 x 20 x 7 mm	52 x 25.4 x 11.6 mm	100 x 30 x 35 mm

Intel R200

The Intel R200 is a stereoscopic vision camera that augments the two cameras with a laser projector which creates a pseudo time of flight camera from a stereo vision. The camera provides texture information which can be overlaid on a depth image to create a color point cloud. A schematic of the camera is shown in Figure 3.

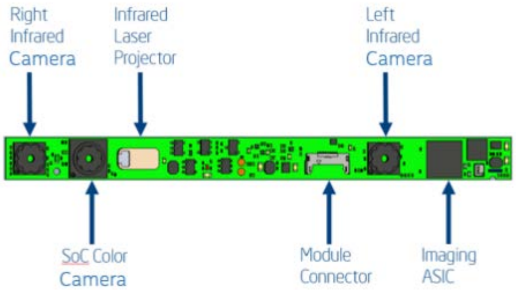

Figure 3: Intel R200 3D Camera[7]

DUO M

The Duo M is depicted in Figure 4 and is another stereoscopic camera with a shorter distance between the two cameras resulting in a shorter range. Its smaller size is ideal for this application due to the space constraints. It comes in various levels of a complete solution with the most complex being the two cameras, a housing case, and an LED light to illuminate the field of view. It has enough processing power to overlay the two images itself and output a textured point depth cloud.

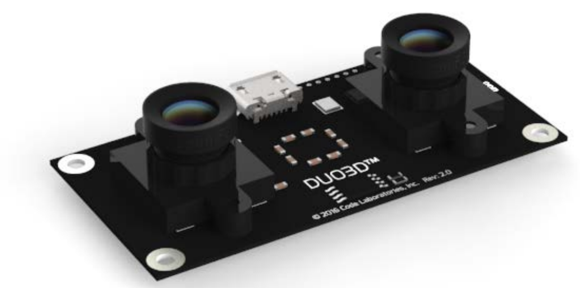

Figure 4: Duo M 3D Camera[8]

Tara

The Tara camera is the most basic stereo vision camera investigated. It is simply a board with two cameras which outputs two images that have to be overlaid by the user. This camera was selected as a backup in case one of the integrated solutions becomes unfeasible for use. The camera is shown in Figure 5.

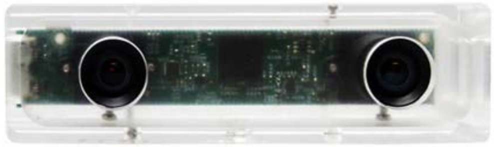

Figure 5: Tara 3D Camera[9]

GROUND TESTING

Ground testing was conducted on the three 3D cameras. The goal of the ground testing was to conduct a basic investigation into the depth accuracy and sensing ability of each camera. This demonstration was broken down into two parts: spacecraft compatibility testing and depth accuracy testing.

Spacecraft Feature Differentiation Testing

Initial testing of the R200 and the DUO M consisted of using a constructed test satellite to verify the camera's ability to recognize distinctive features on the exterior of a satellite. The external features were constructed to imitate the standard features ISAR could expect to see when it is assembling a spacecraft on orbit. Being able to recognize these features enhances the robot's ability to avoid collision and effectively assemble spacecraft on orbit. The following features were included, and a picture of the satellite model is shown in Figure 6:

- Deployed Solar Panels
- Struts
- Impact Holes of Varying Size
- External Electronics
- Sun Shield
- Nozzles
- Antenna

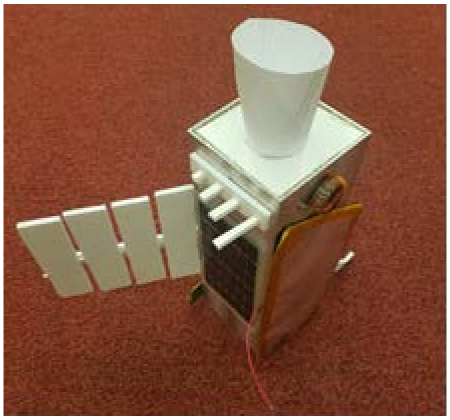

Figure 6: Test Feature Spacecraft

The procedures for the test were as follows. Each camera was placed 1 m away from the test feature spacecraft and an image was taken. Then the spacecraft was rotated by 45 ° and another image was taken until the camera had photographed a 360 ° view of the test satellite. This was to ensure that the camera could detect every feature of the test satellite or be able to identify where the cameras were weak.

The performance of the Duo M camera was consistent with the parameters that were laid out in the data sheet. At 1 m distance the camera had difficulty distinguishing between the various extrusions, as shown in Figure 7. Even though it was rated for up to 2 m distance, it operated more effectively at a much closer range.

Figure 7: Exterior Protrusions

The Duo M camera was sensitive to the lighting conditions as can be seen in Figure 8. The output mesh from the camera shows its ability to detect most of the features of the test spacecraft but not the features towards the bottom. These features are less lit than the top features due to the overhead lighting of the room. Since the difference in incident light is very small between the top and bottom small LEDs could be used to further illuminate the object under study. This figure also shows the camera's inability to detect reflective surfaces as it cannot detect the solar blanket which takes up the right side of the spacecraft.

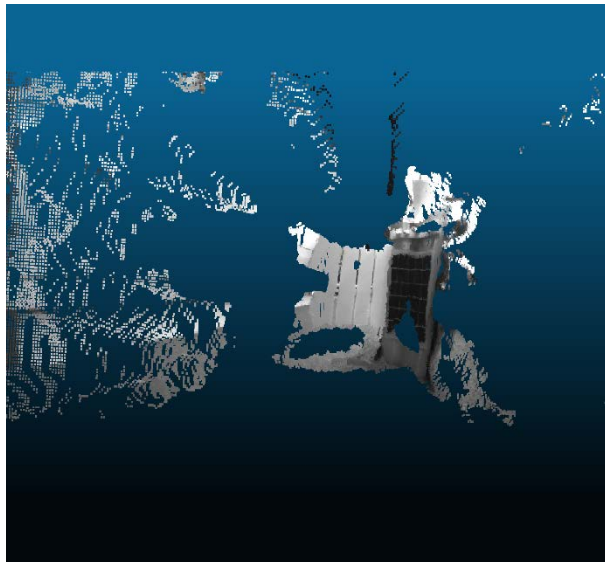

Figure 8: Feature Differentiation Testing: Duo Output

The R200 detected the features of the spacecraft with greater accuracy than the R200. The camera was able to detect even minor differences in range to the features on the test spacecraft. The R200 includes a laser projector and for that reason the R200 was able to output an accurate mesh is varying lighting conditions. As Figure 9 shows the reflective surface of the solar blanket did not affect the 3D mesh the R200 was able to create.

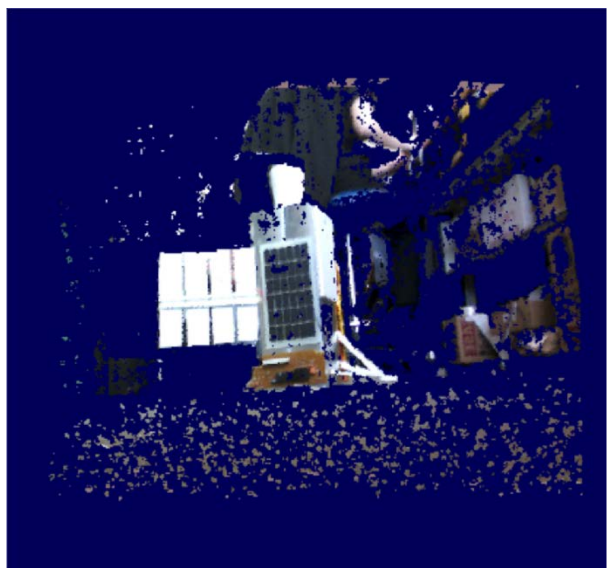

Figure 9: Feature Differentiation Testing: R200 Output

Depth Accuracy Testing

Depth accuracy testing was used to differentiate between the sensing accuracy of the R200 and the Duo M for use as the on board camera for ISAR. The procedures for the test were aimed at standardizing the differences between the two cameras so that their accuracy could be best compared.

A flat box of known dimensions was placed initially 100 cm away from the camera. The camera was mounted 15 cm off the ground so as to minimize the interference from the ground. Then an image was taken and recorded and the box was moved closer to the camera by 10 cm, the lowest test range was 20 cm which is the closest the ISAR arms will come to the body of the spacecraft. Five images were taken by each camera at each range.

The resulting 3D mesh from each camera was recorded, and the mesh of each image at each distance was inputted into a program called Cloud Compare which allows point clouds to be compared. A CAD drawing of a plane of equal dimensions to the box was drawn in SolidWorks. The 3D mesh was cropped down so that only points that represented the face of the box remained. The corners of the mesh were aligned and resized so as the match the corners of the plane. Following the proper alignment and scaling the point cloud comparison tool was used to measure the difference between the real and the ideal depths. This comparison tool outputted a value which corresponded to the deviation of the measured point cloud from the CAD of the box. An example of this comparison can be seen in Figure 10. The red dots represent the point cloud from the camera and the white dots are a sample point cloud derived from the CAD of the box.

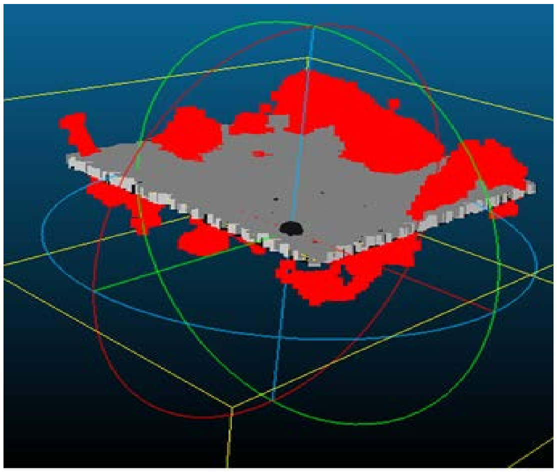

Figure 10: Depth Accuracy Testing for the 3rd Image Taken by the R200 at 80 cm Range

Results of Depth Accuracy Testing

The average deviation was outputted for each image, camera and distance. This number was used to compare the accuracy of both of the cameras at varying distances. Figure 11 is a summary of the depth error calculations for both cameras.

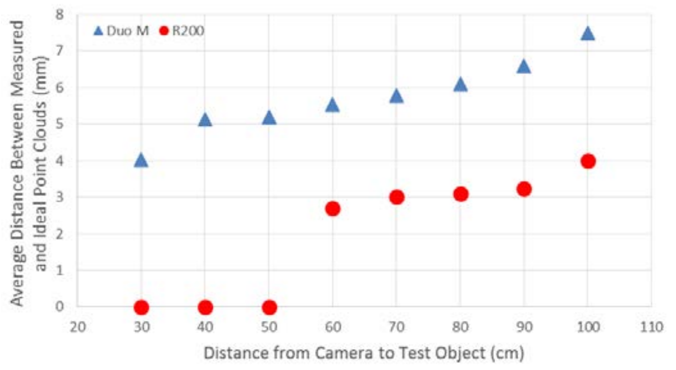

Figure 11: Depth Accuracy Testing Results

As this graph shows the R200 was consistently more accurate than the Duo M camera for every test image. This is to be expected because the laser projector compensated for any shadows or irregular lighting that may have been present. However this test did reveal the very startling fact that the R200 cannot sense objects within a 60 cm range. At that distance the camera returns is a static background without any object in view.

This almost immediately removes the camera from the running because ISAR's robotic arms are 60 cm long when fully outstretched. It is crucial that the camera on board ISAR be able to detect objects within that range. The Duo M successfully accomplished this- albeit with less accuracy. Figures 12 and 13 are a sampling from the Duo M at 30 cm away versus 60 cm away.

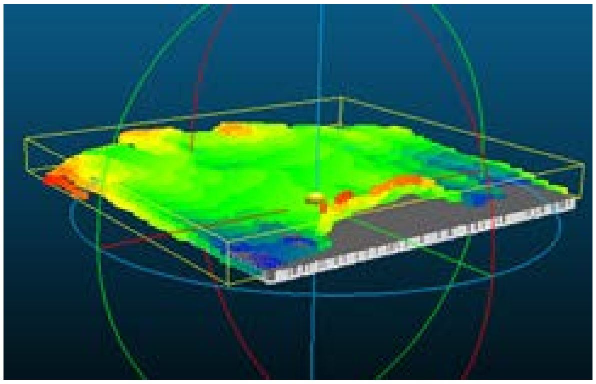

Figure 12: Duo M Depth Accuracy Testing Results at 30 cm

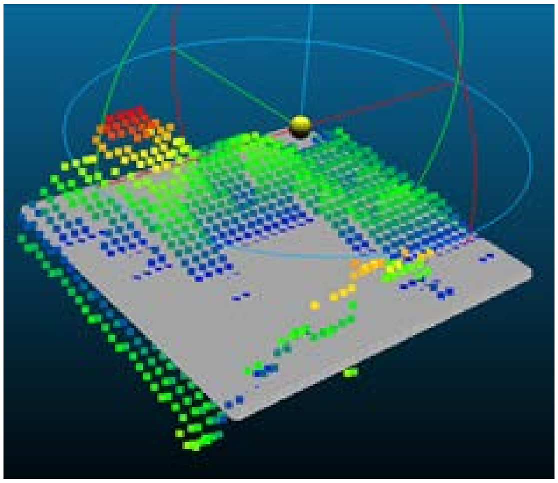

Figure 13: Duo M Depth Accuracy Testing Results at 60 cm

Ground Testing Results

This research showed that while there are downsides to using the Duo M camera in the on orbit demonstration of ISAR's capabilities, given the size and range requirements, it is the better choice. At the robot’s maximum extension the camera is inaccurate to 5.5 mm which does mean there is a potential for collision but that maximum inaccuracy can be offset using the other onboard sensors such as the contact and proximity sensors. The Duo M has a compact size, limited power draw, and an ability to be idled to reduce power draw when not in use. There are relatively few arm modifications that have to occur in order to house this camera and it integrates very easily into the command and data handling structure because it is compatible with ROS. The Duo M will be flown on the ISAR demonstrator launch and used as an environmental feedback system.

The next phase of research is to use the visual feedback that the 3D camera provides to build an environment where the robotic system can see its arms and a target within its field of view and be taught to differentiate between the two. Then once the robot understands what space in free space and what points are occupied by an object it can work to navigate to a specified point using the arm’s degrees of freedom.

REDESIGN OF RSAT

Several features on RSat need to be modified in order to incorporate the new technologies for the flight demonstration of the ISAR system. Most of these changes are on the hardware side which the initial arm software stays very similar to the initial RSat design.

Degrees of Freedom

Through ground testing it has been determined that one of the degrees of freedom can be reduced in each arm at the wrist joint. This is because the three degrees of freedom at the wrist are made redundant by the three degrees of freedom at the shoulder. This was determined through the use of a prototype arm that varied which degree of freedom was redundant and could be removed from the design. By moving that prototype through a range of motion it was determined that an arm with one less degree of freedom in the wrist performed the same tasks correctly as a full seven degree arm.

Arm Layout

The layout of the arm has to be modified so as to properly fit the camera in between each arm. This meant that long sections of the arm have to be reduced in diameter so that when folded the camera can see between the joints.

End-Effector Design

The claw which was originally designed to grapple onto the exterior of a satellite will be redesigned for spacecraft assembly. This means making it more sensitive through the use of sensors and making it larger so that it can hold larger objects. This size increase is achievable due to the decrease in the number of motors sitting in the wrist joint as the number of degrees of freedom is reduced from seven to six. The claw will also incorporate a photodiode gate across the fingers of its claw which will provide the robot with the ability to detect when an object is inside the grasp of the claw. The claw redesign will add contact sensors along the outside so that it can detect collisions and have a sense of touch on the end of each arm.

FUTURE ISAR DEVELOPMENT

The next phase of development is building towards the construction of a terrestrial test robot which allows for testing of the core components of the spacecraft before final construction and integration. The ground testing robot will have the 3D camera mounted on the center of the spacecraft as well as three other 2D cameras, proximity and contact sensors.

The 3D camera capabilities will be augmented with on board 2D cameras which will serve as a backup in case an object drifts too close or too far out of the 3D camera's view. The depth and dimensions of the object will be measured using the 3D camera and that information stored will serve as reference values for the 2D camera. This is so that the robot can continue to avoid collision even when the 3D Camera is not in use or the object is not in optimum range.

ON ORBIT DEMONSTRATION

The on orbit experiment of ISAR will occur in 2019 when the robotic arms and their updated on board sensors are launched to the International Space Station to demonstrate this concept. It will be launched with a "jungle gym" of parts that represent common spacecraft features and miniature spacecraft that ISAR can practice assembling in micro gravity. The on orbit demonstration consists of four main testing sequences: initial deployment and full range of motion check, arm contact and coordination, self-imaging and finally assembly demonstrations.

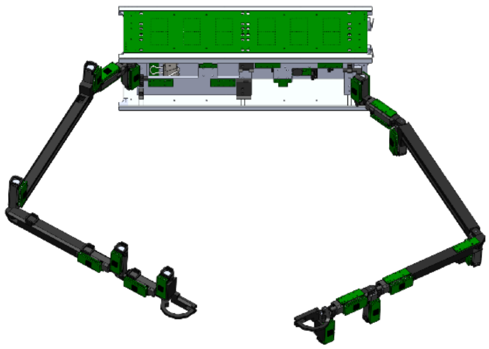

Figure 14: Initial Deployment

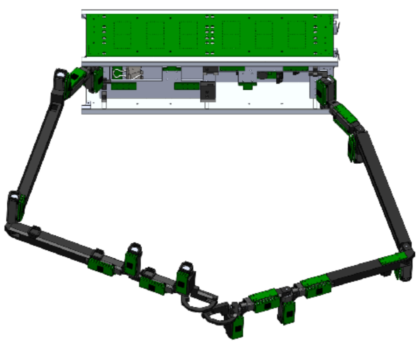

Figure 15: Arm Contact and Coordination

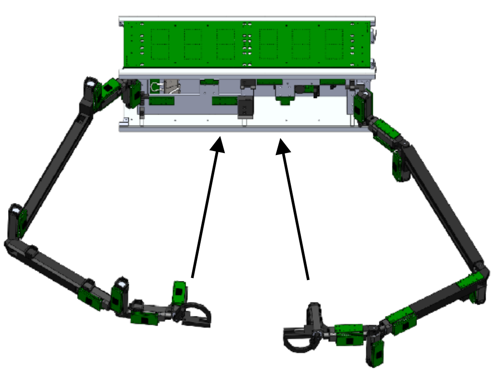

Figure 16: Self Imaging

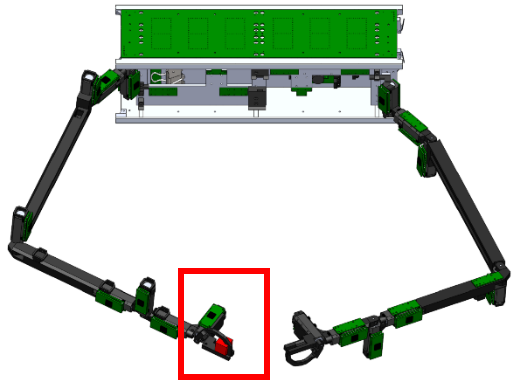

Figure 17: Assembly Demonstrations

CONCLUSION

The selection of the Duo M camera meant that very few design changes have to occur in the robotic arm design. The Duo M was chosen from a criteria design around the space and power constraints of the robotic arm as well as the ability to distinguish features and be accurate at various distances. The ISAR system will incorporate several advance sensors to give the robot the ability to sense its environment while also maintaining the core robotic functions as demonstrated on the RSat spacecraft.

Future work will include the advance development of the machine vision, the final design modifications, integration and finally an on orbit demonstration on the ISS. This process is designed to grow the capabilities of the hardware and software over time. The overall goal being to demonstrate the feasibility of using robotic arms to assemble large spacecraft in space.

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