Advancing On-Orbit Assembly With ISAR

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ABSTRACT

The U.S. Naval Academy (USNA) is looking to advance autonomous assembly with a next-generation Intelligent Space Assembly Robot (ISAR) system, which seeks to demonstrate semi-autonomous robotic assembly capabilities on orbit. ISAR is a small size form, low cost, 3U CubeSat-class satellite intending to mature robotic assembly capabilities. It is comprised of two key subsystems: twin 60 cm seven degree of freedom robotic arms, RSat, and the sensors which utilize one 3D camera and two 2D cameras to increase spatial awareness and aid real-time responsible maneuvering in a dynamic space environment. RSat, developed by the Naval Academy, is an existing set of robotic arms housed in a 3U CubeSat. RSat serves as the foundation for the next-generation ISAR program and will be launched as a free-flyer mission in 2018 as part of NASA's ElaNa XIX launch. On-orbit demonstrations of ISAR will test the ability to perform a test structure assembly with robotic arm actuation at a fraction of size and cost of previous space robotic platforms. This paper will present an overview of the ISAR system, outline design, operation, and demonstration modifications for the on orbit experiment and present a novel concept for autonomous operations.

INTRODUCTION

Autonomous robotic operations are a mature technology offered on a widespread scale for terrestrial applications. Vast examples of autonomous assembly demonstrate that it is not a stretch to imagine that autonomous space robotics should operate with a higher level of autonomy than is currently implemented. Everything from cell phones to cars can be assembled from almost start to finish using articulated autonomous robots without a human operator in the loop during the assembly process.[1] These robots are given their wide range of autonomous tasks because they implement the same small tasks repeatedly and with a high degree of accuracy and reliability.

The relentless expansion of accessibility to space not only calls for groundbreaking satellite programs, but demands innovation in assembly and servicing to ensure those missions are executed in a time-efficient manner. Limited by funds, time, and availability, astronauts cannot keep up with the necessary servicing and assembling of current and future assets in space. Utilizing autonomous systems in space could reduce both costs and time in the long run. Having autonomous satellite systems capable of autonomous space assembly is a clear means to ensure future programs have both cost efficient and time efficient servicing. The dynamic nature of space and the high cost of satellite and spacecraft components mean that repetitive robotic tasks could result in collisions and hardware damage.

To overcome these potential obstacles, advanced autonomous systems that include feedback sensors into the loop are needed. These autonomous robotic systems are the next step in enabling spacecraft assembly. The higher availability and capability of robotic arms could radically change the size of spacecraft and satellites on orbit. A robotic system that can safely and reliably assemble satellites would enable the construction of larger aperture arrays on orbit. In addition to large aperture sensors, autonomous robotics could shorten the construction time for larger spacecraft and space stations that could be used for science mission and long duration human exploration missions.

Current Solutions

Current space robotics are limited in their scope and applicability to autonomous assembly. The majority of past robots and projects in development focus on human in the loop robotic control. These projects eliminate almost all aspects of autonomous operations and prioritize a high degree of safety and reliability.

The first major example of space robotics is the first flights and the continuous use of the Canadarm on shuttle missions and onboard the International Space Station (ISS).[2] This robotic arm has been used to assist in assembly processes, conduct inspections, and perform docking over its lifetime and iterations. While the Canadarm has been moving towards autonomous operations, it still relies most heavily on human operation. Nearly all of these operations are done by an astronaut in space. The problems due to teleoperations are eliminated because the human operator is located in close proximity to the arm they are operating. However this poses a different problem, because the cost and risk associated with launching an astronaut into space is high.

Another program that cuts down on human in the loop robotic operations, is the DARPA Robotic Servicing of Geosynchronous Satellites (RSGS) program.[3] The project focuses on demonstrating refueling and repair operations on geosynchronous satellites. RSGS places on emphasis on using onboard intelligence to avoid collisions with either itself or the client spacecraft. The arms place a high degree of priority on precisely delivering a controlled amount of force from the arms and maneuvering to near exact positions. However despite the high degree of autonomous capability delivered by the onboard system, there are still phases of operation which use human in the loop robotics. This method of implementation is suitable for geosynchronous orbit operations, but becomes less applicable when looking at longer delays present in human exploration missions.

Restore-L is a NASA Goddard lead robotics servicing project similar to RSGS that focuses instead on low earth orbit satellites.[4] Restore-L will be demonstrating its servicing capabilities on the Landsat 7 satellite in LEO. While the real-time relative navigation system is an autonomous operation, the arm operation is still primarily teleoperations. As stated previously, these types of operations can slow the assembly process down or potentially cripple the arm or host with an unintentional collision.

The Kraken robotic arm that is being developed by Tethers Unlimited that is a small scale, highly dexterous robotic arm.[5] Two arms can be stowed into a 3U CubeSat form factor. The arm has a large reach (2.0m) and can have up to 11 DoF for highly precise operations. The feedback to this arm focuses on joint position and force feedback to control the motion of the robotic arm. This approach may not always provide the spatial awareness necessary to perform on orbit assembly.

Proposed Solution

The U.S. Naval Academy is proposing a different approach to autonomous robotics. USNA has developed a 3U CubeSat with two robotic arms housed within the structure. The initial application of this system was focused on providing on orbit diagnostics to failed satellites and was called RSat.[6] However the current focus of the program is to use this hardware as a testbed for autonomous robotic operations, focusing most specifically on autonomous robotic assembly of spacecraft.

The proposed autonomous robot is called the Intelligent Space Assembly Robot (ISAR) system. ISAR combines the hardware heritage of the RSat spacecraft with an advanced autonomous robotic system that should enable fully autonomous spacecraft assembly operations.

ISAR exploits the form factor of CubeSats to be constructed and launched at a low cost and be launched and tested over numerous flights due to the high availability of launches of CubeSats to LEO. This allows the system to be developed over a number of tests and to validate key systems over a series of increasingly complex flights. The first test of the system will be the flight of the original RSat arms in a free-flyer experiment. Then that hardware has been adapted to the requirements of the ISAR system for an assembly demonstration on orbit as shown in Figure 1.

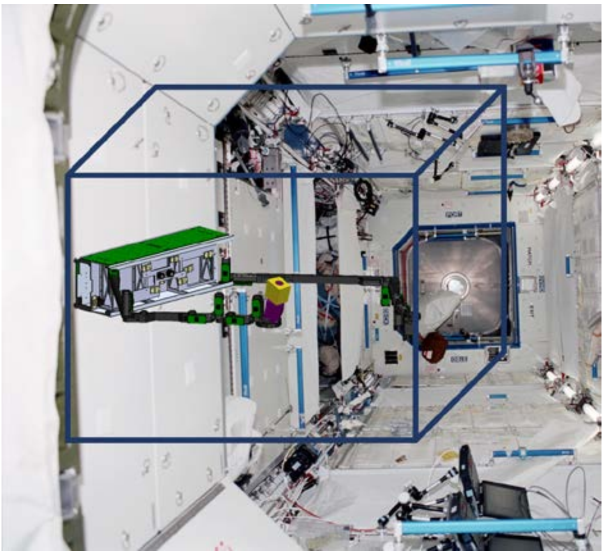

Figure 1: On Orbit Testing Concept of Operations

The on-orbit demonstration will occur on the inside of the International Space Station and focuses on demonstrating the autonomous assembly of scaled, test spacecraft parts. A successful demonstration will pave the way for future flights that are free flyer demonstrations of this system to further enable spacecraft assembly.

SYSTEM OVERVIEW AND CURRENT DESIGN

The ISAR system seeks to exploit the already developed hardware of the RSat satellite with minimal hardware changes a more advanced software system that better enables autonomous robotics.

RSat Hardware

RSat is comprised of two 7 DoF robotic arms that are house in a single 3U CubeSat.[7] The arms are designed to match the degrees of freedom and the range of motion of a human arm. The arms are fitted with end effectors that are designed to act as claws, which allows for grappling on a range of objects throughout the demonstration process. The arms are 3D printed in house for testing using ABS plastic. This allowed for rapid development of the design during the testing process. The flight arm was printed using Windform XT printed material which uses laser printing techniques rather than tubing. The arm is given its large dexterity and relative small size by using small, accurate, low power stepper motors to directly actuate each joint. Each motor uses a quadrature encoder and an encoder counter to implement a closed loop stepping control scheme. The main spacecraft body contains the core processors as well as the EPS and communications systems. The completed arm constructed for flight is shown in Figure 2.

Figure 2: RSat Robotic Arm

RSat is manifest to launch as part of ELaNa XIX. The launch is currently scheduled for fall 2018 onboard the Rocket Labs Electron Rocket. The final hardware has been delivered for launch integration.

The ISAR robotic arms are derived from the RSat initial iteration. This allows ISAR to build on the future flight heritage of the RSat satellite. This approach decreases the risk of hardware failure on the second iteration as well as advancing the capabilities of these initial arms.

The ISAR arms will continue to be designed for the 3U CubeSat form because while this test demonstration is going to be onboard the ISS, future flights of the arm are planned to be free-flyer missions. By staying with the current form design, the design modifications used for the ISAR arm can be implemented in future flights of the robotic arm.

Hardware Modifications

While the heritage of ISAR is the RSat robotic arm, there are a number of modifications that have to occur between the two iterations. This is due to ISAR's need for increased sensor data in order to perform the autonomous assembly operations. The main sensor addition is the 3D camera which is housed in the center of the robotic frame and is used to create a 3D mesh of the environment which is used in the trajectory planning of the robotic arm. The 3D camera that has been tested and selected for the ISAR system is the Duo-M 3D stereoscopic vision camera shown in Figure 3.

Figure 3: Duo 3D Camera[8]

The Duo fits the general weight, and power requirement for ISAR, but it is significantly larger than the 2D camera that sits in that position on the RSat satellite.[9] In order to overcome this size difference, the lengths and configuration of the robotic arm have been modified. This modification allows the camera to be mounted to the center body and still have a clear view past the arms when the arms are stowed. The length changes focused on recessing the arms in on themselves to move them out of the field of view during stowage. The second modification was the removal of a degree of freedom from the shoulder of the robotic arm. While a 7 DoF arm is highly capable, both testing and accepted industry practices have shown high degrees of capability with only 6 DoF robotic arms. The elimination of a degree of freedom allows for a longer link length between the two joints, it also allows the arm to be stowed more securely during launch. A side by side comparison of the RSat and ISAR arms is given in Figure 4 with the 3D camera shown in red.

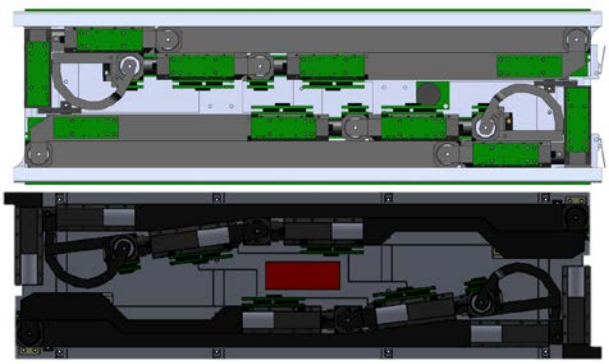

Figure 4: RSat (top) and ISAR (bottom) Arms

The packaging and launch restraint system for ISAR also differs from RSat. Since it is a free flyer, RSat must be able to restrain the arms during launch and deploy them when on orbit and detumbled. The satellite does so using burn resistors attached to fishing line to be able to burn through the line with the resistors are release the arms.

For the ISAR flight, this is not an acceptable method of restraint because ISAR is going to be operating and deploying inside of the ISS where fires, no matter how small, are a hazard to the astronauts. Because of this, the restraint and deployment mechanism had to be modified. Since ISAR will be unloaded and setup by astronauts, the restraint mechanisms can be released by hand. The method of vibration damping chosen is a foam material which encases the test bed as well as sits between the gaps in the robotic arms. The foam is removed for launch and ISAR is slid out of the hard shell cover that it is packaged in for launch. The hard shell cover is fitted on either end with caps used to constrain motion in that axis direction and the whole thing is held together with straps that can be released by the astronauts on orbit. The packaging concept is shown in Figure 5.

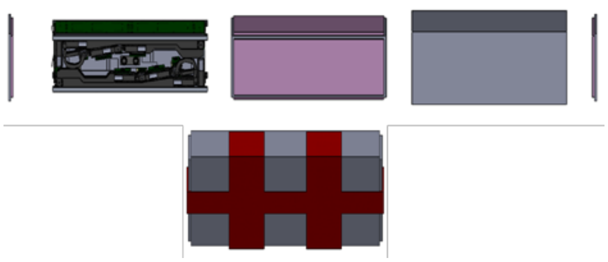

Figure 5: Packaging Concept

Software Overview

The core of the software system for the RSat satellite is a series of Arduino Pro Minis that are connected together with a central processor connected to two processors for each arm and a processor at each joint. The board at each joint is a modified board which has been designed to be smaller size, and only have the pins needed for operations. The Arduinos are connected using multi-drop serial communications which avoids the problems associated with daisy-chaining. This allows for only TX, and RX lines to be run down the length of the arm for communications which limits the bulk of the cable that may resist the motion of the robotic arm. This simple software interfacing works down the length of the arm to control the joints but does not have the processing power to interface with the advanced sensors to be used on ISAR.

Because the sensors require larger processing capabilities the central Arduino processor is being replaced with a Raspberry Pi 3. This board is larger than the current Arduino board, but this area is allocated on the interface board which sits behind the robotic arms because the ISAR system does not need an EPS because it receives its power from the ISS.

The Raspberry Pi will be running the Robotic Operating System (ROS). ROS is ideal for this application because multiple nodes can be interfaced in a simple and fast manner to pull and process data from the sensors, perform the calculations necessary for autonomous operations and send motor commands to the joints. ROS also has a libraries to makes software development easier. The software layout for ISAR is shown in Figure 6.

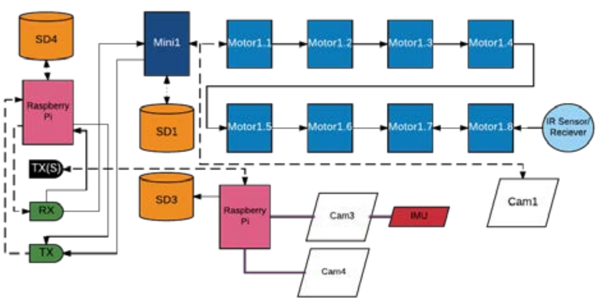

Figure 6: Software Layout

Advanced Autonomous Robotic Control

The largest change to operation and configuration of the system is the move from teleoperated robotics to autonomous operations. The goal of the ISAR program is to autonomously assemble a scaled version of spacecraft and satellite parts. To achieve this, there are additional sensors that are used to create a spatial awareness of the dynamic environment. The major sensors are two 2D cameras mounted on the end of each robotic arm, and a 3D camera which is located in the center of the satellite body.

These sensors are used to implement a new type of autonomous robotic control developed specially for the ISAR program. This allows for almost completely autonomous robotic motion to enable autonomous operations. The robotic controller is a hybrid of two common approaches to autonomous control. The goal of the hybrid system is to exploit the advantages of each approach for this dynamic application. The controller will calculate a weighted average of each method to create a hybrid controller approach to autonomous operations.

SIMULATION OF HYBRID CONTROLLER

Since this is a newly created robotic approach to control, it is important to simulate the motion of the robotic arm to guarantee stability and to test the effect of errors on system performance.

Fundamental Concepts

There are two approaches to autonomous robotics that are used in the hybrid controller on ISAR. The first is model-based trajectory planning and the second is eye-in-hand visual servoing. Each uses a different method of sensing the environment and calculating the trajectory of the robotic arm.

Model-based trajectory planning works by using a 3D map of the space to plan a path from starting position to ending position.[10] The path can be calculated several ways but in general paths look to optimally move through a field while minimizing parameters such as time and distance traveled. This method of trajectory following works best with a high quality understanding of the environment such as is most terrestrial applications. When lighting conditions are good and quality 3D images can be taken, the accuracy and precision of this method are high. However in the space environment there are often errors in the map cause by small errors in detection from the sensor. This degrades the performance of this simple approach and can make it difficult to achieve an accurate end position. While some error can be accepted, these errors often exceed the bounds of what is nominally acceptable during the spacecraft assembly process. This approach also suffers if the environment is dynamic because if the planned path is not recalculated at a high enough rate, collisions may occur due to these inaccuracies.

Visual servoing seeks to remedy some of those problems. This approach works using a 2D camera mounted to the end of the robotic arm.[11] The camera is used to take a picture of the scene and then based on models of the objects in the field of view, calculates a trajectory to move the end effector to a position where the objects are positioned and oriented the correct way at the goal position. This is a highly accurate method of robotic motion because it uses a sensor oriented much closer to the objects in the field of view. The resolution of the camera reduces error and the constant need to take photos to move the arm means that the scene is resurveyed multiple times and can react to a more dynamic environment. However visual servoing performs calculations for the trajectory such that the trajectory the arm follows is not always the most direct path from start to finish. Visual servoing also cannot be implemented when the reference points used to calculate the required motion are outside the field of view of the camera.

The hybrid controller seeks to implement both of these approached using a weighted average. For each point in the trajectory both methods are used to calculate the next movement of the robotic arm. Then based how far along the arm is on its path, the controller weights the effects of the two calculated trajectories. If the arm is at the beginning of the trajectory, model-based trajectory planning is weighted the heaviest because it is the most efficient method of moving the arm. However as the arm moves closer to the end goal, visual servoing begins to be weighted heavier until right at the end where the system is implementing solely visual servoing. A graphic of that “sliding” approach is given in Figure 7.

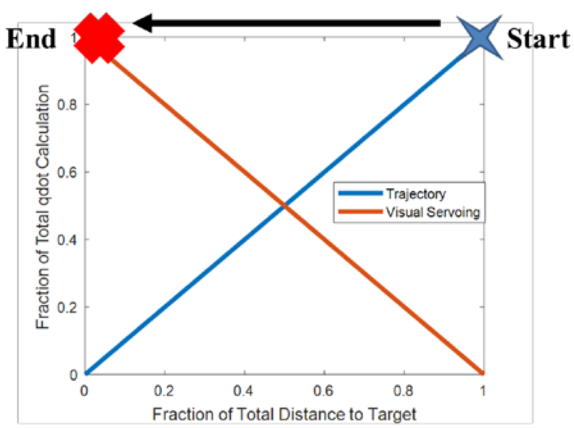

Figure 7: Sliding Controller Overview

Initial Simulation and Results

To show that the new proposed hybrid controller is a sound concept and that the system is stable, it is tested over a series of increasingly complex simulations. These simulations in MATLAB are designed to be a proving ground for this new hybrid controller with special attention being paid to the speed, trajectory, and accuracy of each approach individually as well was the relative performance of the hybrid controller.

The initial simulations simplify robotic operation by only having a 2 DoF robotic arm and constraining motion into a single plane. The initial simulation also uses simplified camera assumptions and only uses one reference point to implement visual servoing. That means that this approach is only slightly representative of the controller and is simply an initial proof of concept for the system. The final key assumption was that for the model-based path planning approach, the path was obstacle free and the fastest path between the starting and ending point is a straight line.

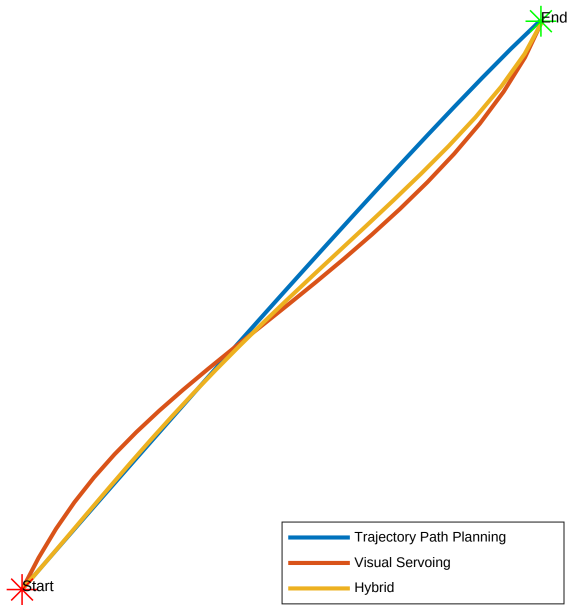

Figure 8: Simulation Results without Simulated Error

The initial results shown in Figure 8 indicate what is already know about these approaches to robotic control. The trajectory path planning flowed almost a straight line from the starting to the ending point. The visual servoing followed a less direct path, but also arrive accurately at the finish position. Finally the hybrid approach slid between the two methods first implementing mostly trajectory following and then near the end mostly visual servoing. While it appears that trajectory following is the most efficient approach this model does not take into account any error in the sampling and following where trajectory planning begins to degrade.

The next simulation presented includes basic error assumptions into the model and offers drastically different results.

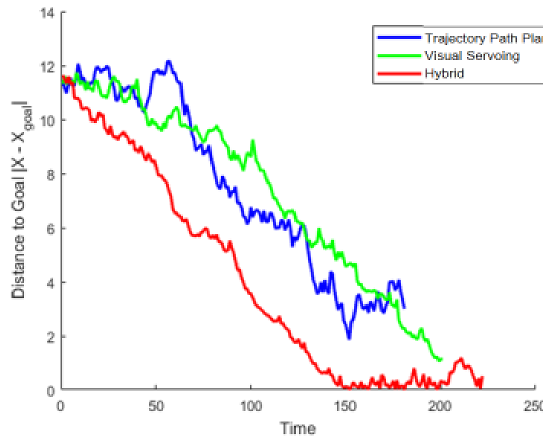

Figure 9: Simulation Results without Simulated Error

The results of the simulation with added error models show that when assumptions about error are included in the system, that the performance of the hybrid controller outpaces both of the standard approaches. The results detailed in Figure 9 show the hybrid path reaching the goal configuration faster and with less end effector inaccuracy than the other two approaches. This initially indicates that in further tests of the system we can expect to see the same improvement in response time and steady state error in the final position of the manipulator when the hybrid controller is applied.

Advanced Simulations

Advanced simulations of the robotic arm are used to validate that the conclusions made by the simpler simulations of the hybrid controller. By increasing the degrees of freedom and allowing for greater motion in all planes, the results indicate more closely the motion of the robotic arm. A representation of this type of simulation is shown in Figure 10.

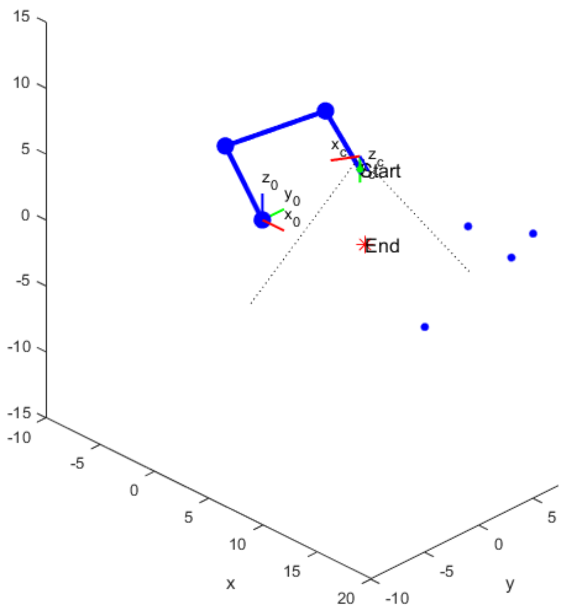

Figure 10: 3 DoF Simulation in 3D

ON ORBIT TESTING

Successful demonstration of the system in orbit will validate both the new hardware used to sense the environment and also prove the stability and feasibility of almost completely autonomous assembly operations. Testing focuses on demonstrating key subsystems and capabilities on orbit.

Concept of Operations for On Orbit Testing

The method of operations for on orbit testing is designed to most closely mimic the method of autonomous assembly without a human in the loop. This method is outlined step by step below.

1. Image Capture

Both the 2D and 3D camera take a picture of the scene with the arm and object being assembled in view. The 2D image is captured as normal and the 3D image is created from the stereoscopic vision of that camera to create a 3D mesh of the environment. An example of image capture is shown in Figure 11.

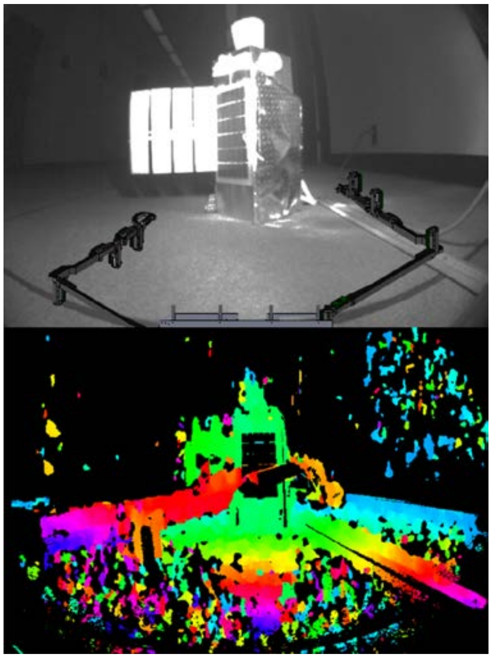

Figure 11: Example Image Capture in 2D and 3D

2. Image Analysis

The image is then analyzed. For the trajectory planner, a path that transits through obstacle-free space is calculated. While for the visual servoing implementation the reference points on the object are located and compared to the goal configuration of the reference points. An example of the image analysis is given in Figure 12.

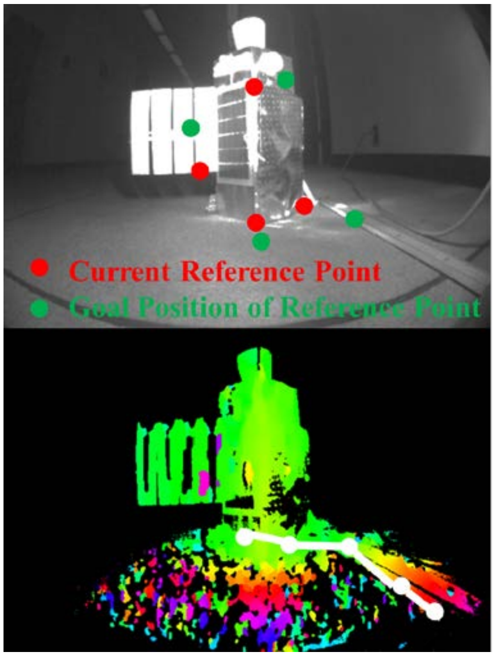

Figure 12: Example Image Analysis in 2D and 3D

3. *Trajectory Calculations*

Then each method of calculating the next motion of the robotic arm is performed by libraries created for ROS to reference. The calculations account for some error tolerances as well as interrupts to the system to allow for human intervention if an imminent collision is detected.

4. *Hybrid Controller Weighting*

Then based on the current position relative to the end position, the calculated methods are weighted according to the hybrid control law to create a single movement command to the robotic system.

5. *Arm Command*

The arm is then commanded to move based on the calculated weighted function and it executes a small step in the wider trajectory before resampling the field of view and starting at step 1 again. An example of the motion of the arm in given in Figure 13.

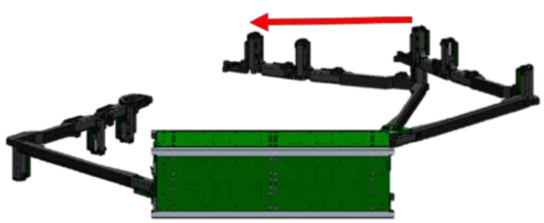

Figure 13: Example Arm Movement

CONCLUSION

The expansion of on orbit assembly capabilities would greatly expand the size and capability of satellites and spacecraft that could be flown. For long distance assembly operations traditional robotic assembly methods are insufficient due to the time delays and the risks of collisions. A new platform for demonstrating autonomous assembly is the ISAR satellite which seeks to perform autonomous assembly operations using advanced sensors and an advanced robotic controller that is ideally suited for the challenges of the space environment. Pushing autonomous assembly research forward is the way to expand the reach of human missions in space and to expand our capabilities on orbit.

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