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Characterization of Semi-autonomous On-orbit Assembly CubeSat Constellation

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ABSTRACT

Demand for more complex space systems is ever increasing as the scale of the future missions expands. Accordingly, much focus has been given recently to innovations in on-orbit assembly and servicing to ensure those missions are executed in a time-efficient manner. The past on-orbit servicing demonstrations have involved large satellites that were designed to dock/berth and service specific client satellites, and did not leverage the current advancements in small satellite technology. The U.S. Naval Academy (USNA) is contributing to advancing the on-orbit servicing and assembly technology with a next-generation robotic arm Intelligent Space Assembly Robot (ISAR) system, which is envisioned to operate independently or as a constellation of 3U CubeSats and seeks to demonstrate semi-autonomous robotic assembly capabilities on-orbit on a nano-satellite scale.

This paper will present an overview of the ISAR system, outline design, operation, and demonstration modifications for the on-orbit demonstrator, analyze the results from the ground test platform, and discuss the interfacing between existing robotic operations structures and advanced sensors. It will also focus on the analysis of cost effectiveness of the proposed mission architecture by characterizing the operation envelope of CubeSat-based assembly satellite constellations and volumetric efficiency analysis of on-orbit assembly using "Bin of Parts".

1. INTRODUCTION

Increases in payload delivery capability and decreases in launch costs hold the promise of delivering greater payload volumes into orbit. This increase in volume of assets in space allows for the potential construction of complex structures and remote servicing of existing assets in order to better support scientific discovery, space exploration, and a variety of services intended to improve human life on Earth. Development of remotely-operable assembly and diagnostic systems is essential in order to ensure the success of these

historically been limited to large space stations and payloads with billion-dollar budgets and multi-year implementation requirements. Assembling and maintaining the rapidly-increasing volume of space hardware will require greater flexibility and lower cost than can be offered solely by manned systems.

With the recent boom in the CubeSat and nano-satellite fields, the small satellite capabilities have drastically increased to a point where many of these satellites are able to provide realistic augmentation, and sometimes replacement, to the larger satellite missions. However, one constraint that the small satellites have not been able to overcome is the physical limitations on the size of required large apertures. One solution to this is to operate assembly satellites that can assemble the required large apertures on-orbit from a "Bin of Parts", then attach them to the host satellites. This type of mission configuration ensures that the main satellite body was developed as efficiently as possible in the small cost-efficient form factor of a small satellite while being able to utilize large apertures.

space, USNA is developing a second-generation robotic-arm 3U CubeSat, Intelligent Space Assembly Robot (ISAR). ISAR is a small form, low cost, 3U CubeSat-class satellite intending to mature on-orbit robotic assembly capabilities, especially when paired with this particularly small and inexpensive form factor. It is comprised of two key subsystems: twin 60 cm, seven degree-of-freedom (DoF) robotic arms and the sensor-suite, which utilizes one 3D camera and two 2D cameras. In addition to the cameras, each arm is outfitted with contact sensors and proximity sensors to increase spatial awareness and aid real-time, responsive maneuvering in a dynamic space environment. The first generation robotic-arm satellite, RSat, serves as the foundation for the next-generation ISAR program. Based on the results from the RSat spacecraft, ISAR will remove the need for manual ground commands as well as improve arm accuracy, restraint systems, and overall longevity.

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 make use of feedback sensors are needed. These autonomous robotic systems are the next step in enabling spacecraft assembly.

2. CURRENT CAPABILITIES AND PROPOSED SOLUTION

2.1 Current, Demonstrated Capabilities

Current space robotics are limited in their scope and applicability to autonomous assembly. Instead, the majority of development programs and past systems focus on human-in-the-loop robotic control. These projects eliminate most aspects of autonomous operations and prioritize a high degree of reliability and safety.

The first major example of space robotic implementation are the first flights and the continuous use of the Canadarm on shuttle missions and onboard the International Space Station (ISS)[1] This robotic arm has been used to conduct inspections, assist in assembly processes, and perform docking operations over its lifetime and multiple design iterations. While Canadarm has tended towards autonomous operations over time, it still relies heavily on human input by personnel in space. As a result, complications due to teleoperations were eliminated because the human operator is located in close physical proximity to the arm during its operation. However, the requirement to launch astronauts and life support systems into orbit increases costs dramatically.

The ISS also contains the Japanese Experimental Module (JEM) which itself contains a primary arm known as the Remote Manipulator System or JEM-RMS as well as the Small Fine Arm (SFA). The JEM-RMS is also teleoperated by astronauts and used mainly to exchange payloads from the JEM through its scientific airlock. As the name suggests, the SFA is of a smaller form factor and can be used the carry out fine manipulation tasks.[2] Like the Canadarm, these arms are also subject to the limitations of their human operators.

The Orbital Express Space Operations Architecture, launched in 2006, was a successful program designed to validate the technical feasibility of conducting robotic, autonomous refueling and reconfiguring of satellites in support of both defense and commercial space interests. This demonstration facilitated further development of on-orbit servicing infrastructure.[3]

Another program that cuts down on human in-the-loop robotic operations is the DARPA Robotic Servicing of Geosynchronous Satellites (RSGS) program.[4] The project focuses on demonstrating refueling and repair operations on geosynchronous satellites. RSGS places an emphasis on using onboard intelligence to avoid collisions with either itself or the client spacecraft. A high degree of priority is placed 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 considering 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.[5] Restore-L will be demonstrating its servicing capabilities on the Landsat 7 satellite in Low Earth Orbit (LEO). While the real-time relative navigation system is an autonomous operation, the arm operation will still primarily utilize teleoperations. As stated previously, these types of operations can slow the assembly process down or potentially cripple the arm or host with an unintended collision.

The Kraken robotic arm, in development by Tethers Unlimited, is a small scale, highly dexterous robotic arm.[6] Two arms can be stowed into a 3U CubeSat form factor. The arm has a large reach (2.0 m) and can have up to 11 degrees of freedom (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.

2.2 Proposed Solution

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.[7] RSat served as a testbed for multi-degree-of-freedom robotic arm architecture that fit inside a 3U CubeSat form factor, manufactured using additive manufacturing techniques. ISAR continues this development.

ISAR exploits cost, testing, and high launch availability advantages of the CubeSat satellite form factor in a LEO mission platform. The system is being developed over a number of tests and validates key sub-systems over a series of increasingly complex flights. The first test of the system was the flight of the original RSat arms in a free-flyer experiment. Next, that hardware was been adapted to the requirements of the ISAR system for an assembly demonstration on orbit as shown in Fig. 1.

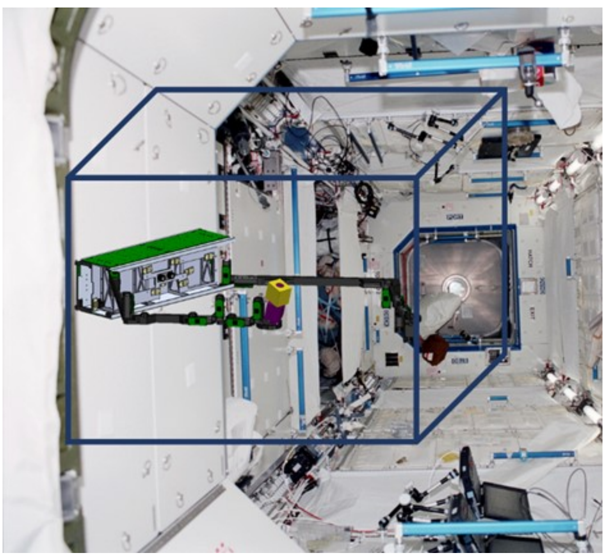

Figure 1: On-orbit Testing Concept of Operations

The current focus of the ISAR program is to use this hardware as a testbed for autonomous robotic operations, focusing most specifically on autonomous robotic assembly. ISAR combines the hardware heritage of the RSat spacecraft with an advanced autonomous robotic system that should enable fully autonomous spacecraft assembly operations. The on-orbit demonstration will occur on the inside of the ISS and focuses on demonstrating the autonomous assembly of scaled, test spacecraft parts. A successful demonstration will pave the way for future flights that will be free flyer demonstrations of this system to further enable spacecraft assembly.

With the desire for larger spacecraft and the limitation of launch vehicle size, on-orbit assembly will be the only method of meeting the demand for larger telescopes and antenna apertures. The automation of ISAR will permit the individual parts of a large satellite to be launched in a more volumetrically-efficient manner to complete the assembly on-orbit. Thus, launching a "Bin of Parts", along with the ISAR system, uses launch capabilities more effectively and can permit larger spacecraft. A notional Bin is packed similar to Fig. 2.

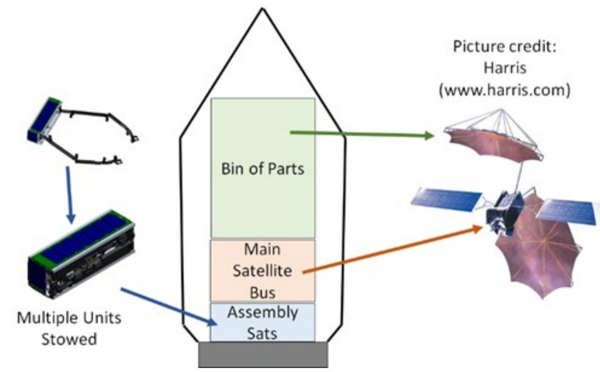

Figure 2: Depiction of Notional Bin-of-Parts and ISAR Launch Configuration

As can be seen, this stacking allows a vertical build-up of the payload, enabling it to take advantage of the internal shroud volume of typical launch vehicles more efficiently. Multiple ISAR CubeSats would be stowed beneath the parts bin. Once on orbit, the ISARs satellites would deploy.

Using their robotic arms to crawl over the Bin, the ISARs will assemble the primary satellite. The assembly would be programmed into the ISAR system, using arm position and the end-effector cameras to ensure proper positioning of various parts. The assembly plan would be modeled and simulated while still on Earth with checkpoints noted during the simulations. Once on orbit, each checkpoint would be verified before moving onto the next assembly section. Using arm position and camera data, along with the model, assembly steps would be reviewed with possible troubleshooting as needed.

For a very large aperture that necessarily requires assembly on-orbit since it will not fit in a single booster, a small change in the operations would be necessary. The assembly robot satellites, along with the multiple Bins of Parts, would be spread over multiple launches. To facilitate the proper coordination between the various deliveries, "tugboat" duties will be needed to provide shuttle services between assembly pieces as it was constructed. These tugboat duties could be a separate satellite that attaches to a piece of the large aperture or built into the different pieces of the assembly. With the progress of each of these tests, ISAR will demonstrate its capabilities for assembly of larger spacecraft.

3. SYSTEM OVERVIEW

ISAR is designed using the CubeSat standard form factor as a 3U payload (30 cm x 10 cm x 10 cm) and is a follow-on to the first-gen mission, RSat (described in section 3.1). ISAR's assembly capability is provided by two 60cm student-designed robotic arms, coupled with a suite of camera hardware and proximity sensors. Through the use of innovative additive manufacturing technologies and implementation of commercial-off-the-shelf components, ISAR provides a wide range of motion, manipulation, and imaging capabilities at low cost and can be launched on nearly any platform capable of delivering CubeSats to orbit.

3.1 Hardware Description

The first-generation robotic arm satellite is called RSat. RSat is comprised of two 7 DoF robotic arms that are housed in a single 3U CubeSat.[4,7] 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. Each joint is actuated by low-power stepper motors. Each motor uses a quadrature encoder and an encoder counter to implement a closed-loop stepping control scheme. The rest of RSat consists of Arduino processors for command and data handling, a 40 Whr battery and accompanying electrical power system, and a CADET S/U radio for data downlink and commanding of the sattelite. The completed arm constructed for flight is shown in Fig. 3.

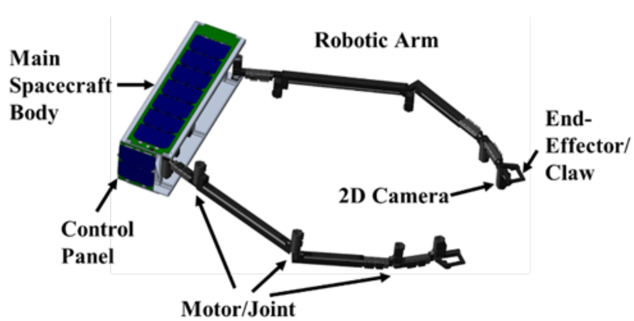

Figure 3: RSat Robotic Arm

The second-generation platform, ISAR, has robotic arms that have been derived from the RSat development cycle and 3D printed robotic arm made of composite and polymer material known as Windform XT. The ability to develop and manufacture these arms using advanced manufacturing techniques allows for more responsive development as well as the potential to field modular systems in the future. The overall satellite will continue to maintain a 3U CubeSat form factor. While the heritage of ISAR is the RSat robotic arm, there are a number of modifications that have occurred between the two iterations, with the main change being the increased sensor suite that can provide more feedback data in order to perform the autonomous assembly operations. The main additional sensor is the 3D camera, which is housed in the center of the satellite frame facing the two arms. This is used for creating a 3D mesh of the environment, which in turn is used in the trajectory planning of the robotic arm. The 3D camera that was tested and selected for the ISAR system is the Duo-M 3D stereoscopic vision camera. Figure 4 shows an example output of the 3D camera. The camera can provide stereoscopic information such as the vector to the target, distance to the target, etc. Of note, the ISAR system is not designed to be able to maneuver by itself in orbit. Any placement of ISARs in desired orbit or orbital maneuvers must be accomplished by a separate host system with propulsive capabilities.

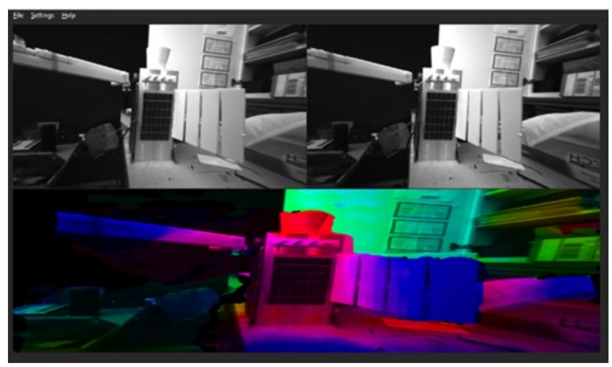

Figure 4: Example Output of the Duo-M 3D Stereoscopic Vision Camera

The second modification for this iteration of the ISAR satellite 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 Fig. 5 with the 3D camera shown in red. This modification was necessary to ensure secure stowage. Critical information will be gained about the 6 DoF arms in the upcoming launches, but depending on what is learned, future systems could be considered with either variant of robotic arm.

Figure 5: RSat (top) and ISAR (bottom) Arms

Figure 6 shows an example configuration for the 6 DoF arms deployed half-way. This depiction represents the first step in the deployment sequence where the "elbows" fold out so that the cameras can be pointed outwards. This way, most of the joints can be tested for functionality. The next step of arm deployment is to actuate the "shoulders", or the root of the robotic arms, to achieve the full 60 cm extension of each arm. When both of the arms are outstretched, the wing-span will be 150 cm. Green rectangles seen in Figs. 5 and 6 are individual microprocessors which control each of the joint motors. These microprocessors will be commanded by a central computing unit, which consists of two Raspberry Pi boards.

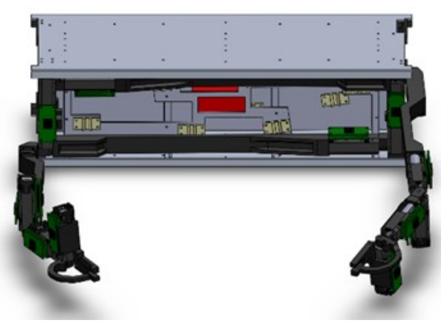

Figure 6: ISAR with its Arms Extended Half-way

The end effector in each arm has two features. The first is a simple claw-like actuator that is able to grab objects, and the second is a small camera mounted outward in the direction of the end effector "claw". Figure 7 shows the end effector design. Using the camera, the end effectors can accurately move to the target object and successful grab an object, or any commanded actuation can be verified through imaging. There are also sensors in the arms that will sense the end effector making contact with objects. The end effector claw itself has a laser photo-gate sensor such that it can sense when an object is within its grasp range.

Figure 7: ISAR End Effector "Claw" Design

3.2 System Verification and On-orbit Demonstration

The first phase is ground-testing of the robotic arm actuation and algorithm verification. A bigger motor with higher strength is used to simulate the flight robotic arms. This modification was required to enable the robotic arms to function in 1G environment. Figure 8 shows the internals of the flight robotic arms, and as can be seen, the joints of the arms are attached directly to the shaft of the motors, greatly reducing the strength of each joint. This was necessary for fitting 150 cm arm-span robotic system into the limited 3U CubeSat volume. Ground testing and algorithm development is detailed in Section 5.

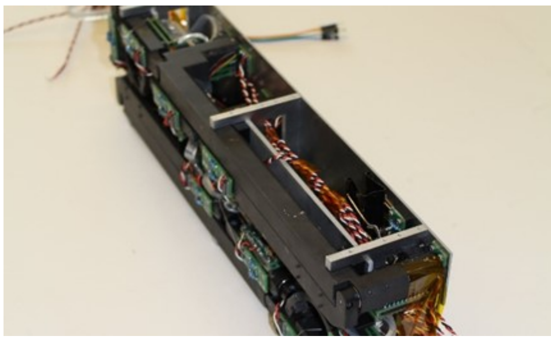

Figure 8: Picture of Internal Arm Assembly of ISAR Flight Model

A second phase of the improved system verification is on-orbit demonstration. Unlike the free-flyer 3U CubeSat experiment of RSat, the follow-on ISAR system currently under development will be installed inside the ISS. As can be seen in Fig. 1, a test enclosure is required when being installed inside ISS in order to ensure astronaut safety. The enclosure will serve both as a protection and sensor augmentation device for aiding in data collection of the experiment. The test enclosure has two main elements, the enclosure structure and the Enclosure Interface Unit (EIU). The structure consists of the basic frame and supporting components such as the payload mount, and storage hardware for the extra payloads and test pieces. The EIU allows the astronauts to perform vital functions to the payload without opening the enclosure.

The Enclosure structure is a 60 cm x 60 cm x 120 cm framed with clear side walls to allow viewing of the experiment from the outside. The clear walls will be ESD-resistant polycarbonate sheets. The framing material is an extruded aluminum provided by 80/20 Inc. 80/20 kits also provide various hardware components that can be utilized for fasteners, hinges, and latches for various components in the design of the enclosure. The latest version of the test enclosure CAD is pictured in Fig. 9. Due to the compact design of the ISAR payload, any repair will be extremely difficult. Accordingly, three identical units will be packaged together to provide redundancy. The green shaded region shown in the Figure denotes the area currently allocated to stow the extra payloads. The enclosure structure will also provide mounting capabilities for four internal cameras, stowage for the experiment test pieces, and storage for two spare payloads. The test enclosure was designed with ease of operation and maintenance in mind.

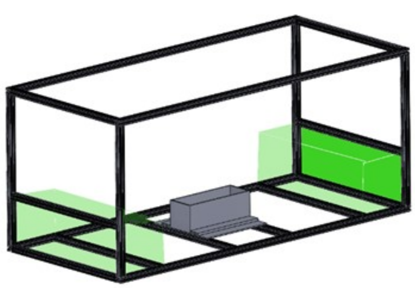

Figure 9: Test Enclosure Design

4. RATIONALE FOR ON-ORBIT ASSEMBLY

The Space Assembly of Large Structural System Architecture was a study conducted to investigate the technologies needed for space assembly. It included the infrastructure for robotic servicing and assembly.[8] This analysis mentions three main areas where on-orbit assembly would be vital if not the only option: large telescopes, large solar arrays, and exploration vehicles. Similar work by Bowman et. al. was recently published highlighting in-space assembly.[9] The study added emphasis on solar shields and persistent spacecraft being serviced over their lifetime, along with telescope sizing and large power generation. An interesting point was discussed about the role of low cost CubeSats. The paper claimed that the small CubeSat form factor significantly hindered the ability of such spacecraft to be a viable option for on-orbit assembly.

To continue to explore the universe, large aperture telescopes will be needed. Innovations with telescopes like the James Webb Space Telescope (JWST) will lead to an improved ability to view space. Using folding mirrors, the JWST provides a diameter of 6.5 m. For these folding mirrors to fit into the current launch size and mass constraints of boosters, it requires very complex packaging. The end result is that the booster will drive the maximum size of the aperture.[10] While not being assembled in space, the JWST will show the utility of a larger telescope, emulating large ground-based telescopes such as the Thirty Meter Telescope and 39 m European Extremely Large Telescope. As scientists look for larger observation platforms, the need to assemble these large systems in space becomes evident.

Another use for assembly on orbit would be for Space Solar Power (SSP) beaming which would provide power directly from space to a ground location. Massive solar arrays with their respective antennas will need to be built. These solar arrays would be on the scale of kilometers, generating megawatts of power with a transmission antenna on a similar size scale.[11] With current launch technology, it would be impossible for such large sized systems to be built on Earth and launched. The SSP system will have to be built in parts and assembled in space as a result of its sheer size. A set of trusses as a foundational system will have to be assembled, then solar arrays positioned on the trusses. Finally, an antenna to beam the power to Earth will need to be assembled.

A final example is a lunar or planetary explorer. In order to house the necessary components for a sustained visit to the Moon or a trip to Mars, more modules are required than available on a single launch system. This assembly method is similar to the construction of the ISS. Parts of the station were launched on individual boosters, then assembled in space.

On-orbit assembly not only permits larger structures to be built in space but will permit more effective use of launch systems. This technology reduces the risk and removes constraints with payload fairing limitations, the need to meet launch load designs, and the catastrophic impact to a satellite if a booster should fail.[12]

CubeSats are already being used to test assembly methods, like in the AAReST program at the University of Surrey.[13] This mission will use two 3U CubeSats to perform rendezvous and docking operations with a central satellite. By performing these operations, a larger aperture will be represented. This mission will break from the current constraints of booster size and demonstrate one possibility of the future of on-orbit assembly using CubeSats.

4.1 Example ConOps Using ISAR CubeSats

The most efficient use of a launch may be to include assembly robots together with a parts bin in a single launch, packaged in a volumetrically-efficient manner. An example of this notional payload was shown previously in Fig. 2. The main payload satellite will launch without its large aperture structure. The parts required to make this large aperture structure will be stored in the parts bin. Depending on the complexity of the assembly, a number of ISAR satellites will also be stowed into multiple deployers attached to the bottom of the payload stack, completing the launch vehicle payload. As can be seen in Fig. 2, this enables a vertical build-up of the payload, allowing it to take advantage of the internal shroud volume of typical launch vehicles.

ISAR leverages having the assembly robot satellites be of small form factor, inexpensive to manufacture, and not include orbit-maneuver capability. Once on orbit, the assembly satellites will deploy themselves from their respective stowed locations, and use their robotic arms to crawl around the surface of the parts bin to perform on-orbit assembly. In this scenario, only one launch will be required for deploying a large aperture onto a host satellite. Significant cost on the order of up to $250,000 is typical in the development of a new and complex CubeSat system.[14] However, with the second generation ISAR design defined, the material cost of an assembly satellite is approximately $30,000 per satellite and can be assembled and tested in approximately 200 man-hours. Assuming an average labor rate of about $50 per hour and an additional $50 per hour for overhead, then the total cost of a single ISAR CubeSat can be conservatively estimated at $50,000. This is in line with available industry data on CubeSats which can range from $5,000 up to about $42,000 to manufacture a single cubesat.[15] Similarly, it is estimated that after development each bin of parts structure and ISAR deployer would cost around $100,000 in material and require an additional 200 man-hours labor and overhead to manufacture. Therefore, the bin and deployer are estimated at a total cost of $120,000. Assuming 10 assembly satellites as well as $120,000 for the added bin structure and ISAR deployer the total additional cost for the mission is estimated to be $620,000. In other words, for an additional cost of $620,000 to a mission, a smaller and more capable satellite with large apertures can be launched into orbit. There can be a potential large cost savings by being able to make the satellite smaller since no complex deployment mechanism is needed, resulting in smaller and cheaper launch vehicle selection. Also, there is a potential of having a larger aperture than the traditional design would have allowed.

The concept of operation will be different for large systems that require extensive on-orbit assembly operations. Such missions, notionally, will require the assembly robot satellites along with the multiple Bins of Parts, to be spread over multiple launches. To facilitate this coordination between deliveries, "tugboat" satellites will also be delivered that will provide shuttle services to bring the robotic satellites together at the assembly site. Baselining a small launch vehicle such as an Electron rocket that has the lift capability of 150 kg to 500 km orbit, 5 tugboat satellites and 25 ISAR robotic satellites can be launched together in a single launch. Each assembly satellite costs approximately $50,000 and each tugboat satellite costs approximately $120,000 in hardware and labor cost. Electron rocket launches cost $5M. This means a group of 25 on-orbit assembly robot satellites could be delivered to the large system assembly site for less than $7M.

4.2 Effectiveness of "Bin of Parts"

The economic case for the "Bin of Parts" solution is made if either the capability of the solution is substantially similar while the cost is significantly less than traditional pre-assembled large aperture satellites, or if the cost is substantially similar and the capability is significantly improved. There is also a potential for cost improvement when considering the economic order quantity benefits of a large number of ISAR satellites.

To illustrate a reduction in the cost of "Bin of Parts" launches as compared with a traditional launch, we should compare the known cost of a large-aperture launch to the predicted cost using on-orbit assembly with a set of ISAR systems. One example of a recently fielded and launched system is the US Navy's Mobile User Objective System (MUOS). MUOS is a next generation narrowband tactical satellite consisting of 5 systems assembled on Earth and launched between 2012 and 2016 aboard an Atlas V 551 Configuration. The as-launched system had a payload mass of 6,740 kg and included 2 deployable solar arrays.[13] If this system were to be launched today aboard the same Atlas V 551 Configuration, estimates suggest that the launch cost would be approximately $179M.[16] The Indian Geosynchronous Satellite Launch Vehicle (GSLV) is a smaller and less expensive launch system currently available and rated to carry a payload of up to 2,500 kg to a Geostationary Transfer Orbit at a cost of approximately $47M per launch.[16] With the availability of ISAR, one option would be to split the MUOS system into three separate launch payloads, break it into parts, and launch it unassembled along with a contingent of ISAR satellites. If each GSLV launch vehicle contained one third of the MUOS system, 25 ISAR satellites, a Bin of Parts, and five tugboat satellites, it would add approximately $1.85M to a launch. Therefore, three launches at $48.85M apiece would result in a total launch cost of about $146.55M, a calculated savings of $32.45M from the nominal case. As an added benefit, conducting three separate launches mitigates some of the risk of a single catastrophic failure event.

Perhaps more compelling, however, is the fact that on-orbit assembly using a Bin of Parts methodology paves the way to enable capabilities and technologies that cannot be realized currently. As mentioned previously, a prime example of such a technology is the Space Solar Power beaming.[11)] On-orbit assembly may be the only way this promising technology can be realized.

Similarly, in the Space Science arena, Dorsey states that there is a particular interest in large space telescopes with apertures on the order of 10 to 50 m in diameter.[11] Once again, these would be very difficult to launch preassembled, and utilizing on-orbit robotic assembly in the form factor of a CubeSat could be instrumental in making these discoveries possible.

5. ANALYSIS OF RESULTS FROM GROUND TEST PLATFORM

The on-orbit demonstration will be carried out by performing robotic arm maneuvers that signify tasks that would be performed by future on-orbit assembly operations. Initially, the arm hardware performance will be tested and validated through a series of planned arm motions including joint-angle-commands, imaging camera accuracy tests, and pre-coordinated arm movement tests. Upon successful conclusion of these hardware tests, the novel robotic arm control algorithm will be tested to assess its performance. The algorithms developed are a hybrid system utilizing both Jacobian path following and visual servoing. The Jacobian path following involves the derivation of a Jacobian matrix which is used to relate joint velocities to task space velocities to execute path following. The visual servoing is based on a previously derived method of executing visual servoing that accounts for the translation and the orientation change in the robotic arm using a camera. The main purpose of all of these approaches is to relate a change in coordinates in 3D space to a change in the joint angles of the robotic arm. Then from there the understanding of how the joint position needs to change can be used to move the robotic arm in 3D space to produce that desired change. On-orbit demonstration of this concept will involve the robotic arms manipulating toy pieces. The arms will first navigate to a toy piece, for example a circular peg, then move the piece to fit into a receptor panel to demonstrate end-effector manipulation and motion planning. Figure 10 depicts an example of this toy-manipulation maneuver.

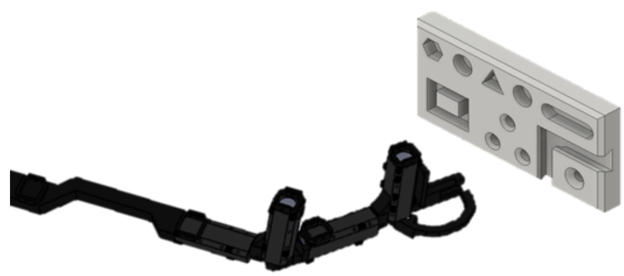

Figure 10: Depiction of Robotic Arm Interacting with a Toy to Demonstrate Performance of the Motion Algorithm

The algorithm was first tested on the terrestrial robotic arm setup. There were three arms that were built in simulation. They were a theoretical 2DOF and 6DOF arm, a ScorBot, and a UR5. The system was also simulated on a real UR5 arm. The initial testing was done using a simple 2DOF robotic arm with several simplifying assumptions, which means that this simulation only moves the robotic arm in a single plane. The robotic arm used is shown in Fig. 11.

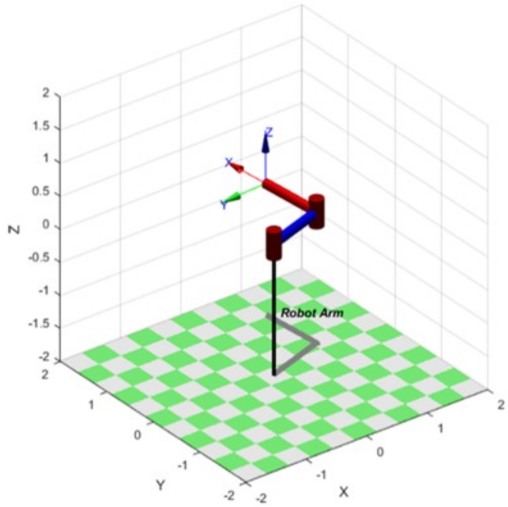

Figure 11: 2DOF Robotic Arm in Single Plane Simulation

The initial results of the simulations showed that the system is initially feasible. They indicated that the trajectory path planning is the most direct method of moving from the starting configuration to the ending position, where the path is essentially a straight line from start to end. This path results because when executing Jacobian path following the arm moves both of its degrees of freedom to achieve a nominally straight line but visual servoing will primarily operate fewer joints resulting in a curved path. This simulation failed to take into account the errors that are inherent in this approach. These are due to errors intrinsic in the sensor, for this application of a 3D camera, where at certain distances from the sensor the Jacobian path following is less accurate. In practice, the robotic arm will not always follow such a straight line from start to finish and will probably arrive at an inaccurate ending position. This non-straight travel was the main reason for the development of a hybrid system to take advantage of Jacobian path following and visual servoing methods. The results of the hybrid system showed that the maneuver can be executed faster and more accurately. The details of the algorithm development and results are outside the scope of this paper, however, and will be published in full in a different article.

6. CONCLUSION

The development of a semi-autonomous on-orbit assembly constellation in a CubeSat form factor enables increasingly complex missions. The United States Naval Academy has developed the Intelligent Space Assembly Robot (ISAR), a remotely-operated orbital assembly testbed that utilizes robotic arms, 3-D camera systems, and a suite of additional contact and proximity sensors to perform various tasks required to maintain and assembly assets in space.

The ultimate goal of ISAR is to advance the on-orbit assembly technology further so that a constellation of ISAR satellites can perform semi-autonomous or autonomous assembly operations in space. This constellation will share a common assembly procedure as uploaded from a ground station, and will be intelligent enough to divide up the tasks, coordinate, and execute assembly of a complete satellite system. An improved sensor suite and better feedback control will be essential in the next iteration of ISAR development as will refinement of the robotic arm design. Ultimately, costs for future ISAR designs will remain low by omitting orbital maneuvering capabilities and leaving this task to separate "tugboat" systems.

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