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Ground Demonstration of New Robotic Technologies for On Orbit Servicing to Enable Maneuver Without Regret for Small Sat Missions Beyond GEO

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ABSTRACT

In this paper we will discuss the demonstration of on-orbit servicing capabilities by a new robotic manipulator, designed from the bottom up to fit within the Size, Weight, and Power (SWaP) constraints and budget expectations of smallsat missions. There is a recognized need for extreme mobility to meet the space domain awareness goals of the U.S. government in cis-lunar space, and on orbit servicing is the key to establishing this capability. In addition, a small spacecraft profile is critical, with transportation costs particularly high beyond earth orbit. In the past, robotic systems capable of on-orbit servicing have resulted from years of expensive development and typically weighed more than 70 kg. This makes them ill-suited to the needs and constraints of small sat missions. The new Modular Robotic Manipulator (MRM) is right-sized in terms of performance, has mass in the range of 10 – 20 kg, and can be rapidly reconfigured for minimal recurring development in order to fit within smallsat mission budget constraints. In this paper, we will provide more details about the MRM, and describe our efforts to better understand its performance, and to demonstrate its ability to perform typical on-orbit servicing tasks. And finally, we will discuss the generation of manipulators beyond the MRM, and our efforts to further improve the accessibility of robotic systems.

MOTIVATION

Activity in the cis-lunar region of space has recently been on the rise, driven by several factors. Chief among these is the NASA Artemis program to return humans to the moon, and to establish a permanent and sustainable presence there. The first deliveries associated with this program are scheduled to arrive later this year, with the Cis-lunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) CubeSat traveling in 2021 to the Near-Rectilinear Halo Orbit slated to eventually be occupied by the Gateway[1], and Astrobotic's Peregrine Mission One landing at Lacus Mortis later the same year[2]. At the same time, the Chinese Lunar Exploration Program is also in full swing, with five missions successfully executed, including two orbiters, a communications relay at Earth-Moon L2, and two landers already on the surface. Five more missions are planned in the 2020s, making cis-lunar space a popular destination[3].

This activity is driving increased attention from the United States Department of Defense, which has historically cooperated closely with civil government institutions to ensure the safety of operations in space. A recently refreshed Memorandum of Understanding (MOU) between NASA and the United States Space Force (USSF) directly identifies space domain awareness as a mission for the USSF. It also notes that public and private sector activities extending into cis-lunar space have caused an extension in its sphere of interest and that new technologies will be necessary to meet the needs of this new mission[4].

We can see this increased interest in cis-lunar space domain awareness reflected in architectures proposed by the Space Development Agency (SDA). They are studying the idea of fielding Advanced Maneuvering Vehicles (AMVs) that would rendezvous with a suspect object returning from deep space in order to gather intelligence on it and to act as a form of deterrent[5]. In addition, we can see interest in this space from the Air Force Research Labs (AFRL), which has recently initiated the development of two flight experiments. The Defense Deep Space Sentinel (D2S2) will demonstrate the extreme mobility that small satellites will need to operate effectively in this region of space[6], and the Cis-lunar Highway Patrol Satellite (CHPS) experiment will investigate sensing technologies and algorithms for Space Domain Awareness (SDA) in this sphere[6].

On orbit servicing will be key to the success of missions like the SDA AMVs, and those that build off D2S2 and CHPS, by allowing them to maneuver on demand and without regret, while remaining small and light to keep the cost of launch and transport reasonable.

BACKGROUND: ON ORBIT SERVICING ARCHITECTURE

In the context of maneuver without regret, on orbit servicing really refers to servicing of the propellant system. Access to space is still a significant portion of the life cycle cost of any given mission, and while this problem is getting a lot of attention from commercial industry, the distance to cis-lunar space and relatively low traffic to that region makes it unlikely that this situation will change in the foreseeable future. As such, spacecraft maneuvering will remain limited by the mass of fuel that it is possible and economical to carry. An ability to refuel on-orbit breaks the connection between launch mass and maneuvering capability, and thereby allows smallsats to address missions that they otherwise could not.

Beyond the sheer mass limitation, there is also a question of thruster throughput. The need for fuel efficiency typically results in the use of an electric propulsion system, and here there is a correlation between thruster life capability and mass and cost. Finding a long-life thruster that matches a small sat mission size and cost constraints can be difficult, and in some cases, this can nullify the benefits of refueling. In these cases, modularization and on-orbit replacement of the electric thruster system would also have to be considered.

Performing either an in-space electric propulsion refueling operation or an electric thruster replacement would involve the use of quick-disconnect fluid couplings capable of high-pressure transfer. This is because Xenon or other electric propulsion system propellants are typically stored at 3000 psig. For the thruster replacement there would also be the need for a mechanical latching system and high-power electrical connectors. Fortunately, all of these are well developed technologies. In particular, NASA has performed several examples of in-space fluid coupling as part of their Robotic Refueling Mission (RRM) experiments, conducted on the International Space Station. One of the outcomes of those has been the development of the Cooperative Servicing Valve (CSV), a drop in replacement part for standard fill-drain valves, design for robotic installation and actuation, and to transfer high pressure propellants such as Xenon[7]. In addition, NASA has performed experiments in robotic replacement of electric thrusters, again using mechanical latching and electrical blind mate systems developed during the RRM program[8].

The final piece of the puzzle is the robotic manipulator that brings all of these interfaces together to connect on orbit. Typically, this has been the mass and cost driver of the servicing system. Previous examples of space robotic systems with servicing capabilities include the Orbital Express Dexterous Manipulator System (OEDMS), the robotic arms of the Robotic Servicing of Geosynchronous Satellites (RSGS) and On Orbit Servicing Assembly and Manufacturing (OSAM-1) 1 missions, and the Special Purpose Dexterous Manipulator (SPMD) system of the ISS. All of these systems required significant investment over many years to reach maturity, which is very much out of sync with the needs of a small sat mission. Also, the OEDMS, RSGS, and OSAM-1 servicing arms all weighed greater than 70 kg[9, 10], which would make a significant impact to any small sat mass budget. What is needed is a right sized manipulator, scaled to smallsat mass and reach requirements, and available without overwhelming development costs and timelines.

COMMERCIAL ROBOTICS AND THE MODULAR ROBOTIC MANIPULATOR

Our goal with commercial robotics was to create a product line that was built out of a set of common, qualified parts, and able to deliver well understood performance within a reasonable range of pre-defined options. We see this as a significant departure from bespoke robotics, where the machine is custom designed and built to exact specifications provided by the customer.

The SPIDER Robot

Our first foray into this realm was the Space Infrastructure Dexterous Robot (SPIDER) robot, built for NASA to fly on the OSAM-1 mission, in order to demonstrate on-orbit servicing and assembly tasks. The SPIDER robot is a seven degree-of-freedom robot, with common motors and gearboxes at all its joints, as well as common controllers. It is architected for minimum impact on the host spacecraft, able to function with slow and simple communications to the ground, and processes all communications on its main control computer, so that the host spacecraft need only provide a bent pipe channel with the ground over a single serial data bus. However, the SPIDER robot is still a large, high performance machine. It is 5 m in length, designed to accommodate walking and free flyer capture (a very demanding activity, in terms of performance), and to perform precise assembly operations at near to its full reach. It is also designed to support what has become a Category 1 mission with a Class C risk posture[11], and is therefore equipped with full redundancy.

The SAMPLR Robot

Our next iteration of the Modular Robotic Manipulator was built for NASA to support the Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith (SAMPLR) mission. This mission is operating under the Commercial Lunar Payload Services (CLPS) program, in which program risk is managed by the commercial payload providers, rather than NASA, and so practices comparable to a Class D mission are common. With this in mind, and to fit within the smaller budget of the early CLPS payloads[12], the design of the SPIDER arm was evolved for simplicity. The same architecture of common joint modules (motor + gearbox) and common distributed controllers was used, but the actuators were redesigned for easier manufacturing, electronics were selected in line with the limited life expectations (one lunar day), and the control system was simplified with stepper motors used rather than Brush-Less Direct Current (BLDC). The result was a small and light robotic manipulator with solid performance, well beyond what was needed for its sample gathering tasks, delivered within a budget commensurate with small sat missions.

DETAILS OF THE MODULAR ROBOTIC MANIPULATOR SYSTEM

Mechanical Design

The mechanical structure of the MRM consists of modular links and joints that use Harmonic Drive transmission. The nominal configuration for the MRM is shown in Figure 1. Components (A) contain two Harmonic Drives placed at a right angle to each other. Component (B) contains a single Harmonic Drive and along with component (C), which is a simple link, is used to extend the reach of the arm. Component (A) can be used as the base or end effector links or can be used at an intermediate location in higher degree of freedom kinematic configurations. The joints are all hollow shaft to allow for easy electrical and data cable wiring.

The baseline configuration of the robotic arm does not include any tip mounted sensors, or end effector. These would be separately developed or procured and integrated with the tip end of the robot. Power and data harnessing would be passed through the hollow shafts for simple management. In our lab, we have developed a variety of tip-mount hardware in order to address a variety of applications.

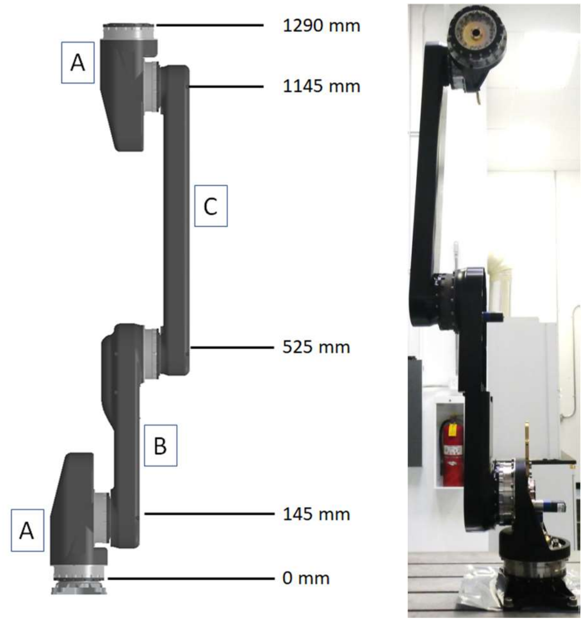

Figure 1: Baseline configuration of MRM in layout pose. The modular components of MRM allow for multiple kinematic configurations. Component (A) contains two joints at a right angle to each other and is suitable for the base joint, connecting an end effector, or as an intermediate joint providing a higher Degree of Freedom (DoF) configuration. Link (B) contains one joint while link (C) doesn't contain any active joints. Both links can be used to extend the reach of the arm.

Electrical Design

The electronics of the arm are contained in components (A) and (B) referenced in Figure 1. These are custom designed low-cost motor controller boards that Maxar has designed for the MRM and can be paired with the MRM or used in other applications. The motor controller boards are designed to accommodate both stepper and BLDC motors, allowing for the robotic system to be further tailored for a specific mission and cost point. The motor controller board can control two axes with closed loop current, velocity, position and torque monitoring. It also supports a high speed EtherCat interface to allow for higher performance and modernized control over other options available in the space market.

Modularity in Software

A robot is only as capable as its software which is why we created suite of products that allow us to efficiently design, simulate, test and operate any configuration of the MRM line. Each software product was built with modularity in mind. This modular architecture means a new configuration could be simulated and validated in software with little effort. Once the final design is chosen, any configuration updates or modules can be added into the test, operation, and flight software products depending on mission need.

Flight Software

One of the keys to rapid development and validation of any software product is the ability to re-use software that has already been proven. This is especially critical in embedded/flight software where it can be tempting to write software that is hyper specific to the target hardware. We have maintained our focus on developing a robust flight software framework that could support applications with a wide array of use cases across various operating systems and hardware platforms. This allows the selection of the arm computer to be chosen on a case-by-case basis without huge development costs. The flight software has been demonstrated on the systems shown in Table 1.

Table 1: Hardware systems on which the flight software for MRM has been tested.

OS	Hardware
Linux	PC
Arm Linux (Yocto)	Xiphos X7 (Arm Cortex A-9)
Raspian	Raspberry Pi 3B
FreeRTOS	PC
FreeRTOS	ATSAMV71 (Arm Cortex M-7)

Robot Command Center (RCC)

The Robot Command Center is a dynamic and configurable tool designed for test and operations. Given an ICD for the flight software, the RCC can dynamically configure which helps drive down costs for customized instances of test and operation software. The tool allows viewing of telemetry and commanding of the robot.

Mission Operations Tool

The Mission Operations Tool (Figure 2) is a 3D planner and visualizer designed for our robotic systems. It increases situational awareness with its high-fidelity graphics and option to operate in virtual or augmented reality. With increased situational awareness, operators can easily design and simulate Con-Ops for a mission. The tool was also built for collaboration by allowing multiple stake holders to participate in the development of Con-Ops whether they are on a computer or in virtual reality, everyone will be on the same page to ensure mission success.

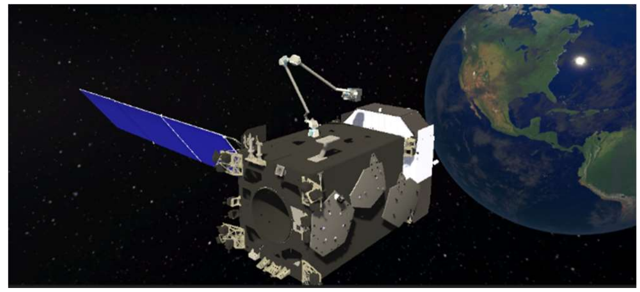

Figure 2: Mission Operations Tool

To enable rapid development and maximize the versatility of the RCC and Mission Operations Tool, ROS2 interfaces have been built into both. Figure 3 shows an example of this interface to command the MRM.

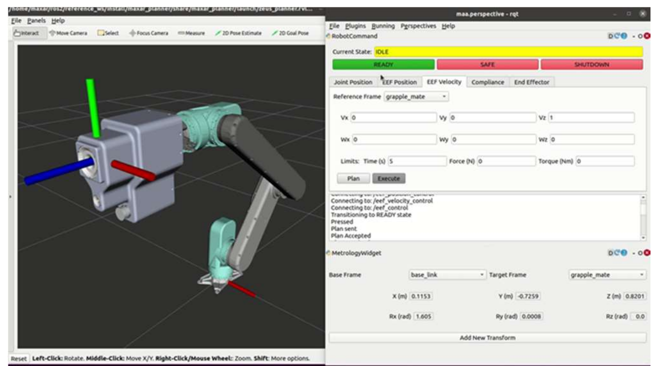

Figure 3: ROS2 based interface to the RCC and Mission Operations Tools.

MODULAR ROBOTIC MANIPULATOR GROUND ASSEMBLY DEMONSTRATION

Goals

The MRM has been developed with modularity, scalability, and reconfigurability in mind, and offers a robotic solution perfectly sized to allow a smallsat mission to take advantage of on-orbit assembly and servicing capabilities. However, the only application of this architecture thus far has been the SAMPLR mission, whose task of regolith probing, inspection, and scooping generally imposes less performance requirements than assembly and servicing. Therefore, we set out to perform a ground demonstration of a task of appropriate difficulty so that we could show that the performance of the MRM would be sufficient for this application as well.

Background

In order to demonstrate the capabilities of the MRM, we chose to use it to perform one of the on-orbit assembly tasks planned as part of the NASA SPIDER flight demonstration. The SPIDER payload aims to demonstrate on-orbit assembly and servicing by constructing (from modular segments) an RF antenna reflector, and by removing and re-installing an avionics package from the host spacecraft. To support these tasks, a number of unique module interfaces have been developed, and the one we chose to use for our demonstration of MRM capability is the segmented panel interconnect, which allows the joining of the RF reflector pieces. This is shown in figure 4. Because this interconnect has to remain as a permanent part of the RF reflector, it has been carefully designed for low impact, in terms of mass, size, profile, and simplicity. For this reason, it presents unique challenges to the robot performance during installation and we determined that it would be a good test for MRM capability. In addition, the cooperative mating interface developed as part of this interconnect has a very similar capture envelope to cooperative servicing interfaces developed as part of the NASA RRM program. These have in turn been successfully operated by the Special Purpose Dexterous Manipulator (SPDM) robotic system on the International Space Station (ISS). Therefore, we propose that successfully demonstrating mating of the SPIDER segmented panel interconnect with the MRM system shows its ability to perform the in space assembly tasks being pioneered by SPIDER, and also that it has the capability to tackle in space servicing tasks along the lines of the RRM program.

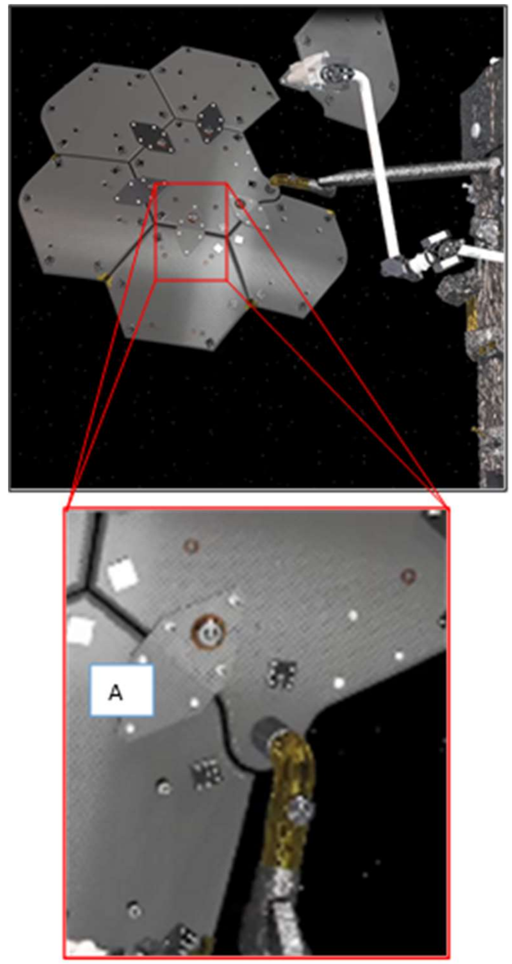

Figure 4: The SPIDER robot performing on-orbit assembly of an RF reflector system, making use of the segmented panel interconnects (A).

Segmented Panel Interconnect Operations

The basic segmented panel interconnect installation procedure is: 1) The robot picks up a segmented panel interconnect by the handling fixture and maneuvers it to a high hover position, where it can see the target fiducial with the alignment camera. 2) With target fiducial in sight, standard machine vision techniques are used to generate a relative pose estimate from the current position to the required installation position (leveraging a-priori knowledge of fiducial to installed position relation). 3) The relative pose estimate is used to plan a robot trajectory to a low hover or pre-install position (Figure 5). 4) Once good alignment is confirmed at the pre-install pose, compliance control is activated, and the robot is commanded to move ahead to mate the two halves of the interconnect. Compliance control uses feedback from the tip mounted force-torque sensor to drive a locally closed control loop that keeps the robot moving in the direction of mating, while also performing off-axis adjustments to maintain reaction loads below a specified threshold.

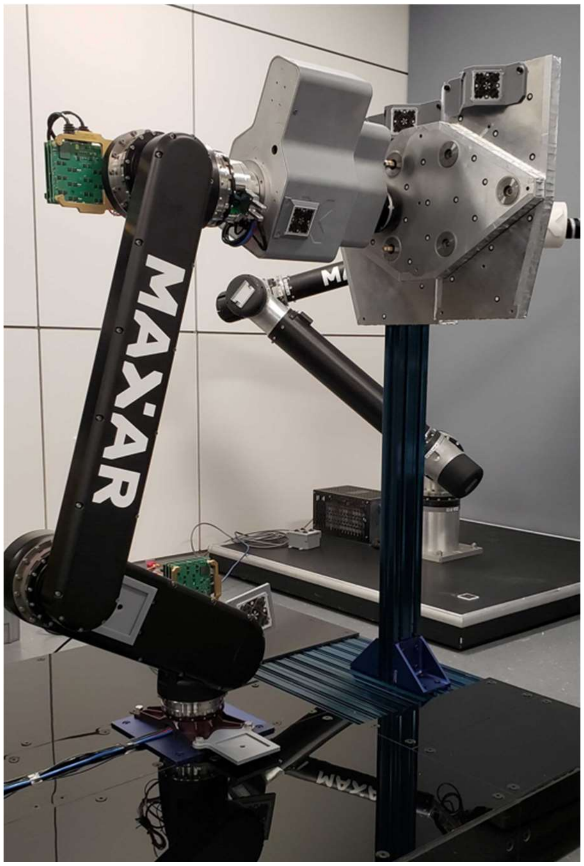

Figure 5: The MRM ground arm performing an assembly operation utilizing the segmented panel interconnect. This is a breadboard version used for early risk reduction testing on the SPIDER program.

During the final maneuver, the end effector force torque sensor is monitored for conditions indicating a successful mate of the segmented panel interconnect interface components and any unintended collisions. 5) At this point the segmented panel interconnect is fully seated at the installation position, and the latching fasteners are driven (one by one) to establish a semi-permanent connection.

Success of this operation depends on the segmented panel interconnect capture envelope being larger than the robot system closed loop trajectory control error. This error term includes a number of contributing factors, shown in figure 6.

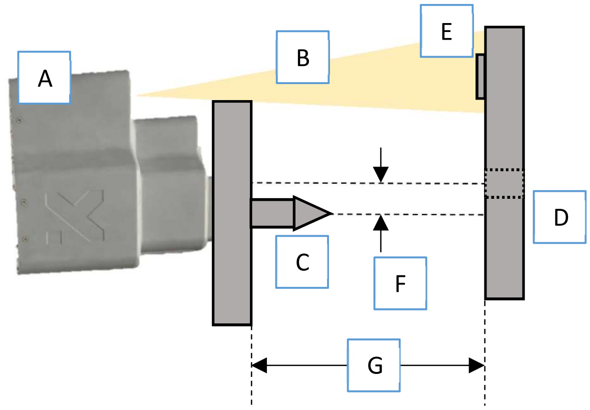

Figure 6: Contributors to a closed loop control error budget. Relative position and orientation of the active half of the interconnect (C) to the passive half (D), is determined by use of an end effector mounted boresight camera (A) to observe a target fiducial (E). Target must be within camera field of view (B). Initial error (F), prior to initiation of final plunge, is limited by machine vision accuracy and robot repeatability. As plunge distance (G) is traversed initial orientation error is propagated, and robot trajectory tracking error comes into play.

Since we are using a camera to target pose estimate to determine the required path from active side of the interface to the passive side, there will be a number of small errors resulting from limitations in hardware assembly and measurement accuracy, as well as from tolerances between the robot end effector and module handling fixture, which are necessary to accommodate thermal expansion. That being said, generally the major contributions are from limitations in the machine vision pose estimation, and in the robot positioning capability. Therefore, we have made sure to include these two factors in our ground demonstration of MRM capability.

Of the two major contributors to closed loop error, we will pay particular focus to the robot positioning and trajectory tracking capability. The reason is that this is generally a greater driver of recurring system cost than machine vision accuracy. Machine vision pose estimation with target fiducials is a well explored field, and a number of hardware and software solutions are readily available that can provide performance comparable to the SPIDER systems within smallsat cost and mass constraints.

Demonstration Operations

The MRM ground arm is a 1 meter configuration of the MRM line, but built with 1 G capability in mind as well as relaxed material requirements since it doesn't need to withstand the harsh environment of space. This provides a low-cost engineering unit for testing and demonstration. The end effector is an in-house development designed for simplicity, and to interact with the SPIDER developed mechanisms and interconnects. The last component required for the demo is the mock segmented panel interconnect panels which are small and flat compared to the larger, curved segmented panel interconnects designed for flight.

The demonstration started with a segmented panel interconnect already attached to the end effector. Since picking up a segmented panel interconnect requires significantly less accuracy than mating it, this was deemed an acceptable starting point. The robot was then command to a pre-mate position based on data from the camera system and a-priori knowledge of the fixed side of the segmented panel interconnect's location. Using target fiducials, the system calculates a relative pose based on MRM's current state and the visible fixed side fiducials.

The accuracy of the 1 m configuration allowed a successful mate repeatedly without the need for alignment features or closed-loop control around the force-torque sensor. For many smallsat applications, a similar configuration would be used and could allow for assembly without the need for extra mechanical or software features. For larger applications, alignment features, force-torque control, and other modern control techniques can be used to ensure a higher accuracy and proper mate of the components which we will examine in the next section.

REPEATABILITY AND MINIMUM MOVE TESTING

To confirm arm level capability of the system, repeatability and minimum move testing was performed with a FARO laser tracker. For repeatability testing, open loop 100 mm Cartesian moves were performed in single axis directions which mimics the plunge action for performing a mate of the segmented panel interconnect interconnects. The data we collected shows a tip accuracy of ±0.8 mm and precision of ±0.5 mm. With better kinematic calibration, and closed loop control, we expect to see the accuracy closer to ±0.2 mm for the 100 mm motions.

For minimum move testing, moves were commanded in descending order until no motion was observed along the single axis Cartesian directions. The minimum move recorded was 0.8 mm with test results showing an accuracy of ±0.1 mm when commanded. Here we also expect closed loop control that accounts for joint friction parameters and other system parameters will decrease this value below 0.2 mm.

DEMONSTRATION RESULTS AND INTERPRETATION

The nature of space assembly allowed us to develop a highly accurate but slow robotic manipulator, which in the 1 m configuration is simple to operate from the controls perspective. Our demonstration showed qualitatively that the arm could be controlled well enough to meet the needs of our chosen assembly interface, and repeatability testing performed separately gave us data to enable us to extrapolate success to longer reach configurations.

It should be noted that the criteria we use to define success in this testing are somewhat different from how this is typically defined, and that this difference is intentional. We have not examined a large number of test or analytical cases here in order to establish statistical measures that show our likelihood of achieving a certain performance. This is how the performance of robotic systems is typically verified, and it allows engineers to say with 2-sigma (95%) or 3-sigma (99.7%) confidence that an operation will be successful.

With our testing, we have shown that success is *possible*, rather than guaranteed, and we feel that this is the correct approach to avoid over-engineering of such systems. To be more clear, that success should be determined on the basis of mean performance rather than 2 or 3 sigma performance.

The basis for this assertion is that success is that on-orbit servicing systems must necessarily be designed such that particular operations may fail due to expected variations in performance without creating a hazardous condition. In such cases, other controls may come into play that prevent the hazard. For example, during the final plunge motion that brings two halves of an interface together, it may be possible that prevailing conditions result in performance even outside a 3-sigma prediction, and alignment features fail to make contact as expected, or jam during insertion. In such a case force-torque thresholding or motor current limits may prevent the system from exerting damaging forces on the contacting hardware, or the interface hardware immediately surrounding the alignment guides may be designed or analyzed for such incidental contact, or all of the above.

Since this is the case, the only consequence of a failed mating attempt is a waste of operational time. Our assertion is that this is not a consequence of any significance, and therefore should not outweigh the potential cost and schedule difficulties encountered during development that are associated with meeting 2 or 3 sigma performance targets, vs. Mean performance targets. After all, with remotely operated on-orbit servicing missions, it is likely that mission timelines will stretch into weeks and therefore must be performed in a benign and stable configuration. Also, when time is being wasted, it is the time of a ground based flight control team, and not highly paid and highly constrained astronaut crew. And finally, there is the hope that this kind of impact can be further mitigated by the application of increasing levels of autonomy in the control system. If an automated system can recognize a failed operation, and set up and execute a repeated attempt, then not only can impacts to operational timeline be reduced, but also the level of supervisory attention required from an operator can be reduced, thus allowing better utilization of flight control assets and a savings in mission operations costs. The beginnings of such autonomy can be seen in the Mobile Servicing System Application Computer (MAC) recently employed to automate robotic servicing operations on the ISS. This system was able to autonomously walk the on board robotic systems through a series of commands that allowed them to power up, maneuver to a grasp point, perform the approach and grasp, and power down[13,14].

Therefore, we take away from this testing a positive impression regarding the capability of the MRM system, and see reason to believe that continuing to develop this system for SPIDER-scale assembly and servicing applications will bear fruit. As this development advances further, we expect it will be useful to perform additional testing to better define the "mean" performance of a given configuration.

CONCLUSIONS

The motivation behind our demonstration activity was to show that on orbit assembly could be performed by a small, simple, and cost effective robotic system. One that was designed to fit within the size and budget constraints of a smallsat mission. Our MRM line of robotic systems is designed to fit within these constraints, and successfully demonstrated a robotic assembly operation, using an interface designed for a much more complex robotic system, with much higher predicted performance. This should give mission designers the confidence they need to take advantage of the advanced capabilities that on-orbit assembly and robotic manipulation can provide.

FORWARD WORK: LARGE SCALE APPLICATIONS

As an exercise in extensibility, we chose to extrapolate the results of our repeatability testing to a 5 m MRM configuration. We found it reasonable to presume a tip positioning accuracy of 2.5 - 4 mm, which is well within the capture envelope of the segmented panel interconnects with alignment features, even with the typical errors from machine vision solutions taken into account. For a manipulator of this scale to be useful for smallsat applications, very creative launch packaging would be required, but still it is good for us to see that the limit of useful performance is potentially significantly greater than the 1 m reach prototype that we used for this testing, and that the MRM system might one day tackle larger scale tasks heretofore reserved for more complex and costly systems.

If this avenue of development is to be pursued, then we feel it worthwhile to reconfigure the system for longer reach, and perform repeated testing in order to validate the extrapolations made here about positioning performance.

BEYOND MRM: THE UNDER-ACTUATED MANIPULATOR

Finally, we will close with a brief discussion of our generation of robotic manipulators beyond the MRM, and their potential to further advance the availability of robotics for smallsat applications. While we continue to examine new and exciting applications for the MRM system, and the testing described in this paper serves as an example, the system itself is fairly mature. The first instantiation of a flight version of this system, SAMPLR, is expected to reach the lunar surface in 2022, just around the corner. Looking beyond this, we have embarked on a new technology development, in partnership with NASA, to develop manipulators based on a completely new type of architecture[15].

This under-actuated robotic system uses a tensioned cable system to transmit torque from a single actuator (motor and gearbox) to any number of separate joints, thus removing the need for actuators at each joint. In this new kind of system, only brakes and position sensors need to be placed at the manipulator joints. This has many significant advantages. The most obvious is that actuator packages are significant mass and cost drivers of a robotic system, and having one vs. many helps reduce both. Less obvious is that actuators also have significant thermal management challenges, and that motor control avionics are often located nearby to reduce harnessing up and down the arm. Packaging the motor and avionics at the base of the robot offers great advantages here, allowing both to be better protected against radiation and allowing greater flexibility in the design of the thermal management system (which can now benefit from host spacecraft structure to reduce exposure to the surrounding environment), and all this has the result of reducing the power draw required for operations and survival. This is a particularly important advantage in lunar or deep space applications, where prolonged periods of low temperature may be encountered, or energy generation capabilities may be limited.

One disadvantage of this kind of system is the inability to drive manipulator joints in a truly independent and simultaneous manner. Since a single actuator provides all the motion, joints may be driven sequentially and independently, or simultaneously but in the same direction (though brake modulation may possibly be used to differentiate speed). However, we believe that this limitation can be overcome with creative control solutions and have done some work to demonstrate that the most challenging on-orbit servicing applications are possible with such a system[16], and that mission developers need not be limited in terms of applicability. It is our hope that over time, the advantages of this type of system will allow smallsat missions of all stripes to benefit from on orbit manipulation capabilities, expanding their range of use cases and enabling new operational capabilities.

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