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Advancements of a MicroSat for On-Orbit Satellite Surgery

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ABSTRACT

The concept of a highly articulated microsat to perform in-space construction, assembly, and repair is emerging due to advancements in microelectronics, robotics, and microsatellite technology. The combination of these has led to investigating foundational elements for conducting remote space robotic missions that will enable machines to build machines. The idea goes beyond robotic systems designed to mate specialty-crafted space modules or in-space 3D printed structures. It addresses a means to work with typical flight hardware in this remote, lifeless environment. The work presented in this research has focused on creating a semi-autonomous platform that shares both autonomous GN&C operations with man-in-the-loop telerobotics. The testbed platform contains a means for target capture, attachment, and for conducting technician-like mechanical tasks that include gripping, cutting, and working with fasteners with an interchangeable tool set. As the system evolves, evaluation tests have shown many aspects are feasible such as cutting thermal insulation and wire. For instance, the system can reach into a harness, isolate a 26 ga. wire, and cut it. It has also been able to perform small cuts in thermal insulation membranes. Fasteners are proving to be more challenging due to robotic tool alignment and management of forces.

INTRODUCTION

Today's space robotic systems are in their infancy. With regard to functionality, they are comparable to where biomedical robots were about two decades ago. Both industries share product environments with extreme consequences when things go wrong and both have substantial quality and implementation control needs. High integrity hardware is a must for both, which brings very high costs and fail-safe designs. For a small satellite to perform delicate and unplanned on-orbit manipulation, there are many challenges with varying lighting, achieving three-dimensional visual feedback, synthetic eye-hand coordination, and effective design of tools, just as biomedical initially experienced [1]. For the many aspects both communities share, we propose that space machines that work on other space machines should be on a smaller scale for maneuverability, functionality, and cost. They need to contain basic functions for mechanical and electrical technician-like tasks. This is a difficult calling. The complexities of building a free-flying space vehicle with robotic capabilities drives one towards using familiar aspects such as staying with human dimensions, working with human-like forces, using human velocities, and always being cognizant of reliable, fail-safe operations. Biomedical developers shared these same concerns in their early research [2]. When compared to designing traditional spacecraft, robotic space systems add the additional burden of co-creating perceptive human-machine interfaces.

Smallsat missions with elements of robotic utility must first master rendezvous, proximity operations, and docking. They immediately face the challenge of tiny volumes, how to fit all the enormous GN&C utility into a very small package. Fortunately, community efforts are underway to address this. The Seeker Mission from NASA, demonstrated CubeSat proximity operations and necessary hosting of GN&C equipment [3]. Others in the smallsat community are laying foundation for these types of capabilities [4]. NASA is sponsoring the Cubesat Proximity Operations Demonstration (CPOD) flight experiment [5]. Some researchers are addressing robotic system integration onto CubeSat sized platforms [6] and into larger earth observation platforms [7, 8, 9]. Efforts such as this are beginning to explore the design space of what is possible, and along the way will develop metrics for cost, weight, power, functionality that are critical for future implementation.

MISSION AND VEHICLE CONCEPT

A Surgical MicroSat bus for this effort would be 3U to 6U and would be hosted in twin pairs as an auxiliary payload on an integrated panel as shown in Figure 1. The host spacecraft is intended to only provide docking port electrical recharging power and serve as a communication conduit to a ground control facility.

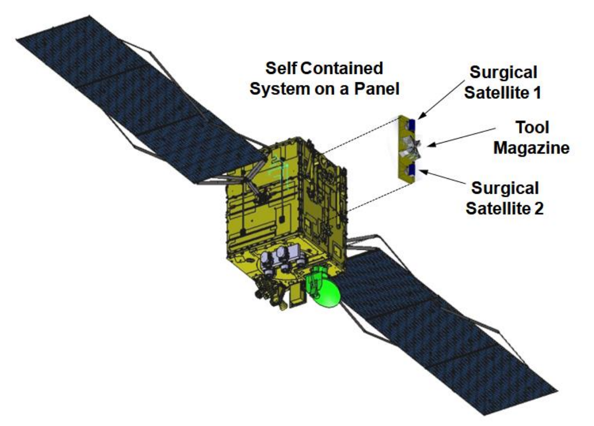


Figure 1: Hosting Two Surgical MicroSats

The Surgical MicroSats would not be intended to fly independently because of practical limitations on power, propellant, thermal, and communications. Rather, the surgical satellites would serve only the host for on-orbit manipulation, provide local sortie inspections, or could coordinate host repairs or self-construction during the mission.

With two Surgical MicroSats integral to a host vehicle, they could be pre-programmed with a number of safe and efficient trajectories to avoid sensitive areas such as payloads, antennas, and attitude sensors as shown in Figure 2. Upon determining an ingress route to a suspected trouble spot, the vehicles could be programmed to follow a corridor or be driven manually to avoid or remove obstacles if debris were present.

For this micro-assist spacecraft to be practical, it's clear the cost of such as system must be low, which is feasible if it's small and volume production is pursued. The surgical satellite must also be fail safe and be recoverable. The capability of its expected on-orbit operations needs to be broad and generic to address any number of potential host issues.

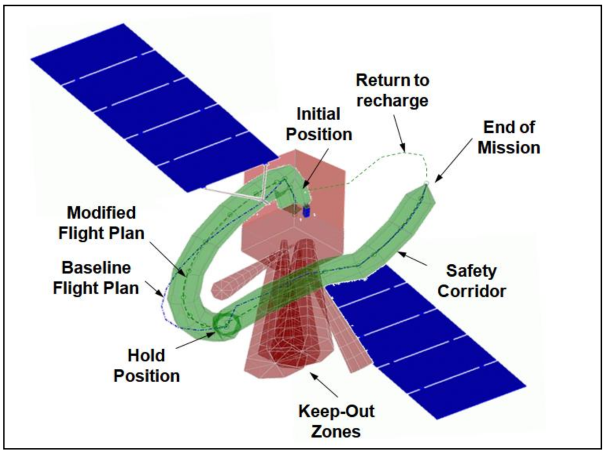


Figure 2: Concept of Surgical MicroSat Self-Inspection Flight Operations around Host Vehicle

With a limited set of on-board robotic arms, tools must exist with a simple detachable universal interface. The interface needs the capability of being mechanically preloaded to provide stiffness and needs to transfer electrical power for end-effecter functions. When doing constrained assembly, it is common to employ arms with excessive degrees of freedom (DOF) to allow many orientations that support a given final end effector tool position.

Beyond the surgical robotics and tool sets, there needs to be new methods developed to reach out and attach or grab nearby space objects, or to make initial attachments to the host. A vision was to use low force, lightweight catheter robotic arms capable of supporting a very large work space, but also be highly compact for stowing. Once these arms attach to an object, they can be used to gently maneuver the surgical satellite into an optimal position to be mechanically locked onto the space object with a rigid, telescoping boom. Thus, our concept Surgical MicroSat contains the following:

- Two 3 DOF catheter arms for target capture
- One 1 DOF telescoping arm for rigid attachment
- Two 7 DOF arms for global surgical tool placement
- Multiple articulated end-effecter tools with 4 DOF each - for pitch, yaw, and individual finger motion

The articulated systems are shown in the concept vehicle design of Figure 3. In this case, the capture and rigidizing arms are in the stowed condition, the surgical arms are in the deployed condition.

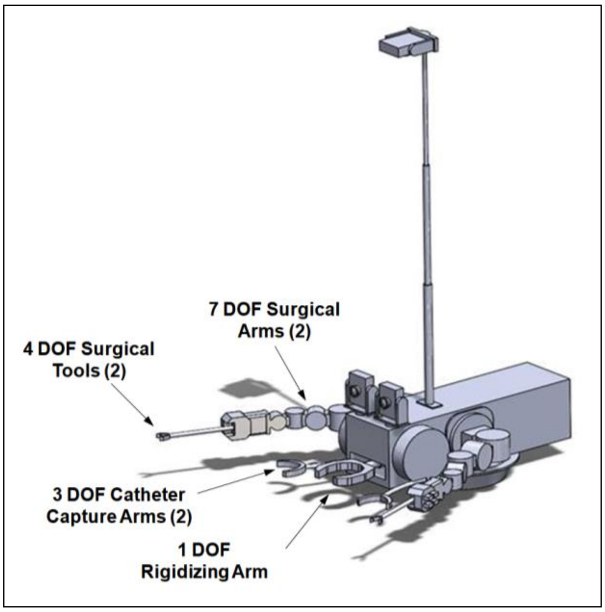


Figure 3: Concept MicroSat Vehicle for On-Orbit Surgical Operations

The concept of operations will influence many design parameters, so it's important to notionally introduce it. As illustrated in Figure 4, an initial survey is expected to provide assessments necessary to determine appropriate tools or diagnostic equipment, and to identify an appropriate attachment site. After flying back and re-docking, tools would be installed and the vehicle would re-fly. The MicroSat would perform the host vehicle attachment with catheter arms, maneuver to rigidize and lock-in the connection, prepare the surgical field, and perform required operations.

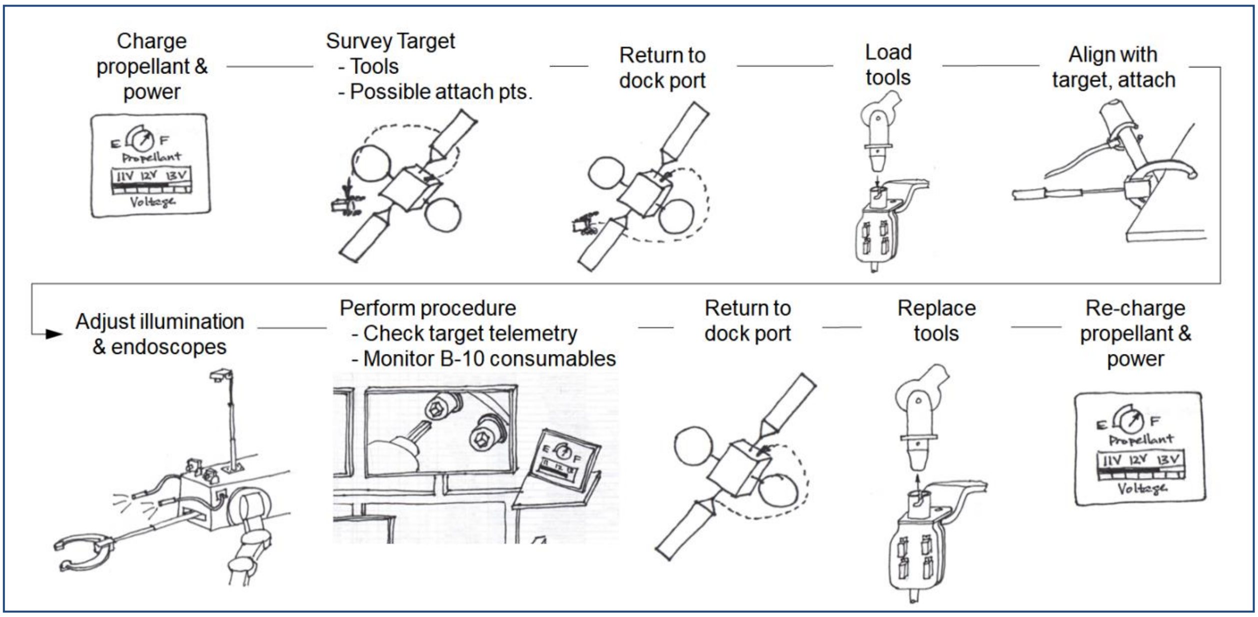


Figure 4: Concept of Operations for the Surgical MicroSat

Once the repair, assembly, or modification is complete, the space vehicle returns to dock and resupplies its consumables. For as simple as this CONOPS appears, any one of these steps is an area of development since very little of the technology exists. For this work, we have focused on the central portions of the CONOPS, dealing with tools, their handling, and their practical operations since without these core capabilities, the rest is moot.

In a literal sense, what we are trying to emulate is a mechanical or electrical technician being present on the scene. How would they go about making diagnostics, planning the work, choosing and retrieving the right tools from the toolbox? Then, how would they perform disassembly, removing insulation and covers, or peer into cavities for further inspection? This also assumes a remote machine would have a clever way to manage parts such as fasteners, clips, and avoid creating debris. The disassembly process may not only involve undoing fasteners, connectors, and tie-downs, but may also be required to remove stuck parts, break bonds, or deal with jammed assemblies. Again, we think of common steps used in ordinary construction, but must now also maintain an eye on our own consumables and health.

TESTBED SYSTEM OVERVIEW

The Surgical MicroSat has numerous technical challenges that are difficult to understand without developing a working hardware testbed [7]. There has been encouraging space telerobotic controls research [11-17] and two-arm architecture and target capture studies [18-21] that have helped to define this system.

Initially, it was envisioned that a single ground control operator could manage all the vehicle and mission functions. This was later concluded to not be even remotely reasonable due to the overload of information and controls. Thus, the system migrated to a two-operator solution comprised of a vehicle controller and the surgeon. The testbed vehicle would be nearby for quick checks and fixes in case procedures didn't go as expected. Figure 5 shows an overview of the entire MicroSat testbed system that consists of two control stations and the vehicle with various targets floating on a small air bearing table.

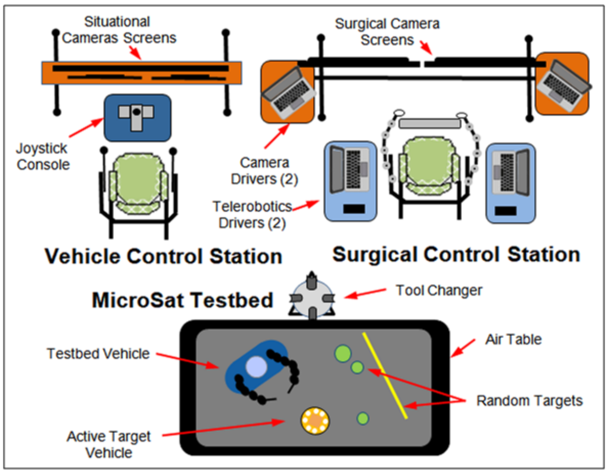


Figure 5: Surgical MicroSat Testbed System

In this construct of the testbed, many of the CONOPS elements such as tool changing, varied lighting and camera conditions, and exploring tool operations were readily testable. Although this research was originally planned to have micro-sized elements, we learned that having our hardware approximately the same as human dimensions was convenient, reduced costs, and avoided scaling challenges.

The vehicle control station, shown in Figure 6, is responsible for conducting all free-flight aspects of the mission, whether they are autonomous or manually driven. The operator, by use of joystick controls, can maneuver the vehicle via the propulsion system when unforeseen events call for this. Any flight maneuvering to position the vehicle for docking is also conducted here. This operator telerobotically controls large displacement, low-force catheter arms used for target capture and to aid in attachment. Rigidization of the Surgical MicroSat to the target vehicle is also coordinated at this station.

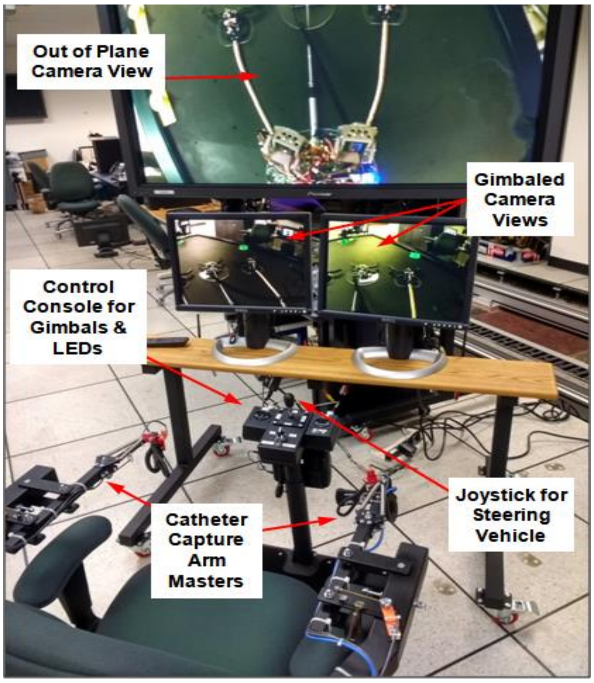


Figure 6: Vehicle Control Station

The surgical control station, shown in Figure 7, is where all technician work functions are coordinated. The operator uses left and right telerobotic arms and endoscope cameras to effectively manipulate the tools to effect target hardware. It contains controls to drive each tool and to conduct tool change-outs when the vehicle is docked. Since these stations are prototypes, after basic man-machine functionality is mastered, the stations could evolve to be better ergonomically and haptic friendly, but for now, this has been considered lower priority.

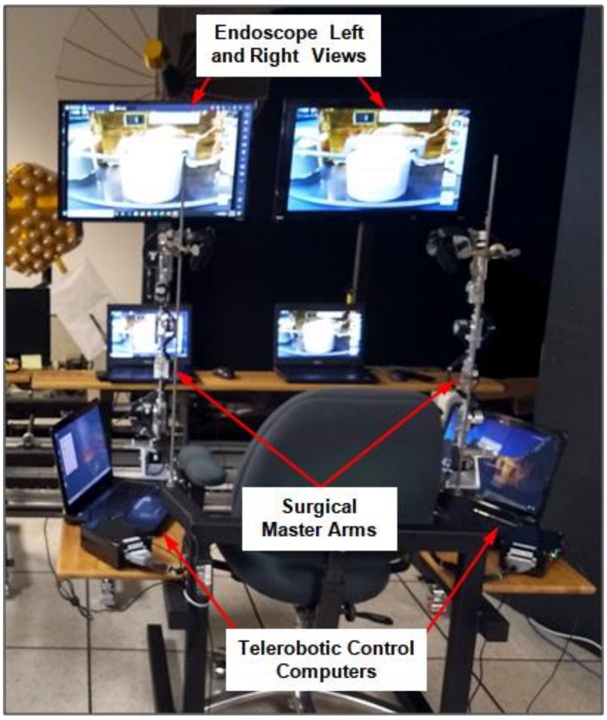


Figure 7: Surgical Control Station

MICROSAT TESTBED VEHICLE

The MicroSat testbed vehicle consists of two surgical arms, two catheter arms, and one rigidizing arm for various manipulations. Figure 8 shows the vehicle with an active target used for testing surgical procedures.

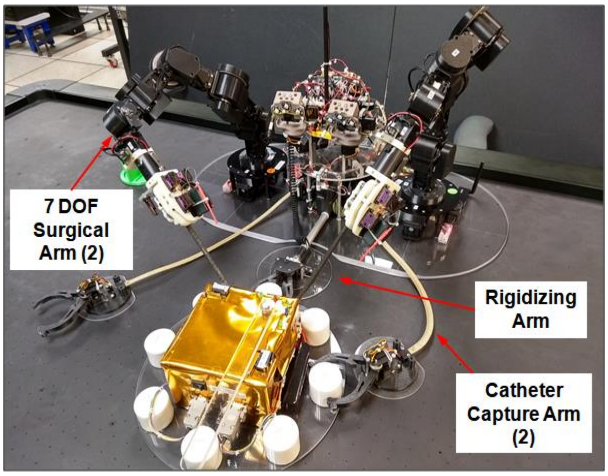


Figure 8: MicroSat Testbed and Target Vehicle

The vehicle has an on-board cold gas propulsion system with 16 thrusters. This allows global vehicle motion in 3 DOF - x and y, with z rotations. Two forward looking cameras with tuned LED lighting are on Az/El gimbals and can be independently steered. One camera is deployed out of plane and is used to gain perspective when retrieving targets and observing the workspace. These three cameras are primarily used for vehicle situational awareness. Additionally, two endoscope cameras are used to both illuminate and view the surgical field with higher resolution. The testbed vehicle weighs about 30 lbs and easily floats on a large plexiglass air bearing when the table is pressurized.

The electrical vehicle architecture has been focused on supporting robotic and manipulation functions as opposed to those traditional subsystems typically needed for a satellite - such as GN&C, TT&C, Data Management, Thermal, and Electrical Power subsystems. That's primarily because we need to prove the robotics designs work before integrating them with traditional subsystems. Figure 9 shows an electrical block diagram of the existing vehicle.

Aside from the observation that this design contains a plethora of actuators, a quick glance at the figure also shows a number of different types of wireless transponders. The testbed strategy was to focus on functionality over the implementation technique, so it uses WiFi, Bluetooth, NRF24 radios, high speed USB links, and hobby grade RC transponders, which are all in the 2.4 GHz bands. This much wireless traffic forced us to use 5.8 GHz cameras to achieve cleaner, real-time video. A take-away is that there is significant and unprecedented real-time communications that must be addressed for this type of satellite.

Another conclusion from studying Figure 9 concerns the number of electromechanical actuators, 40 as the design presently exists. This is an enormous quantity for a space vehicle as each actuator needs power, a driver, a controller, and software, and will need caging to survive launch loads.

Catheter Arms

Two catheter arms reach out into the workspace, and even behind the vehicle, for initial target capture and attachment. These arms are made from soft silicone tubing (shore D hardness 45) with a Mylar jacket overwrap to provide torsional stiffness. The arms are steered with RC servos pulling cables commanded from a 2 DOF telerobotic master. The master arms can move forward and back, driving the arms in or out. Moving a rotary link from side to side commands the arms in the same manner. The master arm also has finger loops, that when squeezed, move the catheter grippers in the same way. There are several advantages for these types of arms. First, they extend out over 20 inches and apply soft capture forces below 0.5 lbs. Second, they are thin and manageable with +/- 100 deg of travel about two axis. Lastly, they can be coiled onto a small drum for internal storage. Figure 10 shows the catheter arms in both the stowed and deployed condition. The center arm, used for making a rigid connection to the target, is a 6 segmented, telescoping boom, with an approximate 5 foot reach length.

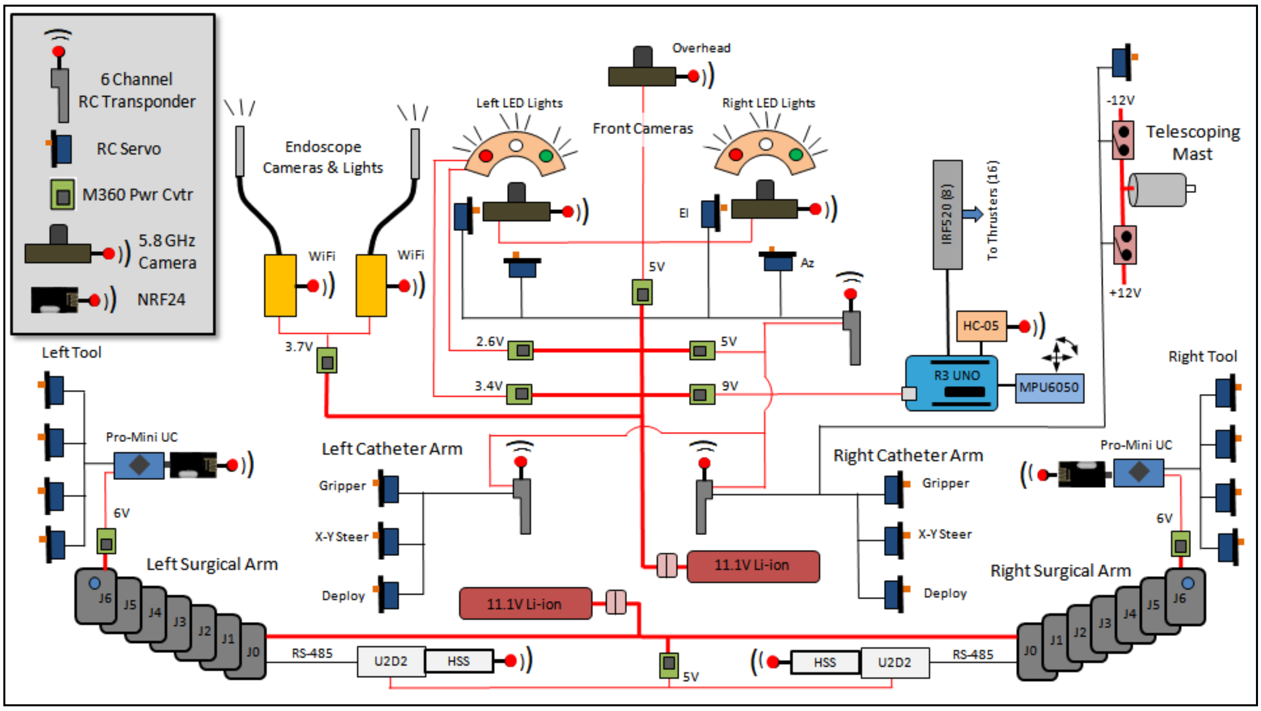


Figure 9: Electrical Block Diagram for the Surgical MicroSat

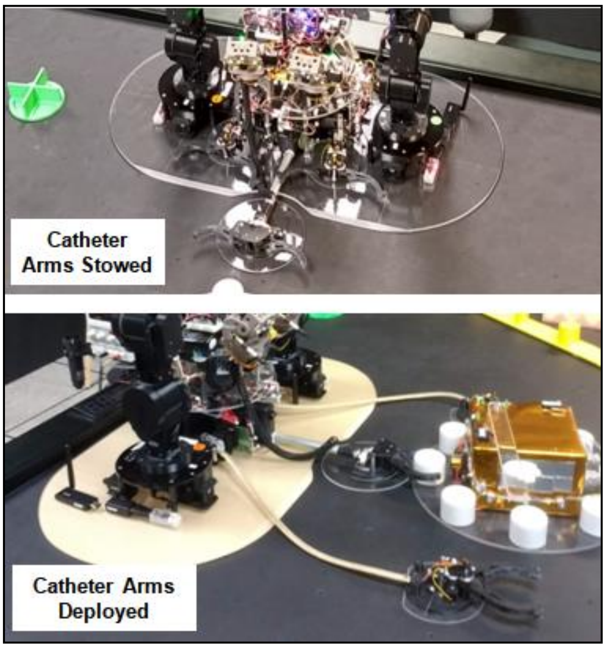


Figure 10: Stowed and Deployed Catheter Arms

Surgical Arms

Surgical arms on this testbed are repurposed Cyton Gamma 1500, 7 DOF manipulators. Each joint uses Dynamixel servos, either model MX-64 or MX-28, that communicate with an U2D2 interface controller through an RS-485 serial bus. This 3 wire interface also provides 12 VDC to each servo at the end effector. Each controller interfaces to a dedicated laptop computer sending initializations and joint angle commands via a HuddleCamHD USB2AIR wireless link, capable of up to 30 Mbps over auto or selectable channels. The arms are approximately 30 inches in length and weigh 4.2 lbs each. They draw between 0.5 to 1.5 amps depending upon the operation and can manipulate up to 3.3 lbs maximum force.

Each surgical arm is telerobotically slaved to an identically scaled and joint oriented master. The master uses incremental encoders at each axis location and broadcasts positions to the robot arm with approximate 700ms updates, which is deliberately slow to allow for error correction and minimize commanding errors. Figure 11 shows the right robot arm and its master control arms. Power grips are used to position each master, held by the surgical operator hands. Power grips were chosen for this system, in contrast to using finger pinch grips [22], because of their advantage with hand fatigue. Although there are a number of ways to drive telerobotics, these power grips are based on Oculus™ Touch Controllers, which received years of development to create a very friendly and ergonomically comfortable human interface [23].

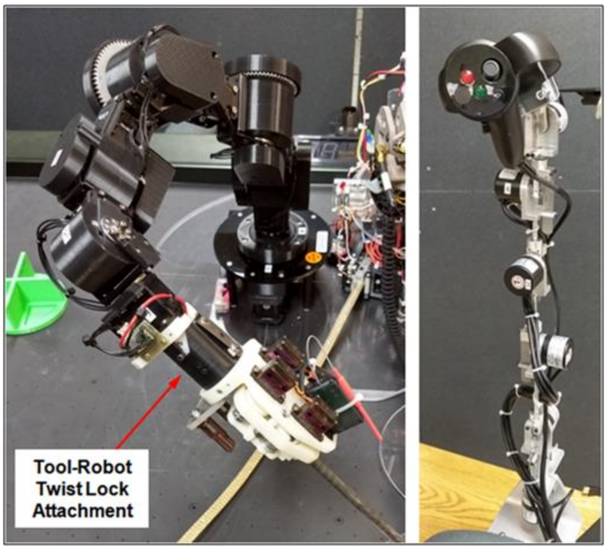


Figure 11: Right Surgical Arm Slave and Master

Tool Changer

Each surgical arm requires the ability for simple and easy tool change-outs, consistent with the operation required. Design trades showed many ways to do this, but ultimately a system much like is used in CNC machines was chosen. For these systems, the tool changer brings the requested tool into a staging position and the CNC machine then performs the attachment with all steps done automatically. Figure 12 shows the prototype tool changer designed and built for this system.

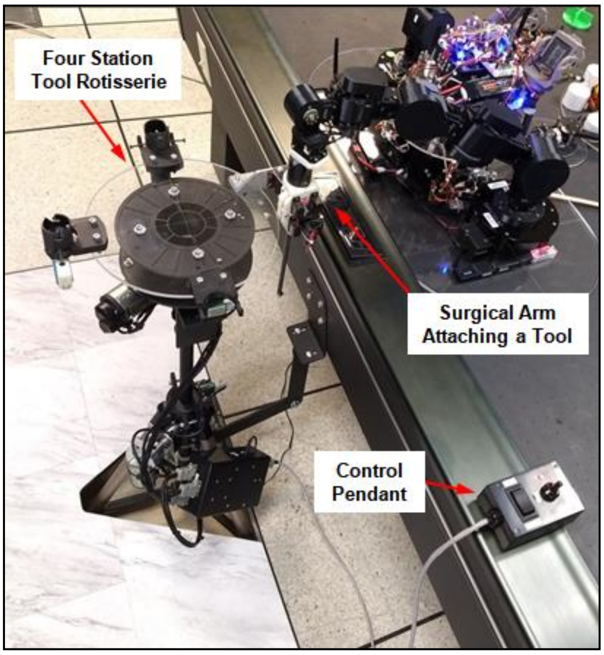


Figure 12: Tool Changer used for Testbed MicroSat

It works by having the vehicle first locked in a caged position. A rotisserie table rotates the needed tool into position towards the back side of the vehicle. The surgical arm then reaches over the edge of the table and holds position. The tool changer raises the tool approximately 1 foot and performs the tool insertion into the end effector interface. At this point the robot wrist joint performs a twist lock to secure the tool.. The rotisserie table is then lowered, releasing the tool. Once the table is back in the lowered position, the robot arm is moved to its straight-up zero position. We found this simple approach worked well and could likely host up to eight or more tools per arm. This rotisserie table however relies on gravity to hold the tools in place. For space, this would be more complex with capture and release mechanisms providing preload and secure caging.

Surgical Tools

The heart of the Surgical MicroSat is the tools and instruments, and their ability to perform useful, technician-like functions. Recent developments concentrated on three classes of tools - cable/direct drive, impact, and pyrotechnic. Figure 13 shows force regimes and examples of each type of tool. All the tools are designed to interface with a twist lock, bayonet-type connection to the robot end that can also support a 12V electrical power connection. The interface needs to maintain reasonable preloads for stiffness and strength while operating.

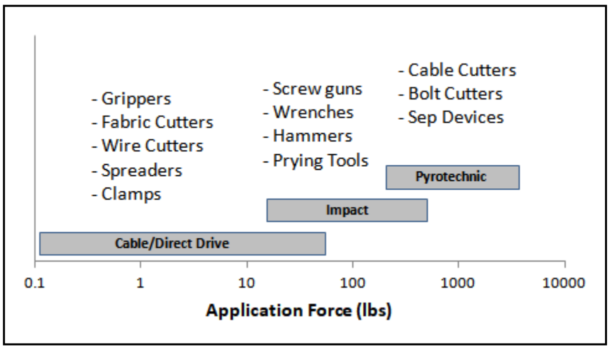


Figure 13: Candidate Micro Surgical Tools

Each tool is driven by buttons or a joystick located on the power-grip touch controller handles. Figure 14 shows details of a power grip touch controller. The buttons use Hall Effect sensors, so that variable motion can be performed. The X-Y joystick also provides proportional actuation with stick displacement. Lights are included on the touch controllers to indicate power (red) and to indicate that a tool is communicating (green).

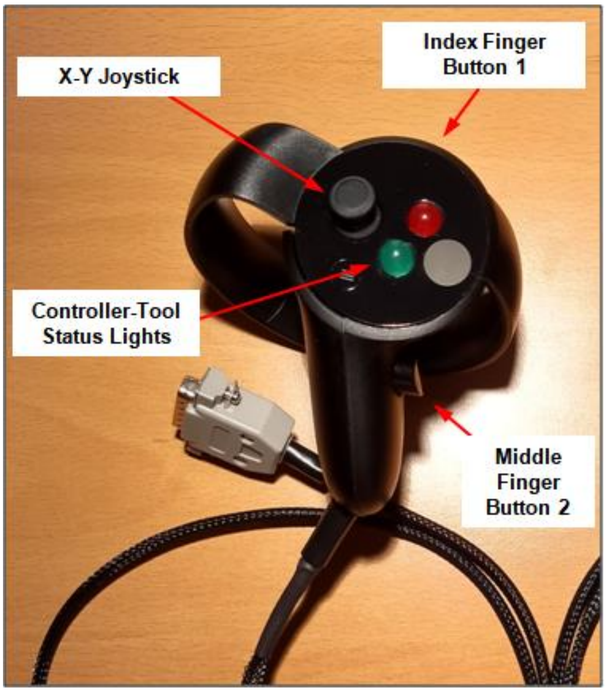
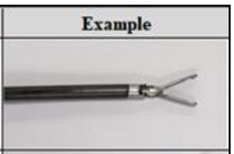
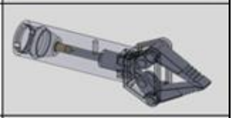


Figure 14: Left Hand Controller to Actuate Tools

A number of tools have been investigated and are still in development. It's important to note the small scale of these tools as opposed to larger, more conventional space systems [24]. Oftentimes, many tool design iterations are required to achieve satisfactory performance, and this system is no different. Table 1 shows a summary of tools investigated to date. All were designed to be interchangeable with the existing surgical robotic arms on the testbed.

One major concern for multi-actuated tools on orbit is vacuum. Within the space mechanisms community, it has been long recognized that vacuum can degrade surface oxides, causing parts to adhesively weld, unless they are well lubricated [25]. The problem can become more acute with parts not intended for disassembly. For example, preloaded fasteners are prone to extremely high surface pressures in threads and under their heads [26]. If oxide layers are removed, adhesive welding and faster galling is common, and a bolt will often break or strip upon removal. Most fastener torque-preload data, especially for flight hardware, is specified to be at standard operating pressures and temperatures within manufacturing facilities. There is little data for typical space-grade bolt torques in vacuum. At best, we expect removal and insertions torques to be high, and likely to be wide varying. In the same category of high concern is debris. Any creation of debris, even chipped paint, can be a problem [27]. These are all challenges to address, once fundamental manipulation elements are mastered.

Table 1: Initial Surgical Tools Evaluated

Tool	Actuation	Typ. Capabilities	Example
Small Gripper	Servo and Cable	1.5 lbs at tip Measured	
Long Gripper	Servo and Cable	0.7 lbs at tip Measured	
Scissors	Servo and Cable	3-10 lbs shearing Measured	
Wire Cutters	Servo and Cable	15 lbs cutting force (typ. for 26 ga. wire) Measured	
Impact Driver	Direct/ Impact	20-25 in.lbs (adjustable) Measured	
Cable Cutter	Pyrotechnic	~300 lbs at knife edge Calculated	
Spreader	Pyrotechnic	~200 lbs at tip Calculated	
Clamp	Pyrotechnic	~200 lbs at tip Calculated	

Cable/Direct Drive Tools

Cable drive tools used for this work were modified versions from the DaVinci© Biomedical Robot System. These tools, all intended for soft tissue human surgery, have been studied and reported in the literature [28, 29]. The tools use four bobbins that wind and unwind cables attached to actuated portions on the tips. They are designed with an approximate 1:1 torque ratio in that the torque applied to the bobbins corresponds to the torque on the grippers. In our application, RC servos drive each bobbin, which are in turn commanded by a co-located Pro-Mini microcontroller and a dedicated NRF24L01 radio, as shown in Figure 15.

DaVinci tools come with an approximate 16 inch thin tube extension out to the tool tip. In our system, this seemed excessive, so we shorten this to 8 inches. During system testing, we still found this to be too long. It was a little like being Edward Scissorhands© when trying to position the gripper and cutter as shown in Figure 16. We could grab and cut wire or insulation, and could grab appropriate edges, but it took more effort than it should have as tip motion was highly amplified when the surgical arm moved. We also found that in some cases, more grip or cutting strength was needed. Testing showed the cutters, for instance, could handle much larger forces than RC servos provided, which is now an area where capacity is being added. In general, driving these tools with touch controllers takes a little practice, but appears to be feasible for many operations. While cable driven tools provide adequate forces for working with insulation or wire harnesses, they have limited utility for dealing with common joined hardware including fasteners and slip-fit connectors.

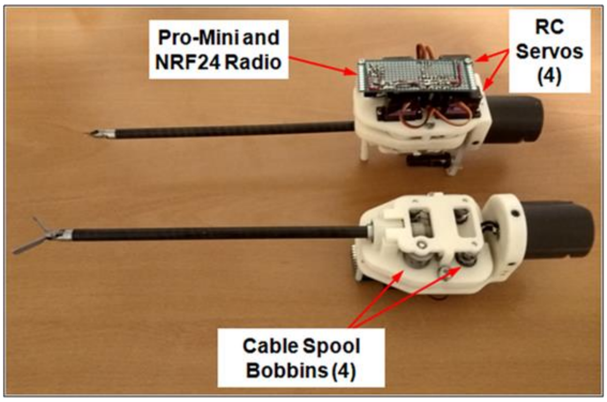


Figure 15: Controllers and Cable Driven Tools

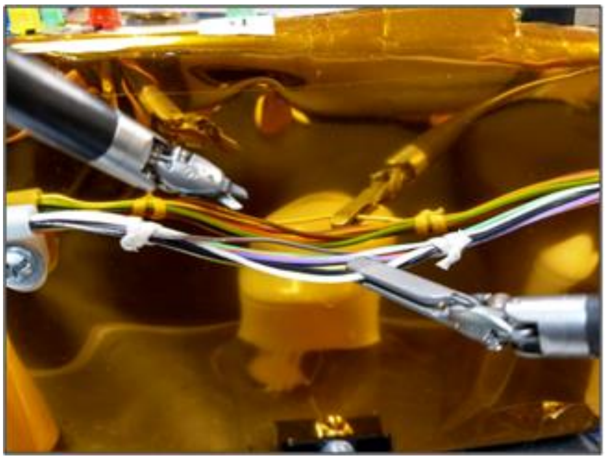


Figure 16: Cutter and Gripper Working on Harness

Impact Tools

The most common attachment method for any satellite assembly and harness termination involves fasteners. These are mostly Allen-head types, with sizes 4, 6, 8, 10 through 1/4 inch. There's little way around this if any type of disassembly work on existing hardware is to be performed in space. Our research investigated a number of impact wrenches, drivers, and hammers [30, 31].

Impact drivers appear critical for the tool set because of their ability to deliver high forces or torques, while minimizing reaction loads on the tool holder. Our approach was to work with existing commercial impact drivers to understand just what they could deliver under our operating conditions of 12V and attached to a very soft robot arm. Figure 17 shows our modified commercial tool on the end of the surgical arm (note the blue plastic spur gears). These are driven by an RC Servo and provide for adjusting the impact setting (i.e. impact magnitude), thus controlling the torque into the fastener. This driver, as opposed to a commercial unit, only rotates at a maximum 60 RPM and holds the interchangeable bit magnetically. For this figure, a Phillips head driver was installed, but can be easily swapped out with a number of Allen or hex nut driver attachments.

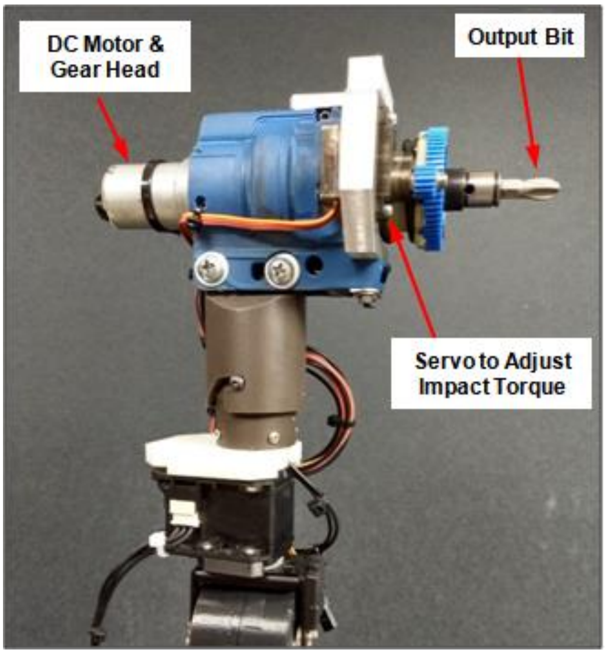


Figure 17: Impact Driver Developed for Fasteners

Although this tool contained internal steel parts and was relatively heavy, we were able to dynamometer measure both torque delivered to a fastener and the reaction torque back onto the arm. Figure 18 shows these test results. The approximate 10:1 advantage of using an impactor tool indicates this technology will likely be included in the mix for flight surgical tools.

Some practical measures were gained while trying to implement this driver. Although the tool works as intended, it is a challenge to perfectly align it with fastener heads in the three axis required for bit insertion. The surgical arms are not conducive to micro-movement, even if one can see how to align the tool through cameras. As a result, we decided to pursue a machine learning approach that will identify the type and size of the fastener, and once the proper bit is installed, will automatically position the tool into the fastener.

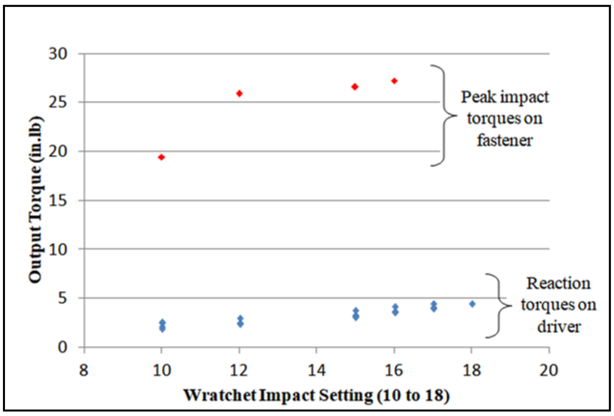


Figure 18: Impact Driver Testing Results

Working with fasteners, there's an obvious parts management problem on what to do with small items that have been removed (and associated parts) while in space [32]. This is another major development but is fruitless to solve unless basic fastener removal and installation steps can be mastered.

Pyrotechnic Tools

It's clear that sometimes in assembly, things become stuck. A few pounds of force will just not fix the problem. If parts don't quite fit, or if there is a large deployment cable wrapped around something unintended, or if a big power cable needs to be spliced into, much more local force is needed. For these sorts of problems, we studied developing pyrotechnically driven tools. These are not uncommon in some industries, for instance, that drive metal studs into concrete or for separation systems on spacecraft.

We investigated using small 0.22 caliper powder loads of different energy levels that can be merely purchased off the shelf at hardware stores. Once initiated, they can generate chamber pressures upwards of 25,000 psi, resulting in significant forces. To get a sense for requirements,: cutting 12 conductor cable of 26 ga wire, requires an average of 605 lbs, with a variation of +/- 6%; whereas, cutting a single 26 ga. wire requires an average of 14.45 lbs. What's actually needed in space may be in between. Figure 19 shows an example pyrotechnic tool. Three tools consisting of a cutter, clamp, and spreader were investigated, but only to the point of modeling and building 3D printed ABS plastic prototypes. Designs for tools shown in this report were specified to meet a 250 lb force requirement.

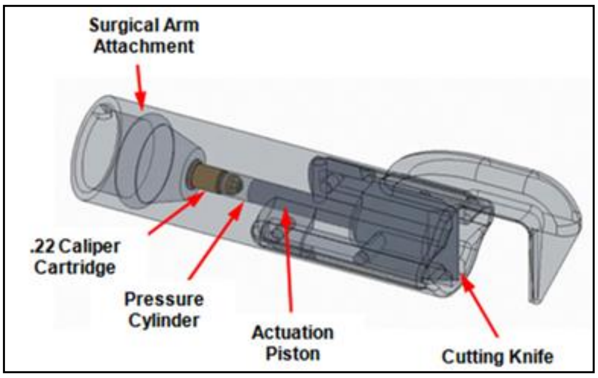


Figure 19: Example Pyrotechnic Cutting Tool

It was anticipated that these tools could be either one-time actuated, or multiple-times actuated, if a magazine and shell capture container was added. In some applications, it was envisioned a tool like the clamper could join two bodies, and the tool could be detached from the surgical arm and just remain in place like a C-clamp. There are many possibilities and these tools carry the distinct advantages of delivering high forces in very small packages, provided the robotic arm mechanisms can withstand the shock loads.

Other tools still in consideration include impact hammers, nut wrenches, lasers (for ablating and welding), sticky cleaners, steerable borescopes, electrical test probes, and sensors to perform diagnostics (thermal, torque, force). This list could be as big as a technician's roll-away tool chest, so careful judgment and prioritization will be needed to decide what is worthy of investment.

SURGICAL WORKSPACE LESSONS

Combining all the functions at once to perform a sample mission provided insight into areas of the testbed that worked well, but also uncovered many unforeseen complexities.

1. It was expected to have a spherical surgical work volume approximately the size of a soccer ball. What we actually experienced was a volume more like a thick book. Close range became an issue for the surgical arms to reach due to with complications from the long stems on the tools. Endoscope cameras had difficulty with focus and resolution in the outer reaches of workspace zones.

2. Once target touching occurs, forces other than gripping/cutting from the surgical tools must be reacted back through the rigidizing arm. Holding target objects at a single point with the rigid boom makes for poor stiffness and stability. More target holding points are needed.

3. When starting any telerobotic motion, the operator needs to see the surgical arms moving. Otherwise, there's no certainty the motion is actually occurring as intended. We found the out-of-plane situational awareness camera needed a wider field of view to see the arms, plus the surgical operator needs this camera feed to gain a global perspective of the environment.

4. Tools need to be small and light. Early version heavy tools caused a few joints of the surgical arms to get hot while reacting against gravity. Later tools were made lighter to help this.

5. Mating or de-mating simple electrical D connecters could be much more complex than anticipated. Removing the small fasteners that hold them in place appears doable, but connector removal and insertion forces could be insurmountable without a special impactor tool. This requires more study.

The Surgical MicroSat system moves slowly as intended, has acceptable latency, but is sometimes noisy (command hiccups), camera dropouts occur, and power usage varies widely while performing various tasks. It is a continual effort to modify and improve various components as the system evolves.

CONCLUSIONS

The Surgical MicroSat testbed development added significant complexity and functionality in the past year. The testbed space vehicle was integrated with surgical arms and capability to interface with different tools. An active tool changer was completed that coordinates with the surgical arms to exchange end effectors. Several tools were built and tested, including an impact driver. A surgical operator station was completed to allow telerobotic operation while observing through fixed endoscope cameras.

Key findings showed basic gripping and cutting functions are feasible. Basic mechanical operations such as cutting thermal insulation and wire cutting were demonstrated. Telerobotic motion for both arms and hands must be reacted through the target vehicle attachment in order to achieve predictable work functions. Performing surgical tasks in a distant, weightless environment must provide techniques for the observation and management of a very wide spectrum of forces and torques. The testbed design is indicating that the Surgical MicroSat will need to support an unprecedented number of servos and actuators. In addition, real-time, high bandwidth, and secure communication will be essential to support dozens of channels of control, with high speed video and telemetry feedback.

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