Development of a MicroSat for On-Orbit Satellite Surgery

Ted Nye, Andrew Schurr, Mark Milam
Northrop Grumman Corporation
One Space Park, Redondo Beach, CA 90278; 310-251-2502
ted.nye@ngc.com

ABSTRACT

Advanced technology is emerging that can now provide rudimentary on-orbit spacecraft fabrication, assembly, and repair. New research was started in 2013 to develop a CubeSat-sized spacecraft capable of performing telerobotic surgery on an existing asset. The surgical functions involved freeing a snagged appendage, cutting and splicing into a wire harness, cleaning a surface, repairing thermal insulation, and cutting/welding structure via laser technology. Through testbed demonstrations at Northrop, technology was developed for a number of these critical mission needs. These involved development of a miniature 6 DOF propulsion system, creating monitoring sensing methods that work under various lighting conditions over a very wide field of regard, target attaching with retractable catheter articulation, and performing a variety of articulated surgical operations using slaved commanding from telerobotic controls. The evolution for many of these technologies was through rapid prototyping and continuous improvement testing on an air bearing testbed to understand utility, reliability, and predictability. Miniature 7 DOF arms use interchangeable 4 DOF end effectors to perform surgical operations. This paper overviews the technology developed for these systems and provides foundational lessons for a surgical microsat.

INTRODUCTION

Today's high-value, manually assembled spacecraft can experience a number of unforeseen events once in orbit. These vehicles are not only inaccessible, but details are impossible to observe. Recent advances in robotics combined with on-orbit rendezvous and proximity operations, has resulted an opportunity to develop machines in Geosynchronous Earth Orbit with the potential of fabrication, assembly, and repair. Other than manned space programs in Low Earth Orbit, each of these sophisticated capabilities have largely remained undeveloped and unproven.

The need for on-orbit repair and even diagnostics is well established[1]. In a study of over 650 international satellites over a 10 year period, about 25% of them suffered significant anomalies, many resulting in loss of the vehicle[2]. Figure 1 shows the breakdown of these anomalies across the subsystems typical for many spacecraft.

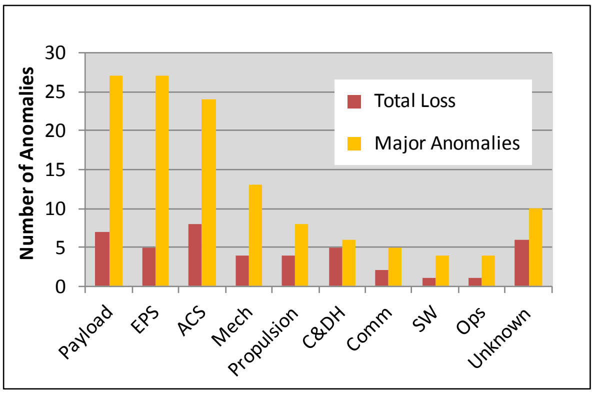

Figure 1: Subsystems Affected by On-Orbit Anomalies in a Study of over 650 Spacecraft[1]

For the types of failures experienced, most are associated with electrical components. It's also important to see that there is a percentage where the failure root cause is never found. On the $1.39B Galileo spacecraft sent to Jupiter, its high-gain antenna failed to fully deploy after its first flyby of Earth[3]. It was hypothesized that antenna hinge pins were likely seized, where just a small nudge could have freed it - had such as simple operation been possible. Anomalies are rarely repeated and often result from compounding problem that were never foreseen. Thus, they are almost never repeated. The Defense Advanced Research Projects Agency (DARPA) has provided the most leadership to date in servicing with several on-going programs including Phoenix, Robotic Servicing of Geosynchronous Satellites (RSGS), and Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) program. Figure 2 shows the concept vehicle for the Phoenix on-orbit servicing satellite.

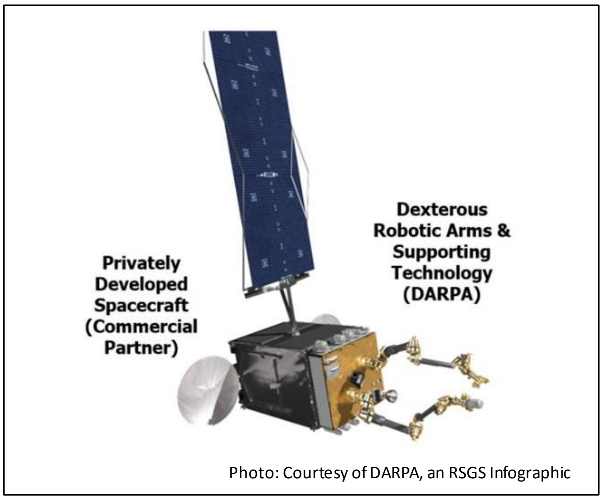

Figure 2: DARPA's Phoenix Servicer Vehicle

In a parallel development path, sophisticated robotics in biomedicine have been progressing for over 15 years[4-7]. Most impressive of these biomedical systems is that they mimic the quality and integrity of space hardware. Attention is paid to failures and anomalies where the consequences of a problem during a surgical procedure could be life threatening. It is useful to note that biomedical robots are for the most part, all controlled by telerobotics. Autonomy has not yet reached a point of reliability and predictability to perform human surgery.

The future of fabrication, assembly, and repair in space requires much more dexterity and finesse than what large and cumbersome servicing satellites can provide. First, there is a problem of scale. How can a machine the size of a car be expected to attach wires or unscrew small 4-40 connector fasteners for instance? There is the issue of agility, namely getting into tight spaces behind antennas or solar arrays, or reaching into narrow equipment compartments. Satellites are delicate when deployed on-orbit. A massive repair machine has very limited accessibility and can bump into and potentially damage instruments or precision hardware. The most ominous issue with big construction and repair satellites however is the enormous costs of the servicing vehicle. There are 60 years of proven metrics that associate the size and weight of satellites to their cost. Quite simply, size equates to money. Large servicing satellites with this complexity and risk lead one to wonder if it makes sense to sustain a $500M mission to repair a $200M asset? A fresh approach leveraging miniaturization is warranted and technology is emerging to make this possible.

It's useful to take a step back and consider the forces and torques required for operations in zero gravity. Figure 3 gives a sense of scale to appropriately manipulate objects on-orbit. The ranges of these numbers are largely empirical, based on small satellite design, but show small assets can do the job.

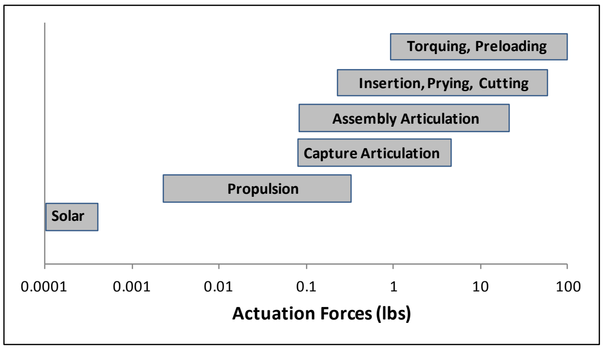

Figure 3: Typical Actuation Forces to Fabricate, Assemble, and Repair in-Space by Small Satellite

There is much talk about the sophistication and attractiveness of autonomy. For predictable and repeatable task where the cost is warranted, it's a great solution. The guidance, navigation, and control of a servicing vehicle for instance is a great candidate for this technology as the space environment is mostly understood, sensors detect obstacles (no matter the composition), and fly-through way points are common. When it comes to dealing with anomalies and unforeseen events, this technology has challenges and man-in-the-loop can easily address complexities beyond the capability of machines[8-12]. Thus, the technology pursued in this paper assumes autonomy for vehicle positioning, and real-time man-in-the-loop telerobotics for touching and manipulation.

VEHICLE CONCEPT

The differentiating thought behind this research was to not only develop on-orbit surgical capabilities, but to do it on a micro-satellite scale. The surgical vehicle bus would be 3U to 6U and would be hosted in twin pairs as an auxiliary payload on an integrated payload panel as shown in Figure 4. The host spacecraft would only provide docking port electrical recharging power and would serve as a communication conduit to a ground control facility. This would not be a satellite intended to fly independently at GEO because of practical limitations on power, propellant, thermal, and communications. Rather, the surgical satellite would serve only the host in the case of on-orbit emergencies, provide local sortie inspections, or could coordinate adding more payloads during the mission.

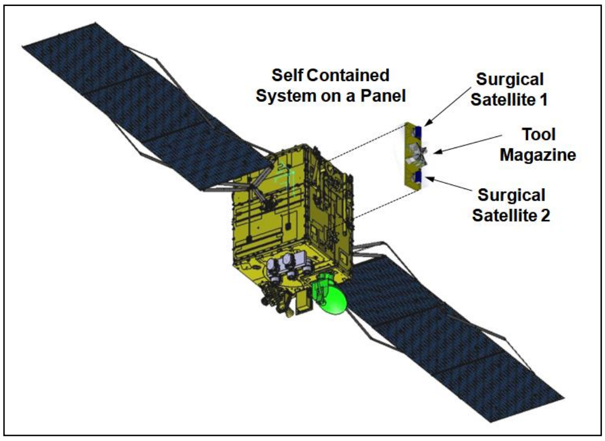

Figure 4: Host Example of (2) Surgical Satellites on a Panel Providing Docking Ports and Tool Magazine

With two surgical satellites 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 and attitude sensors as shown in Figure 5.

Upon determining an ingress route to a suspected trouble spot, the vehicle could be programmed to follow a corridor or driven manually to avoid or remove obstacles if a debris field is present.

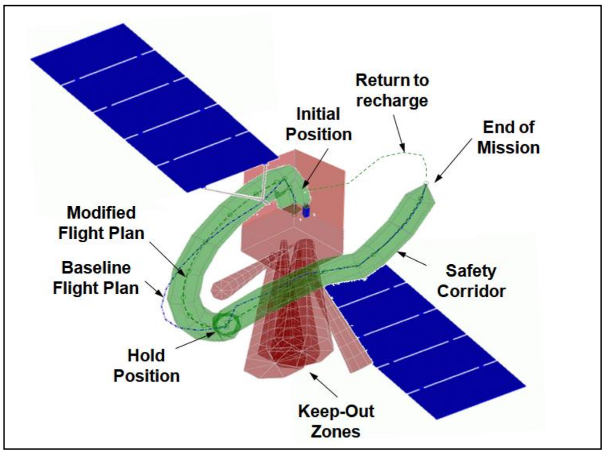

Figure 5: Concept of Surgical Satellite Self-Inspection Flight Operations around Host Vehicle

For this micro-assist spacecraft to be practical, it's clear the cost of such as system must be low, which is most feasible if 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. During this research, trade studies were used to determine the initial types of surgical operations and tool sets. Table 1 lists the preliminary tool sets chosen that could support a variety of operations.

Table 1: Trade Results of First Generation Tools

Tool	Example Operation
Gripper, Clamp	Handling components, wire, removing insulation, applying adhesives, separating items, capturing/removing debris
Mechanical Cutter	Trimming/cutting insulation, wire, insulation jackets, cable ties, catenaries, wire mesh, adhesive tape
Cleaner	Removing particle debris, surface films, condensed residues, adhering to flat surfaces
Laser Cutter/Welder and Ablator	Sublimination of films and wire insulation, debris, welding of wire, cutting of structure, surface cleaning
Optical Inspection	In-close observation of toll operations and providing local zone lighting

With a limited set of on-board robotic arms, the tools of Table 1 also came with constraints of having a simple detachable, universal interface. The interface needed the capability of being mechanically preloaded to avoid backlash and needed 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 arm configurations to support a given final tool position. Our approach was to use 7 DOF arms for global tool placement.

Beyond the surgical robotics and tool sets, there needed 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 lightweight catheter robotic arms capable of supporting a very large work space, but also be highly compact in a stowed condition. Once these arms attach to an object, they can be used to maneuver the surgical satellite into an optimal position where it is finally locked onto the space object with a rigid, telescoping boom. Thus, our concept surgical satellite contained the following overall manipulation systems:

- 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 roll, pitch, yaw, and tool closing

The articulated systems are shown in the concept vehicle design in Figure 6. In this case, the capture and rigidizing arms are in the stowed condition, the surgical arms are in the deployed condition.

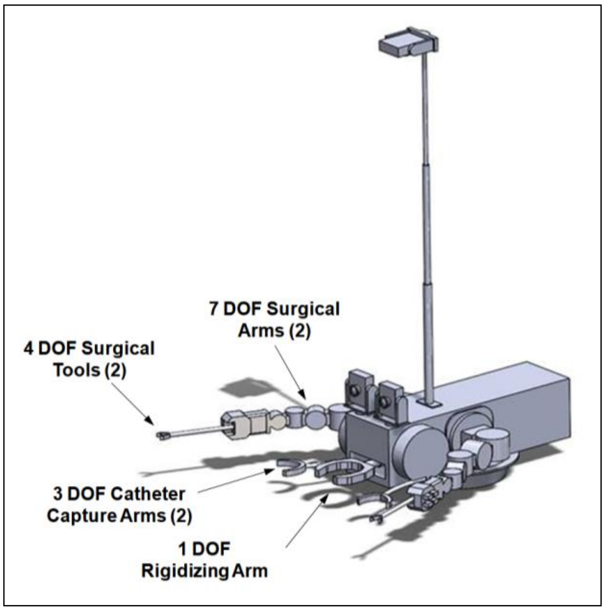

Figure 6: Concept MicroSat Vehicle for On-Orbit Surgical Operations

TECHNOLOGY DEVELOPMENT AREAS

1. Sensing and Situation Awareness

Several camera systems and configurations were investigated to assess versatility and effectiveness. Although there are many active devices for proximity operations navigation such as Lidar and Radar, passive visible camera sensing is less risk to the host and provides situational awareness with a broad field of view (FOV)[13]. Table 2 summarizes the various camera configurations tested with conclusions.

Table 2: Camera Architectures Evaluated

Camera Type & Apertures	Locations	Conclusions
- Wide FOV Fixed (Qty 2) - Steerable Fiber Optic (Qty 1)	Body mounted and co-located with endeffecter	Limited ability to see workspace Difficult to continuously orient and locate
- Single Camera with First Person View (Qty 1)	Camera on body mounted 2- axis gimbal	Too narrow FOV, constant head motion Headset didn't allow seeing vehicle console
- Stereo Cameras with First Person View (Qty 2)	Dual cameras on body mounted 2- axis gimbals	Stereo was only meaningful at very short ranges, was not necessary
- Independent Cameras (Qty 2) - Added Tuned LEDs (Qty 3/per)	Dual cameras on body mounted 2- axis gimbals	Big monitors allowed individual camera tasking Lighting improved feature recognition
- Deployed out-of-plane (Qty 1)	Body mounted, orthogonal to workspace	Was most useful for unobstructed view of workspace
- Wireless, Remote Fiberoptic (Qty 1) - Internal LED	Surgical arm mounted - or - attached to target vehicle	Provided custom observing of near-field surgical tool workspace Could be left behind

We found it harder than expected to arrive at an architecture that was effective to see key activity regions of interest without a lot of operational complexity. A solution emerged, much like an auto mechanic or dentist would want, where we'd want to establish the camera view and then forget about it. First Person View (FPV) is where a headset worn over the eyes is slaved to a gimbaled camera. As the operator's head turns, the camera moves with it, giving the sensation of being resident on the vehicle. These are commonly used in hobbyist quadcopter systems. The headset was just not practical as it did not allow for the operator to observe other telemetry and touch the many controls of the vehicle in real time. A deployed, out of plane camera offered the most utility as it was usually the least blocked by the robotic arms.

2. Capture and Attach

The first order of business after completing site inspections is to attach and stabilize the surgical satellite. Early expectations were that propulsion could hold a vehicle in place while the arms went about their business. This idea turned out to be completely off-base as we discovered the magnitude of arm forces are 100-1000X propulsion. Previous researchers have also investigated gripping and attachment schemes, and some clever designs have emerged[14]. We built and tested dozens of gripping schemes including using Gecko materials, two and three finger devices with rubber and silicone coatings, pyro-actuated spreaders/clamps, and shape memory alloy actuated grippers. In the end, simple, two finger (thumb and forefinger) gave the best results.

We looked to biomedical applications and came across an idea to use catheter robotics to effect a versatile capture scheme. Catheter arms use a small, flexible tube where actuation cables are passed down through internal tubing lumens. They are capable of steering while extended from only a few inches to several feet. Figure 7 shows an early prototype of a stowed two-arm assembly. Pulling and releasing the internal cables would cause the tubing to steer, much like pulling reins on a horse. These types of appendages have several notable advantages. First, they support a very large workspace as the arms can reach around, even behind the vehicle. Because they are made from thin sections, they do not obstruct views. Lastly, they can be tightly stowed by being wrapped around a small drum. They are low force, but in space, we found low force is all that is needed.

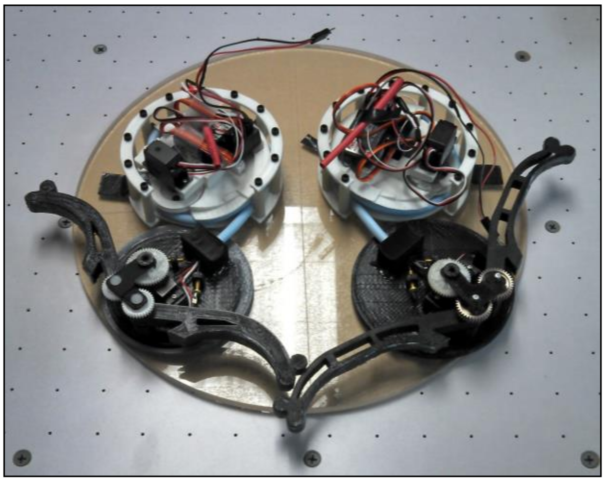

Figure 7: Early Prototype of 2 DOF Catheter Arm

A series of catheter robotic arms were fabricated and tested. Our investigation evaluated materials, key

dimensions, maximum extension ranges, actuation forces, and retractability. It was found that very soft bending stiffness is required, however very high torsional stiffness is needed to prevent twisting of the catheter body. Our testing primarily evaluated several polymer materials with the intent to eventually use stainless steel, laser cut, flex tubing that is typical in the medical industry.

An example of force vs. displacement results is shown in Figure 8. Mechanisms to do retraction and steering were later improved to show stowed and deployed concept feasibility as shown in Figure 9. Through testbed experiments, an operator could easily reach out and grab surfaces or objects. Because these arms had such low mass, the reaction torques on the vehicle were small and manageable, despite only having thruster based control.

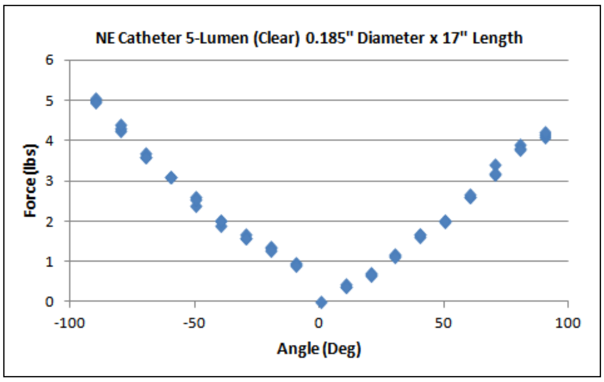

Figure 8: Example of Actuator Pull Force versus Catheter Displacement for Steerable Arm

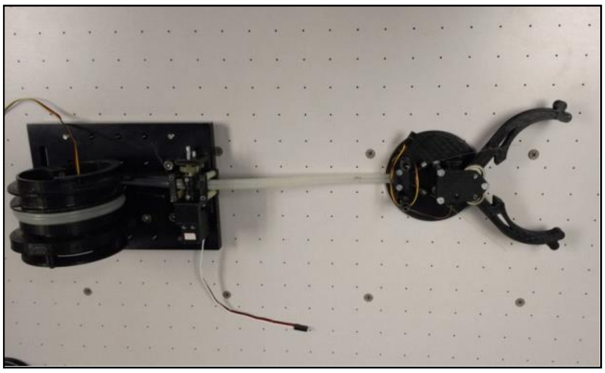

Figure 9: Second Generation Catheter Arm

Although catheter robotics can be tightly stowed and have a large workspace, they tend to be soft and pliable when extended. The feature of having low stiffness makes them good technology for capturing things, but not for supporting articulated, precision tools.

3. Surgical Articulation

Dynamic reach, servo holding stiffness, and having multiple arm joint configurations for end-effecter positioning are just some of the driving concerns with robotics intending to perform on-orbit surgery[15-18]. Figure 10 shows a Cyton Gamma 1500, 7 DOF manipulator used for this development. This manipulator is capable of position, velocity, acceleration, and torque control at each of its 7 joints. An RS485 serial data bus was used to individually access each joint controller. A 12V battery powers all the electronics. Shown on the left end is the male portion of a tool detachable interface that allows exchanging tools during surgical operations. The robot can be driven from a number of software packages, but our development had it slaved to a telerobotic master. The master was of the same scale as the robot and used optical encoders to command each Cyton joint.

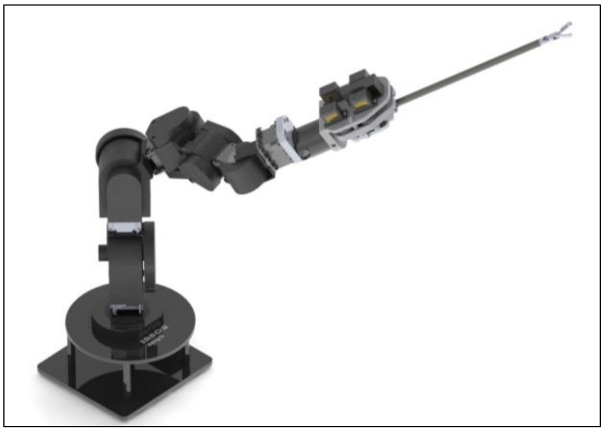

Figure 10: Cyton Gamma 1500 Robot used for Testbed Development of the Surgical Sat

A example 4 DOF tool designed to interface with this manipulator is shown in Figure 11. The tool was designed and built with integral RC servos to create the operational end tool motions of R_x, R_y, R_z and tool opening/closing.

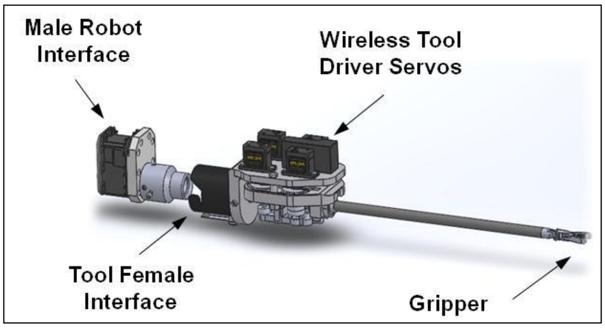

Figure 11: Example Detachable Tool Created for Surgical Gripping

For the initial operations outlined in Table 1, five separate tools were built as a means to evaluate the system functionality. Figure 12 shows details of each end-effecter tool. Two of the prototype tools used portions of actual DaVinci® surgical instruments. The operational scheme was that the Cyton robot arm would position the tools under telelrobotic control and special thumb and finger controllers on the master would drive the tool actuators.

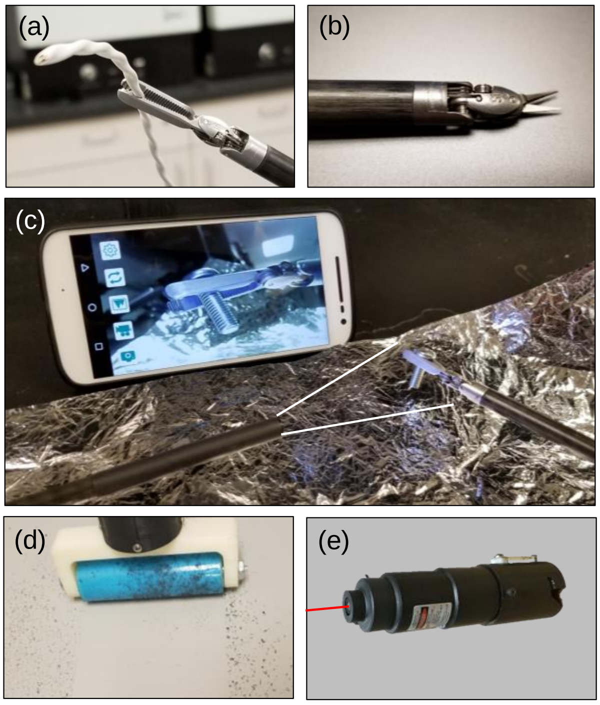

Figure 12: First Generation Concept Tools (a) Gripper, (b) Cutter, (c) Fiber Optic Camera, (d) Cleaner, (e) Laser

4. Vehicle Propulsion

The actuation scheme for overall vehicle positioning uses a safe, 6 DOF, cold gas propulsion system. Many types of micro-propulsion solutions are emerging within the CubeSat community. They however bring features not suitable for in-close proximity operations. First, many expel hot gasses and potentially contaminating chemical by-products from their combustion processes. For example, with ion engines, the exiting velocities of hot plasma can etch and damage neighboring structure. Many need complex plumbing or require high voltage or high power. For this mission, it was found that simple, compressed dry air works well. It has features of exceptionally low cost, it's safe, it works. It comes with a downside however with its low Isp and low efficiency. To help solve this, a concept using solid gas generators was designed, analyzed, built, and tested. Figure 13 shows a schematic of the cold gas system, including the gas generation portion.

For the gas generation, 30 different chemical candidates were studied. Ammonium Nitrate was selected as the most promising solution because it left no solid residue after combustion, it remains stable after years of storage, it presented the smallest stowed volume, it met the burn-rate requirements, and it had a proven history of safe use in other gas generators, such as automotive airbags.

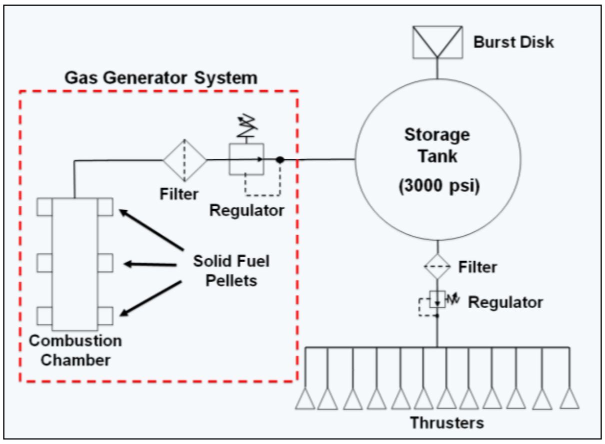

Figure 13: Schematic of Cold Gas 6 DOF Propulsion System for Surgical Satellite Concept

Preliminary testing indicated 3,000 psi in a 14 in^3 storage tank, regulated down to about 30 psi, produced about 0.003 lbs of thrust (calculated and measured). This testing was done by using a small SCUBA 'Spare-Air' tank re-pressurized off a large tank. This provided enough gas for about 30 minutes of operations - depending upon how aggressive the vehicle was driven. With constraints on meeting a 1U size and minimizing weight, the goal was to achieve a system with six re-charges to replenish 3,000 psi. Early designs resulted in determining a volume efficient, 3D printed toroid tank which allowed locating a pressure regulation system in its center. 3D Printing also allowed us to pursue the idea of making the gas distribution to each thruster integral to the frame, and thus minimized dealing with micro-tubing. An early 3D printed 1U prototype is shown in Figure 14.

It was important that the final propulsion design be realistic for a 3-6U vehicle with appropriate flight packaging. Figure 15 shows a final version of the design that include all the necessary components such as the regulation and the solid gas generator combustion chambers. It is expected this final component will be 3D printed from titanium and will have final surfaces finish machined.

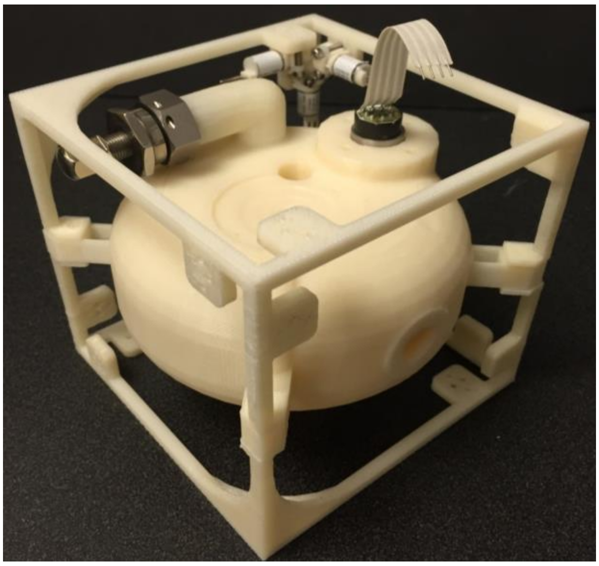

Figure 14: 1U Gas Propulsion System Prototype

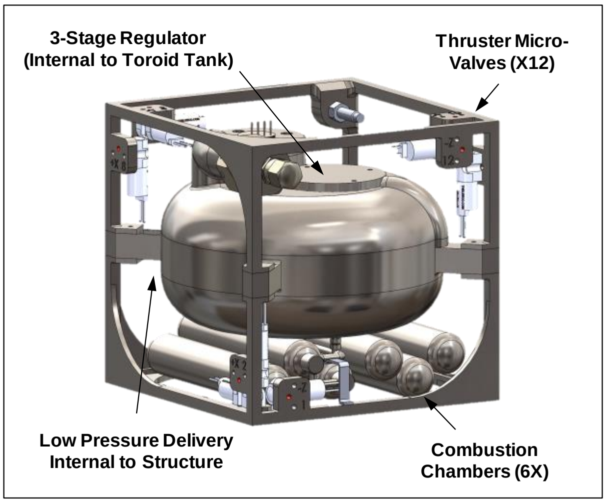

Figure 15: Final Design of a 1U Cold Gas Propulsion System Based on Gas Generator Pressurizing

Although the testbed used compressed air, a prototype of the gas generation system was built to validate the thermodynamic models. The combustion process created a significant amount of heat and it was unclear how the overall system components would respond thermally. A scaled combustion chamber was built, but more attainable Potassium Nitrate was used as the propellant instead of Ammonia Nitrate. This was due to complexities of procuring and testing a regulated explosive. Approximately 5 grams was combusted in an instrumented set-up, results are shown in Figure 16.

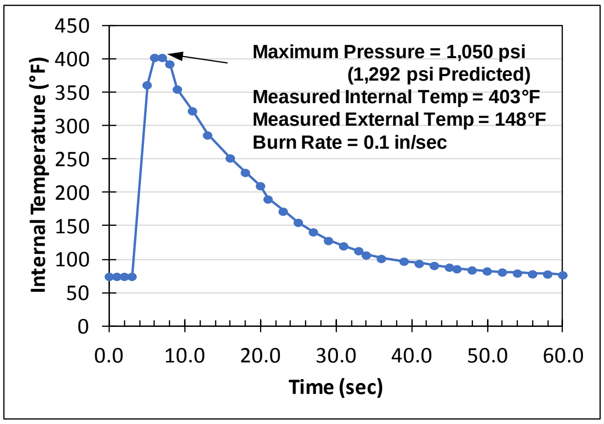

Figure 16: Bench Top Gas Generator Testing that Validated Computer Model

Measured pressures and temperatures reasonably compared with predicted values and the fuel analysis and combustion process was validated. Potassium Nitrate burns very dirty so effectiveness of in-line filters was also confirmed.

SYSTEM VALIDATION WITH TESTBED

A small vehicle testbed was created and evolved to operationally test various mission concepts. Propulsion, vision, manipulation, target capture, stationkeeping, commanding and control dominated the tests completed. The testbed uses a flow-controlled air bearing table with a number of fixed and floating targets that represent various space objects. The primary test vehicle, shown in Figure 17, weighs approximately 6 lbs and is driven through numerous wireless technologies by a command and control console shown in Figure 18. It is important to note the testbed was designed to evaluate operational concepts, not as a flight hardware engineering model.

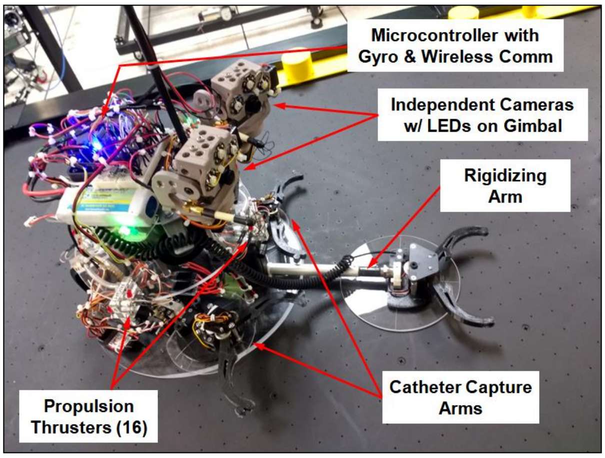

Figure 17: Testbed Vehicle Key Components.

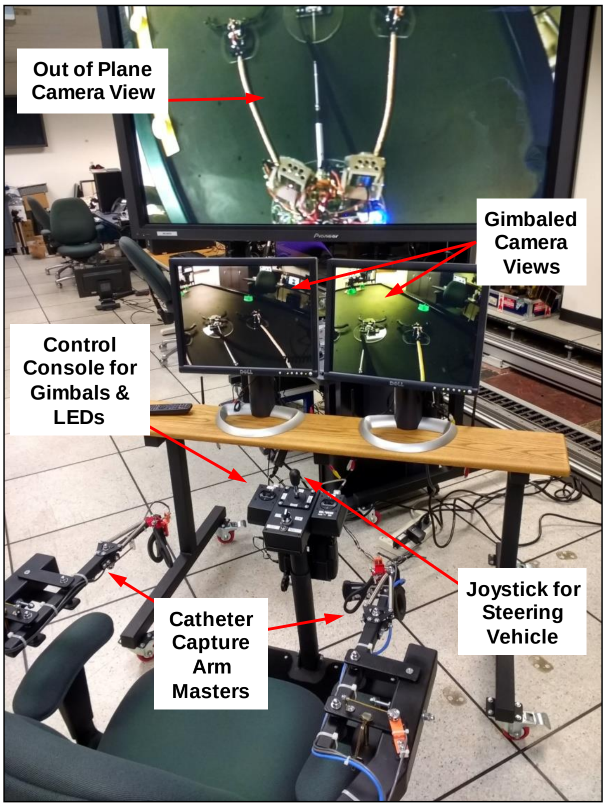

Figure 18: Testbed Operator Controls

With a goal of developing operational concepts, our approach allowed rapid prototyping to validate functionality and usefulness before spending time and energy on flight qualifying designs. The vehicle is approximately 14 in. in diameter and is 12 in. tall. It supports 20 wireless command channels in S-band that include a multiple of RC servos with Bluetooth two-way communication providing command and state of health feedback. Cameras operating in C-band were used for transmitting color visible images. Each camera was independently steered from the control console using set and forget joysticks. The testbed vehicle used a 3 DOF compressed air propulsion system with 16 pulse driven thrusters. With a simple IMU, the vehicle had the ability to hold at station autonomously and can be manually steered via a master joystick to a desired position and orientation. A single 3000 mAhr, 11.1 volt Li-ion battery provides about an hour of operations between recharges.

The control console used monitors to allow for operational workspace awareness but also housed the drive masters for steering the catheter arms. These masters consisted of 4 bar linkages that extend and retract the catheters, and include an elbow joint to allow steering the catheters in-plane. Each arm had operator gripper loops for fingers to actuate the individual grippers. The right side master also contains finger controls for actuating functions on the rigid boom.

The air bearing table was custom built and can support loads on the order of approximately 0.06 lb/in^2. Thus, it could easily float our 6 lb vehicle. A number of practice targets were created as shown in Figure 19. These consisted of lightweight, dynamic pucks that get pushed randomly around by table air. Weights of the targets ranged from 3 oz. to about 7 lbs that encouraged complex interaction dynamics.

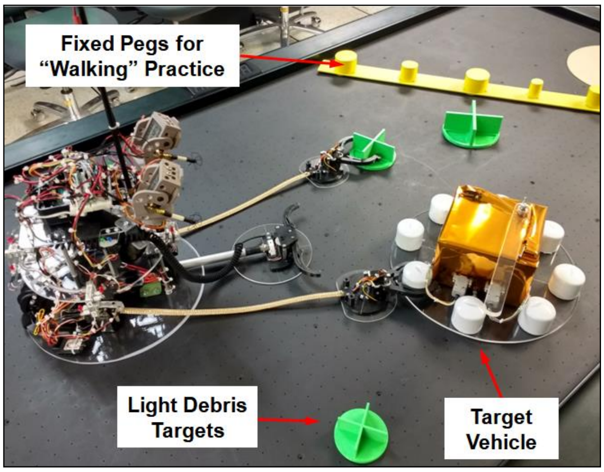

Figure 19: Capturing Multiple Targets

As the targets matched or exceeded the weight of testbed vehicle, the catheter robot arms more manipulated the testbed vehicle versus the target (providing relative motion). In relative space, what object moves does not matter as the operator is always driving through the vision system. The system also has a heavy, non-floating peg-stick that is used to practice moving the vehicle in a linear direction by "walking" with the catheter arms (easier said than done). Figure 20 shows the vehicle capturing a dynamic target with the rigidizing arm. As expected, the testbed is a grand illustration of Newton's third law where no vehicle arm motions go unreacted.

Some lessons learned from the vehicle testbed were that this operational environment is unforgiving. It is easy to touch a target without a successful capture, and the object is now rocketing away. In space, the 3D aspects will be much more complex. It is easy for an operator to be overwhelmed with too many controls and information. Foot pedals were also used for some operations, but they were confusing and were removed. The best solution, much like newer medical systems, is to go with multiple operators with limited tasks that can supervise and controlled. More autonomy is also being looked at and holds promise, but it means even more

sensors and feedback in a packed machine. Haptic force feedback was also considered, but it also greatly complicates the machine and system.

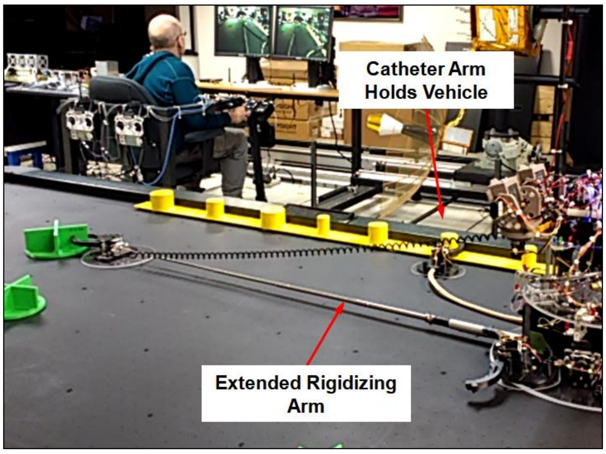

Figure 20: Capturing Targets with Rigid Arm

Notably absent from the previous figures are the surgical arms and tools. Every testbed is a work in progress and this one is no different. Figure 21 shows a surgical arm being driven by its robotic master. The master, highlighted in Figure 22, will eventually be mounted to another frame surrounding a chair so that the operator can observe and control the robotic tool motions through on-board cameras. Obvious the surgical portions and the vehicle potions have yet to be made integral onto a single floating platform, but that will be the next steps. Tests completed to date include investigating reaction torques to the base, determining workspace limits, and adjusting the master controller PID software to get smooth motion.

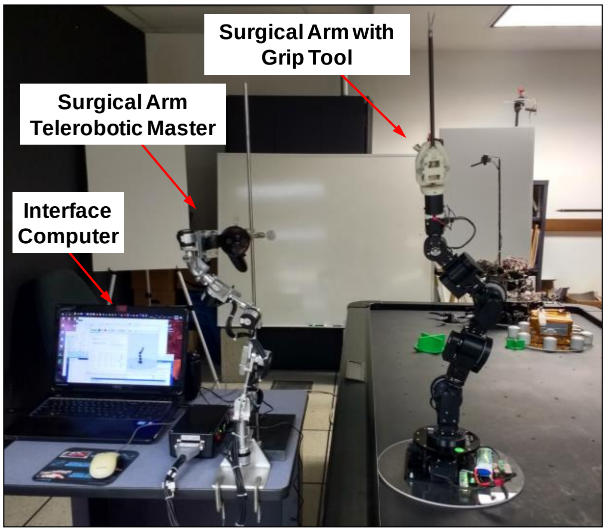

Figure 21: Surgical Tool Robot and Master

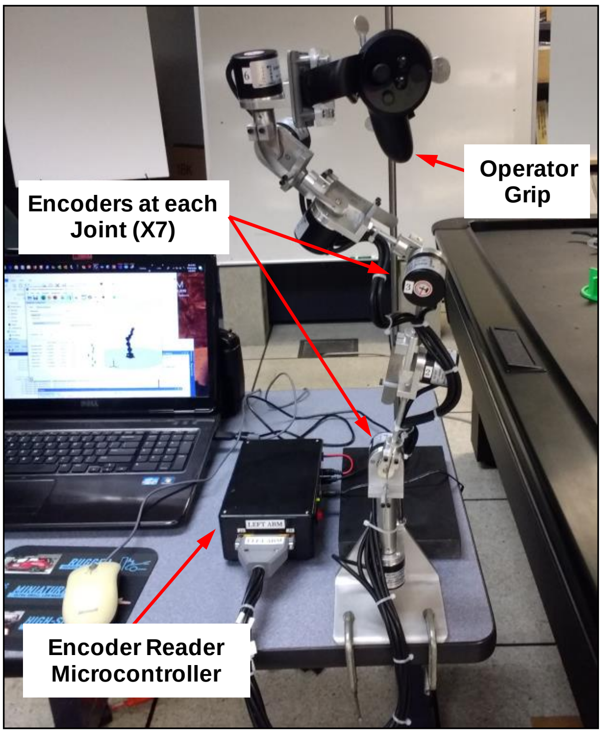

Figure 22: Surgical Robot Telerobotic Master

Additional set-up work for the telerobotic master is still underway. This includes optimizing high speed USB wireless control links and tuning the various microcontrollers and computer loops to minimize communication errors and lag time.

The 4 DOF tools are presently driven from a wireless RC controller but will eventually be slaved to a game controller attached to the end of the telerobotic master. Figure 22 shows a picture of one of these controllers, which is also used to position the robot arm.

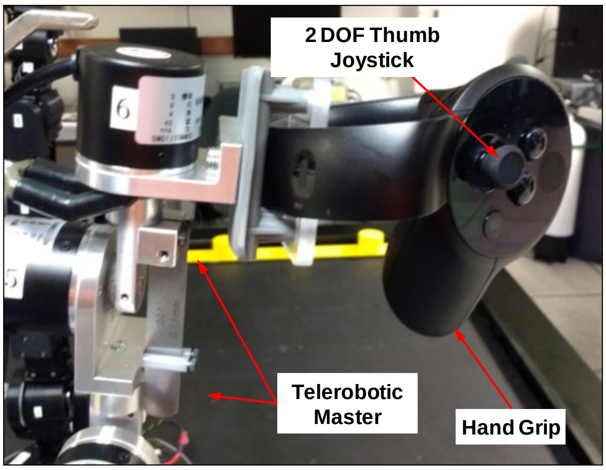

Figure 22: Surgical Tool Controller and Telerobotic Master Hand Interface

Using the combined robotic arm and tool, the system has been able to pick-up small objects and cut thin insulation while stationary. While floating, it is difficult to control and react against an object.

The surgical robotic system started as a simple idea but grew in complexity as we discovered the articulation complexity required to actually perform intricate tasks. The testbed has proven to be useful to assess the practicalities of various architecture ideas. Controlling all the arms, lights, cameras, and vehicle positioning in a dynamic environment has resulted in too much stimulation for a single operator. The addition of many improved features has also resulted in significant size and weight growth. This makes for a design that has not stabilized, but does show promise as concepts are tested and accepted.

CONCLUSIONS

Manipulation and actuation concepts for a surgical satellite have been investigated and tested in a space simulated air bearing environment to capture and attach to a target space object. Testing showed small scale surgical operations requires a rigid attachment as a means to react forces. Five tools were developed that are interchangeable on two robotic arms. The tools perform basic functions of gripping, cutting, cleaning, heating, and observing. The full-scale testbed was used to evaluate and improve functionality of many of the system components. Lastly, our research effort is continuing with unifying all the robotic capabilities onto one platform and adding roles for two or more operators due to tasking and information comprehension complexities.

ACKNOWLEDGMENTS

Progress on many portions of this system has been through several engineering Senior Design teams at Cal State University, Los Angeles. The students developed and pursued many additional ideas not elaborated on in this paper, but nevertheless were critical in determining the existing architecture. We are grateful for their help.

REFERENCES

1. Harland, D.M. and R.D. Lorenz, "Space Systems Failures," Praxis Publishing, Chichester, UK, 2005.

2. Robertson, B. and E. Stoneking, "Satellite GN&C Anomaly Trends," 26th Annual AAS Guidance and Control Conference, Paper AAS 031071, Breckenridge, Colorado, February 5-9, 2003.

3. Evans, B., "The Galileo Trials", Spaceflight Now, [https://spaceflightnow.com/galileo/030921galileohistory.html], posted September 21, 2003, accessed May 4, 2019.

4. Simaan, N., R.M. Yasin, and L. Wang, "Medical Technologies and Challenges of Robot-Assisted Minimally Invasive Intervention and Diagnostics," Annual Review of Control, Robotics, and Autonomous Systems Volume 1, 2018, pp 465-490.

5. Zapiain, R., "Miniaturizing Medical Robots," MDT Magazine, pages 14-16, May/June 2017.

6. McKinley, S. et. al. "An Interchangeable Surgical Instrument System with Application to Supervised Automation of Multilateral Tumor Resection", IEEE International Conference on Automation Science and Engineering (CASE), Fort Worth, TX, August 21-24, 2016.

7. Brahmbhatt, J.V., A. Gudeloglu, P. Liverneaux, and S.J. Parekattil, Robotic Microsurgery Optimization, Archives of Plastic Surgery, May 2014.

8. Hanlon, E.A.S, B.P. Keegan, B.H. Bailin, and J.S. Kang, AMODS: Autonomous Mobile On-orbit Diagnostic System, 29th Annual AIAA/USU Conference on Small Satellites, May 13, 2016.

9. Flores-Abad, A., M. Ou, K. Pham, and S. Ulrich, "A Review of Space Robotics Technologies for On-orbit Servicing", Progress in Aerospace Sciences 68, pp 1–26, 2014.

10. Fong, T., J.R. Zumbado, N. Currie, A. Mishkin, and D.L. Akin, "Space Telerobotics: Unique Challenges to Human–Robot Collaboration in Space," Reviews of Human Factors and Ergonomics, Vol. 9, 2013, pp. 6–56.

11. Feng, G., W. Li and H. Zhang, "Space Robot Teleoperation Experiment and System Evaluation Method," 2nd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC 2018), March 23, 2018.

12. Liu, G., X. Geng, L. Liu, and Y. Wang, "Haptic Based Teleoperation with Master-slave Motion Mapping and Haptic Rendering for Space Exploration," Chinese Journal of Aeronautics, March 18, 2018,

13. Nye, T., "Spacecraft Health and Forensics from Video Telemetry," AIAA Space 2014 Forum, San Diego, CA, September 10-12, 2013.

14. Zhang, X., J. Feng, J. Jinguo, "Experimental Platform of Space Robot Grasping Various Non-prehensile Targets"' 50th International Symposium on Robotics, München, Germany, June 20-21, 2018.

15. Wang, Y., Y. Liao, K. Gong, "Workspace Calculation of Free-floating Planar Dual-arm Space Robot," 2nd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC 2018), March 23, 2018.

16. Shi, L., H. Jayakoby, J. Katupitiya, and X. Jin, "Coordinated Control of a Dual Arm Space Robot," IEEE Robotics and Automation Magazine, December 2018, pp 2-11

17. Huang, P., et.al., Dexterous Tethered Space Robot: Design, Measurement, Control, and Experiment," IEEE Transactions on Aerospace and Electronic Systems, Vol. 53, No. 3, pp 1452-1468, June 2017.

18. Cheng, W. L. Tianxi, Z. Yang, "Grasping Strategy in Space Robot Capturing Floating Target," Chinese Journal of Aeronautics, pp 591-598, February 24, 2010.

19. Kandaswamy, I., T. Xia, and P. Kazanzides, "Strategies and Models for Cutting Satellite Insulation in Telerobotic Servicing Missions," IEEE Haptics Symposium, February 23-26, 2014.

20. Maharjan, N., et.al. "Femtosecond Laser Cleaning for Aerospace Manufacturing and Remanufacturing," 2017 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR), July 31-August 4, 2017

21. Mete, D., "Pet Hair Collector", US Patent 20140373252A1, December 25, 2014.