Miniature Orbital Dexterous Servicing System

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Abstract

Current concepts for robotic satellite servicing use robotic systems similar in size to candidate client spacecraft, requiring similar launch vehicles and roughly equal costs. To achieve economic viability, proposed systems require multiple clients on each mission, restricting applications to geostationary orbit to ensure an adequate number of potential clients and limiting each system to one repetitive common task such as refueling. This paper investigates the potential to create a new class of dexterous servicing vehicles based on small satellite technologies, including recent developments in highly capable lightweight dexterous manipulators. A notional design for a Miniature Orbital Dexterous Servicing System (MODSS) vehicle was developed and applied to a candidate servicing opportunity from recent flight history. While much work remains to be done, all indications are that a MODSS system offers a realistic potential for economically viable missions to a single client, allowing individualized logistics supply and launch-on-need to any required orbit.

1 Introduction

On-Orbit satellite servicing is rapidly becoming a common phrase in the space industry. More and more servicing experiments and missions are being planned and executed, not merely as technology demonstrations, but because satellite servicing has demonstrated that it has the potential to be financially profitable for both the client and servicer. Nevertheless, it is a common belief that satellites must be specially designed in order to be serviced. Past studies indicated that the cost of making a satellite serviceable would represent a 5-10% weight increase, in addition to increasing developmental and recurring costs. [1] However, as experience with satellite servicing has grown, results indicate that satellites do not need special, expensive, hardware on board in order to be serviced. For example, the Hubble Space Telescope (HST) was designed to be serviced only at the orbital replacement unit (ORU) level; over the course of multiple servicing missions, repair activities became more ambitious, even down to circuit board replacement using specialized tools for the crew in extravehicular activity (EVA). [2]

Sullivan [3] divided satellite servicing tasks into five generalized categories: orbital correction, deployment assistance, component repair, consumable resupply, and removal/disposal. Studying all spacecraft failures from 1984 to 2003, he concluded that there are annually an average of 4.4 component level failures, 0.3 deployment failures, and 3.8 more complex failures. In addition, an average of one GEO satellite per year is deployed at an incorrect orbit and is declared a complete loss and another thirteen satellites must use up station-keeping fuel in order to relocate from GEO to a superstationary retirement orbit. This reduces the lifetime, and profit, of these satellites.

While HST, as the "existence proof" of on-orbit repair and upgrade, was serviced by astronauts, robotic systems have demonstrated in ground-based simulations and on-orbit experiments that they are capable of a similar level of dexterity upon need. The Space Systems Laboratory (SSL) performed the first robotics servicing demonstration on HST in neutral buoyancy in 1987, and performed extensive servicing both robotically and via EVA/robotic collaboration in 1989. Ranger, a more capable robotic system developed by the SSL, used HST as the source for its standard canonical servicing tasks throughout the 1990's. Developed under NASA funding as a low-cost flight demonstration of on-orbit dexterous robotics for servicing applications, the four-manipulator Ranger system was the first U.S.-built dexterous robot to pass NASA payload safety reviews for both flight and operation on the Space Shuttle. [4] After the loss of Columbia, NASA Goddard Space Flight Center was directed to develop the Hubble Robotic Servicing and Deorbit Mission (HRSDM). While mission manager conservatism led them to pass over the flight-qualifed Ranger system in favor of the Canadian Special Purpose Dexterous Manipulator (SPDM) system, Ranger was modified by the University of Maryland to replicate the kinematics, configuration, and end effector dexterity of SPDM to perform independent validation and verification in neutral buoyancy simulations. Over the existence of the HRSDM mission,

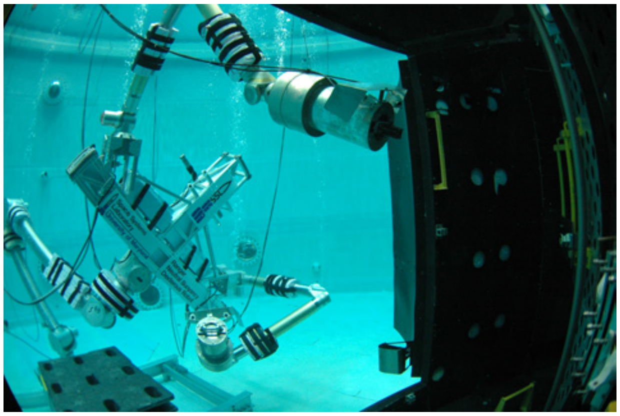

Figure 1. Ranger in the same configuration as SPDM/Dextre servicing a HST mockup

Ranger performed almost all HST servicing tasks (Figure 1) eventually performed on-orbit by astronauts after a new NASA administrator canceled the robotic program in favor of another EVA servicing mission on the shuttle. Since that time, the DARPA Front-end Robotics Enabling Near-term Demonstrator (FREND) project has performed ground demonstration of autonomous grappling of a Marman band and bolt holes. [2] Common interfaces, such as Marman bands, allow servicers to grapple to provide assistance without requiring the client to have specially designed system. The NASA Goddard Robotic Refueling Mission (RRM) experiments on the International Space Station have demonstrated the ability to perform complex servicing tasks such as refueling of satellites through ground-service ports, even with the limited dexterity of the SPDM.

When astronauts are not available, dexterous manipulators are necessary to repair the majority of spacecraft failures. [5] Typical servicing configurations utilize three manipulators, to allow one to grasp the client while still having two manipulators to perform servicing tasks, either as a two-handed coordinated task or alternating between different end effectors for specific tasks. Generally, this approach assumes the "grappling" manipulator must be large enough to reach all areas of the client's surface which represent potential workspaces while remaining attached to a singular grapple. Dexterous manipulators tend to be be sized appropriately as well, particularly needing to grow longer as the servicer bus increases to avoid potential contact issues. As the size of the servicing vehicle approaches the size of the client satellites, they require the same launch vehicles, at the same cost, as a replacement satellite. Given the general advance in satellite capabilities with the advancement in technology, the owner generally opts for a new satellite rather than a repair, especially since insurance frequently covers the lost revenue due to early system failures. To make a viable business case, many satellite servicing architectures are predicated on a requirement of servicing multiple clients, to allow the cost per client to be reduced by spreading the large development and launch costs between multiple planned missions. This in turn leads to business plans aimed at "low-hanging fruit", such as specializing in orbital modification or refueling.

In order to service multiple satellites, the clients must have similar orbits and orbital planes to allow for maneuvering between orbits without exorbitant costs. For this reason, most servicing plans default to specializing in satellites in geostationary orbit (GEO). [3] Even large constellations of low Earth orbital satellites such as Iridium have assets in multiple orbital planes, with no feasible ability to transfer a servicer between the planes. Satellites in GEO are by definition in a single orbital plane at 0^{o} inclination, allowing transfers between widely separated orbital latitudes as long as time is not a critical issue. Other than single-digits of satellites in a single orbital plane of a constellation, GEO is the only orbital destination with a large number of satellites at a single orbit, differing only in longitudinal positions. Also, the vast majority of commercial revenue comes from GEO satellites, making them better targets for commercial servicing. Current commercial servicing entities, therefore, are focused on dedicated single-task missions (e.g., refueling) along the geostationary arc.

With an eye to relieving the inherent limitations in "large" servicing systems, in recent years the SSL has been focusing on robotic and spacecraft technology miniaturization, with the goal of validating a feasible approach to on-orbit robotic servicing based on a small satellite bus, and taking advantage of the rapid development of cubesat technologies. The Miniature Orbital Dexterous Servicing System (MODSS) is a "smallsat"-based robotic system concept capable of simple modular reconfiguration, creating wide applicability to human and robotic space missions. MODSS is significantly smaller and lighter than FREND and other large servicing systems currently under development. As a result, both development and launch costs are significantly reduced, to enable economic viability for a single dedicated servicing target. This will enable a number of other supporting capabilities, such as launch-on-need and the ability to tailor robotics configuration and logistics of replacement parts to each individual servicing client.

2 MODSS Overview

MODSS consists of a base spacecraft, which provides command and data handling, electrical power, attitude determination, propulsion, and communication systems. Advanced mission packages (AMPs), containing mission-specific payloads ranging from passive instruments to suites of appropriately scaled robotic manipulators, are generally added to the base vehicle for specific missions, providing a system capable of adapting to a wide range of objectives with open-ended capabilities for future expansion.

The basic MODSS spacecraft bus is based on the Exo-SPHERES vehicle, prototyped by UMD under support from NASA and DARPA, and designed specifically to be capable of performing inspection tasks around the International Space Station. The basic ISS vehicle would be equipped with an inspection AMP, consisting of high performance cameras and lighting. AMPs are in general limited to mission-specific payloads; all spacecraft operations are provided by the base vehicle. Exo-SPHERES was designed with a CO_2-based cold gas propulsion system, providing 40 m/sec total ΔV, which was shown via simulation to be adequate to support an 8-hour active inspection sortie at ISS with suitable maneuvering reserves. The selection of a CO_2-based cold gas system also allows the vehicle to be brought inside the ISS to allow the vehicle to be repaired, upgraded, and equipped with different AMPs without the complication of an EVA. A docking platform on the slide platform of the Kibo airlock allows the vehicle to autonomously dock and be brought inside. While this method is adequate for initial testing and infrequent repairs, it is not ideal to require a repressurization of the airlock after every mission. The alternative is an external docking facility with a secondary docking port that would take one of the JEM exposed facility sites. This docking facility can recharge the vehicle batteries as well as refuel the vehicle, minimizing the number of airlock cycles needed to support a mission. Operationally, the vehicle could autonomously dock and then recharge and refuel before continuing its mission. Additionally, AMPs for other missions can be located on the external dock, further decreasing the necessity to dock with Kibo and perform a repressurization cycle. Figure 2 shows a notional mission for Exo-SPHERES in support of EVA repair of an ISS solar array.

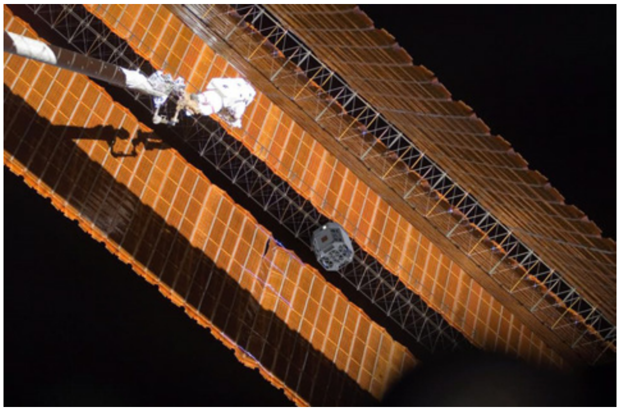

Figure 2. Exo-SPHERES performing a notional inspection mission

While the ISS-specific Exo-SPHERES mission placed many constraints on the design of the system, the extension and enhancement to MODSS takes advantage of the small spacecraft bus to facilitate a much wider range of missions. At 50 kg, MODSS is ideally sized to fit on an ESPA ring or equivalent secondary launch adapter, only limiting orbital access to available rideshare opportunities. Design studies have shown that the development of a similarly-sized hydrazine or bipropellant propulsion module with AMP interfaces will allow the integration of a complete MODSS vehicle system after primary payload separation which is capable of reaching any orbital location in cislunar space with full satellite servicing or orbital assembly capabilities. Such a system would be able to perform extended satellite servicing in a GEO orbit in a single launch, ready for launch-on-need on one of the many geostationary transfer orbit delivery missions. It should be noted, however, that most primary payload providers would not be comfortable with a significant propulsion capability as a secondary payload; this will limit the acceptance of this approach until the safety of the ESPA-mounted propulsion module is verified and demonstrated on-orbit.

Table 1 shows the top-level mass breakdown of systems in the MODSS spacecraft bus. These figures are based on SSL experience with both Exo-SPHERES and DYMAFLEX payloads, and incorporate a 10% mass margin in the listed figures. Table 2 shows a similar breakdown of component masses for a three-armed dexterous servicing AMP. As in the Exo-SPHERES architecture, the AMP payload is responsible for its own energy storage, although recharge can be accomplished through the base vehicle electrical system.

Table 1. Mass breakdown; MODSS base system

Component	Mass (kg)
CO_2 Thruster System	5
CO_2 Propellent	7
Communication System	4
Electrical Power System	7
Sensors	5
Structures	12
Sensors	5
Margin	5
Total Mass	50

Table 2. **Mass breakdown; MODSS DM3-AMP**

Component	Mass (kg)
Cameras Manipulator	5
Dexterous Manipulators (x2)	7 (14)
Electrical Power System	7
Sensors	3
Structures	9
Sensors	3
Margin	9
Total Mass	50

2.1 Example Orbital Correction Mission

In 2001, a Japanese communications satellite named BSAT-2b was launched into an incorrect orbit on an Ariane 5 rocket. This 1.3 Mt satellite had a target orbit of 35,853 km apogee, 858 km perigee, and 2.0 degree inclination. [6] It achieved an apogee of 17,528 km, perigee of 592 kilometers, and inclination of 2.9 degrees, beyond the capacity of its on-board propulsion system to reach geostationary orbit, and rendering its intended mission impossible. [7] It took another two years and over $100 million to launch a replacement satellite, BSAT-2c, into a correct orbit. However, instead of building and launching a new satellite, a dedicated servicing system such as MODSS could have been used to capture the client and perform the needed orbital correction; the following section investigates the pivotal issues of the technical feasibility and economic viability of such a mission. While the actual BSAT-2b satellite has deorbited, it provides an excellent case study for assessing the potential of a MODSS servicing approach.

Starting with the concept of rendezvousing with BSAT-2b to change its orbit, a MODSS system would need to be outfitted with a three-armed dexterous manipulator AMP (DM3-AMP) and extended mission package (EM-AMP), as shown in Figure 3. In this configuration, MODSS could be launched on a Pegasus XL launch vehicle to intercept the client from various launch sites to minimize inclination change. This conceptual MODSS stack, weighing only 210 kg, includes 90 kg of hydrazine monopropellant in its EM-AMP to complete its mission (Table 3). After insertion into the client's orbit, MODSS would perform orbital maneuvering with the hydrazine engine in its EM-AMP and attitude control and fine translation with the cold gas thrusters onboard the MODSS base unit. After rendezvous and proximity operations, MODSS would then use the three dexterous manipulators in the DM3-AMP to capture and rigidize the client spacecraft via teleoperation or vision-based autonomy. An apogee-raising maneuver using the EM-AMP would put BSAT-2b into its design GEO transfer orbit, from which its on-board propulsion system would perform a nominal orbit circularization and orbit stationkeeping. MODSS can then be left grappled with the client for additional maneuvering, or be placed into a degrading orbit for disposal. Costing about $25 million, MODSS is not only a faster solution to correcting satellite insertions, but also much more cost effective than total system replacement.

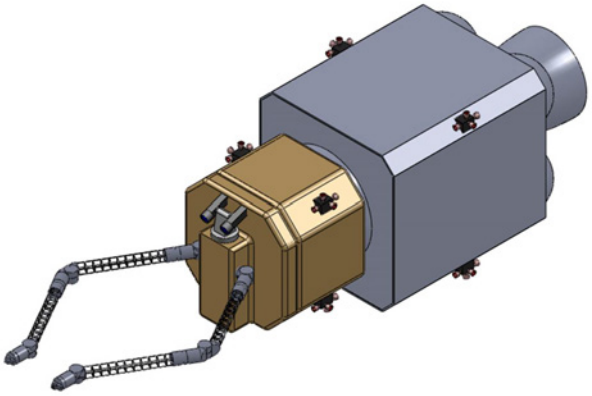

Figure 3. Artist's rendition of an example MODSS, EM-AMP, DM2-AMP stackup

Table 3. Mass Breakdown for BSAT-2b orbital correction; chemical propulsion

Component	Mass (kg)
Mono-propellant (with 20% margin)	90
Propellant and Pressurant Tank Mass	20
Exo-SPHERES Base + Manipulator AMP	100
Total Mass	210

With further development of the EM-AMP, MODSS could complete the same mission in alternate modes. There was a second payload on that 2001 launch, Artemis, which was able to correct its orbit via an onboard electric-ion motor within 18 months. [8] This engine was only intended for station keeping, but a similar approach can be taken with a larger engine to create an Extended Mission Ion-engine AMP (EMi-AMP). While the correction time with an electric engine is increased to over fifty days from the chemical system, it makes the system much more flexible. This MODSS stack would weigh about 250 kg, using a 400 watt ion engine allowing it to also be launched from a Pegasus XL at a similar total mission cost. The advantage of this approach is that the electric propulsion system would also serve as a highly efficient stationkeeping upgrade to BSAT-2b; the MODSS system could use a dexterous manipulator to plug into the Ground Support Equipment port on the client for data communication as a

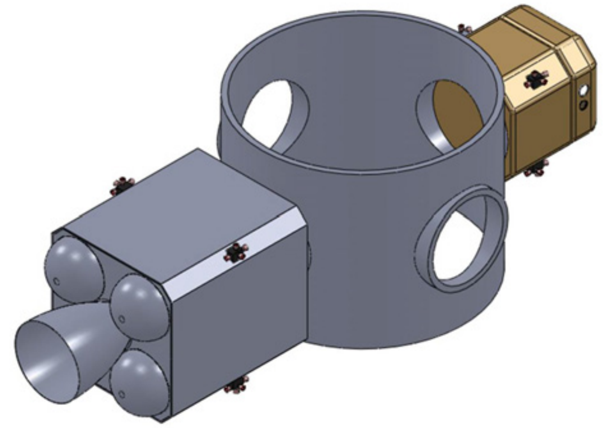

Figure 4. MODSS and a refueling AMP attached to an ESPA Ring

Table 4. Mass breakdown; MODSS Refuel mission base system ESPA ring 1

Component	Mass (kg)
Base MODSS Vehicle	50
DM2-AMP	30
Propellant	70
Refueling AMP	30
TOTAL MASS	180

Table 5. Mass breakdown; MODSS Refuel mission base system ESPA ring 2

Component	Mass (kg)
Tank Mass	15
Structure + Engine	40
Propellant	125
TOTAL MASS	180

permanent installation.

2.2 Example Refueling Mission

The MODSS system can be used to refuel satellites in GEO that are nearing the end of their station keeping reserves. By using an Extended Mission Refueling AMP (EMr-AMP) and DM3-AMP, MODSS can deliver 100 kg of hydrazine to a client in GEO. Such a mission would not be extremely time critical when compared with an orbital correction, so costs can be reduced by placing MODSS as a secondary payload. A MODSS stack would be launched in two parts on an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) on a Falcon 9, or similar vehicle, into a Geosynchronous Transfer Orbit (GTO). Limited to 180 kg per spot on the ESPA, the EMr-AMP would fill one spot while MODSS and the DM3-AMP would be mounted to a separate point (Figure 4). Once separated from the ESPA, MODSS would use its cold gas thrusters to dock with the EMr-AMP. It would then perform a single circularization orbit to intersect the client. MODSS will use its cold gas thrusters to maneuver into the dexterous workspace for the DM3-AMP manipulators and grapple to the client's launch interface using a single arm. A second manipulator can then be used to connect to the GSE fueling port on the client, using the third manipulator as a camera arm for teleoperation. Once fueled, MODSS will detach from the client and place itself into a disposal orbit. This mission, costing approximately $30 Million, can double the life of an average satellite in GEO. Table 4 and Table 5 provide a mass breakdown for such a mission.

2.3 Ground Based Testing

MODSS is a system concept widely capable of adaptation to human and robotic space missions. Not only does the flight system have to be readily adaptable, but ground based testing platforms must be rapidly reconfigurable as well. In addition to flight systems, UMD's development of MODSS included validating and operating multiple ground test-beds, including 2D testing (air-bearing facilities) and 3D testing (neutral buoyancy and parabolic flight). MODSS system bus and the DM3-AMP are currently being developed on several test beds at the Space Systems Laboratory.

The ground-based protoflight vehicle has been developed to test command and control of the system for parabolic and air bearing environments. The vehicle includes 16 cold gas thrusters, power, all necessary vehicle sensors, and computer systems to emulate the flight system. Additionally, a neutral buoyancy vehicle named EUCLID (Exo-SPHERES Underwater Closed Loop Inspection and Docking), serves to simulate missions as well as test controllers and operator interfaces. EUCLID has six thrusters to give it the same capabilities of motion control as the 16 thrusters in MODSS while in the underwater environment (Figure 5). The system is capable of being run autonomously as well as via teleoperation.

Historically, robotic arms have often been slow and lightweight in comparison to their host spacecraft; but as economic incentives drive the development of smaller, faster, lighter vehicles, the dynamic coupling between spacecraft and manipulator will present an increasing challenge in the development of suitable control systems. To address this issue, a prototype manipulator AMP is being developed by the SSL to study the closely coupled dynamics between a manipulator and a base vehicle with similar levels of inertia. The study derives from the issue

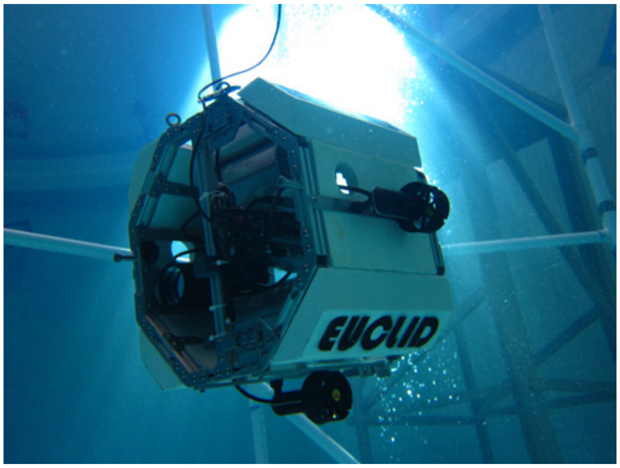

Figure 5. EUCLID in the Neutral Buoyancy Research Facility

that a spacecraft is a free flier, and therefore also moves in response to any forces or torques resulting from a manipulator. This results in highly coupled dynamical behavior not seen in traditional, fixed-base robotics or the low dynamic coupling seen in large dexterous servicer systems. Nevertheless, a high performance manipulator AMP represents the ideal test bed for space manipulator dynamics and control testing.

The manipulator being used for this development comes from the Dynamic Manipulation Flight Experiement (DYMAFLEX), a smallsat development project performed by the SSL under the sponsorship of the AFOSR University Nanosat Program. This manipulator was designed to have sufficient tip forces and torques to accomplish operational servicing tasks, at a total arm mass of 5 kg in the nominal seven degree of freedom (DOF) flight configuration with all structural components machined from aluminum. The prototype shown in Figure 6 is made of ABS plastic made using a fused deposition rapid prototyping process, and would have an equivalent flight mass of 3 kg. One planned development activity is to develop one or more actuators for this arm using rapid prototyping in Windform XT, a material which has already been flown in space in a number of cubesat applications. This could provide even lighter manipulators with shorter development cycles.

3 Future Work

Many of the test beds required for MODSS development, including a parabolic flight vehicle (Figure 7) and neutral buoyancy vehicle, are currently functional and under test, including not only hardware and functionality, but also simulations to determine how the systems can best be used in real world applications. For example, the test beds will be used to determine the effects of time delay on human teleoperation performance, in order to build mitigation strategies into the architecture from the outset.

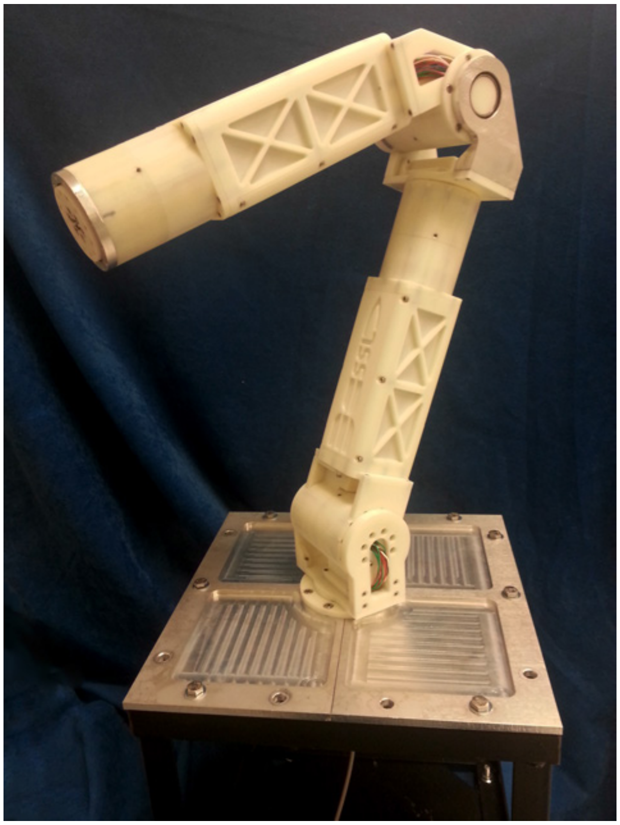

Figure 6. The DYMAFLEX high performance 4 DOF prototype manipulator

One of the advantages of the prior work on Exo-SPHERES and DYMAFLEX is the existence of prototypes of all critical systems. The Exo-SPHERES protoflight vehicle is being modified to mount the DYMAFLEX arm for studies of coupled dynamics in parabolic flight before the end of this year. EUCLID is a fully-functional 6 DOF underwater free-flying vehicle, which allows end-to-end simulations of complex maneuvering activities in the University of Maryland Neutral Buoyancy Research Facility (NBRF). While hydrodynamic forces generally limit simulation fidelity in neutral buoyancy, the presence of a 12-camera motion capture camera system in the NBRF provides high data rate documentation of motions and trajectories in the tank, and provides full state feedback to allow active control algorithms to eliminate the dynamic effects of water drag up to the saturation limits on the EUCLID thrusters. The DYMAFLEX arm was designed to allow future versions to be made watertight, which would allow the development

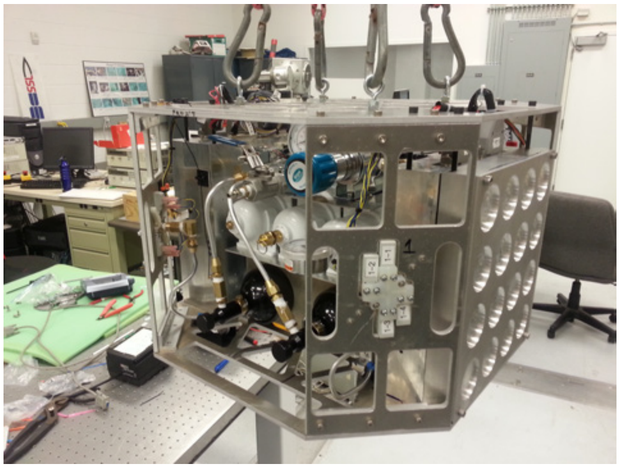

Figure 7. MODSS protofight vehicle attached to crane

of an underwater dexterous manipulation AMP and allow full simulations including dexterous servicing in the neutral buoyancy environment.

In parallel with the experimental development and testing, more effort will be placed on systems analysis and mission application studies. One of the complaints about current commercial servicing proposals are their focus on “low-hanging fruit”, such as orbit modification and refueling. While the simple mission scenarios developed for this paper address the same techniques, a high priority will be placed on developing detailed concepts of more complex servicing environments, including dexterous servicing and a full logistics analysis of a “launch-on-need” dedicated servicing system.

4 Conclusions

MODSS is a lightweight servicing architecture that aims to avoid the shortcomings of servicing systems based on more conventional large vehicles. Taking advantage of the rapid development of smallsat and cubesat technologies, MODSS focuses on providing single-use vehicles to complete complicated servicing missions inexpensively. A “toolkit” of extended mission packages which include more capable orbital maneuvering systems and dexterous manipulators AMPs will allow the system to respond to “launch-on-need” by quickly assembling the correct spacecraft, consumables, and spare parts for each specific mission. This is a departure from monolithic servicing architectures, which require multiple clients to be serviced before they are financially viable. MODSS has the potential to provide individual clients cost-effective servicing customized for the needs of the mission. In addition, this opens up new types of satellites to servicing that were previously non-viable due to the need to service many clients per launch. With a MODSS-type architecture, orbits other than GEO become viable in terms of both technology and economics. While still early in the development process, the Miniature Dexterous On-Orbit Satellite Servicer demonstrates the potential to go where other servicing systems cannot, successfully complete a dedicated mission, and still make sense economically.

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