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MORPHbots: Lightweight Modular Self-Reconfigurable Robotics for Space Assembly, Inspection, and Servicing

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Under support from the Defense Advanced Research Projects Agency, the University of Maryland Space Systems Laboratory has been developing advanced miniaturized robotics for dexterous space operations. The final robotic architecture, now in prototype form, is a highly modular system capable of self-reconfiguration. These "MORPHbots" are composed of standardized actuator, sensor, and computational modules, interconnected by androgynous interface mechanisms capable of being actuated by the robots themselves. In a microsatellite configuration, a six degree-of-freedom serial manipulator with interchangeable end effectors has a total mass of only 10 kg, but is capable of performing assembly and servicing work typically performed by astronauts in pressure suits. Due to the modular nature of the system, a failed component can be easily removed and replaced with another unit, or the entire kinematics of the arm can be changed to better perform a given task. In a "depot" situation, a collection of MORPHbot components stocked on an orbital platform can be used to assemble a wide variety of robotic systems, optimized for specific operational requirements, such as structural assembly or satellite servicing. This paper presents the MORPHbot concept in detail, along with samples of MORPHbot configurations for specific missions such as a robotic servicer for International Space Station and a low-mass orbital assembly system for exploration vehicles or large aperture science platforms. Results of performance and environmental testing on prototype MORPHbot actuator modules will be given, along with plans for near-term ground-based tests of the concept in end-to-end high fidelity simulations.

I. Introduction

In 1990, the University of Maryland Space Systems Laboratory began the development of its next generation research robot. Called Ranger, the paradigm for this project was to design and fabricate a dexterous robotic system capable of performing any servicing task currently performed by astronauts in space suits. The system would be designed as a space flight capable vehicle, based on the lowest cost launch vehicle then existing: the Orbital Sciences *Pegasus* vehicle. Under NASA research funding, the SSL would then develop an underwater analogue for research purposes.

As the design process proceeded, it became more and more clear that the concept of a small, low-cost expendable servicing robot made a great deal of sense on multiple levels. The then-recent NASA experience with the Flight Telerobotic Servicer left the impression that any flight robotic system would approach a billion dollar price tag. This exacerbated the traditional conundrum with space robotics: no support for development is forthcoming until the robotic system is tied to a mission requirement for a flight program, but lacking an existing robot, no sane program manager would agree to a requirement for a robot for the danger of being required to pay the "sticker price" for the system. In 1992, the University of Maryland was selected by NASA to develop the Ranger Telerobotic Flight Experiment (TFX) as a low-cost, near-term robotics flight demonstration.

The concept of Ranger TFX is shown in Figure 1. Based on extensive prior SSL robotics experience in neutral buoyancy simulations of diverse space operations, including structural assembly and Hubble Space Telescope servicing, the system configuration was based around a pair of dexterous manipulators, with equivalent reach, force, and speed of motion as human arms. A third manipulator provided a mobile positioning arm for stereo video cameras for feedback to the ground operator, while a fourth manipulator grappled the target spacecraft; in the case of

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the Ranger TFX mission, the third stage of the Pegasus launch vehicle. NASA providing funding for a neutral buoyancy development and qualification vehicle (Figure 2) and initial development funding for the flight vehicle, with the understanding that no NASA funding would be available for the launch vehicle, and that the UMd team would have to arrange for launch costs to be donated. Total program costs (to NASA) were capped at $15M.

One of the methods of achieving two order of magnitude cost reductions as compared to FTS was to design the Ranger TFX system with generous margins, and to use none of the limited resources of the program to pursue more traditional lightweight flight structures. Ranger TFX vehicle mass grew to approximately 800 kg, nearly double the payload limit of the Pegasus launch vehicle to low Earth orbit. The direct line-of-sight communications strategy adopted required minimum orbital altitudes of 1000 km, to obtain 20-minute contact passes over the single ground station for restricted telerobotic operations. This led to a search for shared launch opportunities on Delta II-class vehicles, further increasing the difficulty of obtaining a "free" launch. In 1996, after four years of promising results from the Ranger neutral buoyancy vehicle and disappointment in launch negotiations, NASA directed UMd to redesign the robotic system for flight on a Space Shuttle mission.

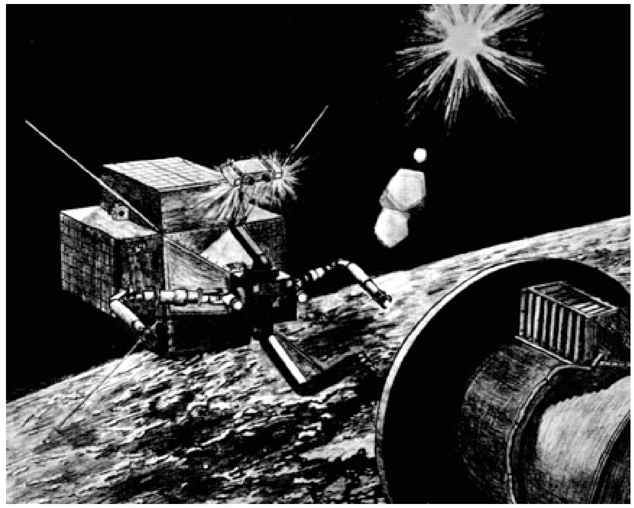

Figure 1. Ranger Telerobotic Flight Experiment (TFX) concept. *Free-flying robotic servicing vehicle approaches upper stage of Pegasus launch vehicle.*

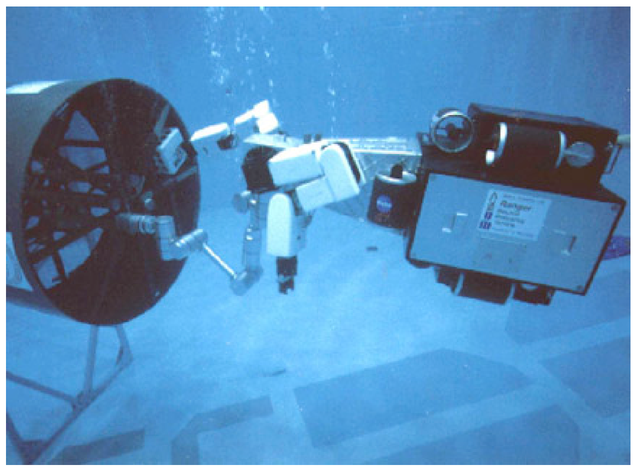

Figure 2. Ranger Neutral Buoyancy Vehicle. *Test operations in the UMd Neutral Buoyancy Research facility include orbital replacement unit (ORU) exchange on simulated launch vehicle upper stage.*

Conversion to the Ranger Telerobotic Shuttle Experiment (TSX) allowed an additional design revision of the dexterous manipulators, resulting in highly capable dexterous arms for spacecraft servicing. The Ranger TSX dexterous manipulators (Figure 3) feature eight degrees of freedom, with internal co-located electronics and interchangeable end effectors. Equally capable of operating in the laboratory or underwater, the Ranger TSX manipulators have demonstrated equivalent capabilities to astronauts in extravehicular activity (EVA), and have been tested against a wide variety of tasks. Despite the cancellation of the Ranger TSX program in 2001 because of the lack of available shuttle flight opportunities, the Ranger arms have become highly productive laboratory tools for advanced space robotics research.

From the standpoint of a flight robotic system, however, Ranger is hampered by the 80 kg mass of each dexterous manipulator. Although mass was not an issue for the shuttle flight demonstration, the all-up freeflying Ranger servicing system based on Ranger TSX would have a gross mass in excess of 1000 kg.

A UMd study[1] from the early days of Ranger TFX showed that there is a significant market for commercial spacecraft servicing in geostationary orbit; however, economic viability is a strong function of servicer vehicle size. Given a servicer of the same mass class as the geostationary satellites being serviced, it is more advantageous to replace the satellite with a new one if the capability of the new technology is more than a 15% improvement on the previous communications satellite. This is primarily driven by the cost of the launch vehicle, which is comparable in that case for the servicer or the replacement satellite. Break even would require successful servicing of at least five satellites on a single mission for this class of servicer to compete with the economics of satellite replacement.

A subsequent market analysis[2] of commercial spacecraft servicing, performed in much greater detail, reiterated the conclusions of the first study. Based on an extensive survey of all satellite failures in orbit between 1980 and 2005, this study showed that on-orbit failures which can be remediated to extend spacecraft life or enhance performance occur several times a year on average. While about 20% of these failures could be remedied by a "space tug" mobility system such as the System for the Universal Modification of Orbits (SUMO) under development by DARPA, fully 60% of all repairable failures require dexterous manipulation similar in capabilities to the Ranger system. Again, however, economic viability (driven by launch vehicle costs) require servicer vehicles substantially smaller than the satellites under repair.

II. Miniature On-Orbit Dexterous Servicing System

To address the issue of servicing system mass, the UMd Space Systems Laboratory performed the preliminary design of a lightweight system for on-orbit servicing in the dexterous category described above. This was named the Miniature Orbital Dexterous Servicing System (MODSS): a RASCAL-class free-flying robotic servicing system. The RASCAL program, currently in initial design by DARPA contractors, would be a low-cost ($750K) launch-on-demand system with a maximum payload mass of 100 kg. Based on two decades of SSL experience with robotic systems for space operations, the MODSS concept was aimed at pushing the robotics technology base to the greatest extent possible to validate the concept of a low cost, ultra-lightweight system with wide servicing applicability.

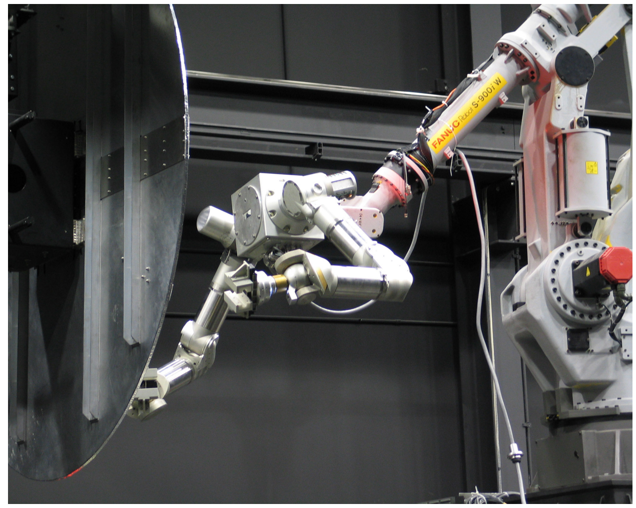

Figure 3. Ranger flight-configuration dexterous manipulators. *Arms are shown mounted in Naval Research Laboratory proximity operations simulation facility, performing SUMO grapple and ORU servicing tasks.*

A. Lightweight Dexterous Robot Arms

The principal system challenge for MODSS is in the dexterous manipulators. The Ranger TSX dexterous manipulators have superb performance and reliability, but weigh 80 kilograms each. For that reason, the SSL performed a detailed design of lightweight manipulator arms for this class of servicer.

The baseline design for the lightweight manipulators is shown in Figure 4. This is a six degree-of-freedom (DOF) one meter-length manipulator, with an interchangeable end effector mechanism based on the version developed for Ranger. This arm incorporates a modular actuator design, using brushless DC motors and harmonic drives as in Ranger. Attachments to the standard actuator design allow it to be used as either a roll or pitch joint in the manipulator.

The dexterous manipulators are designed around a modular roll/pitch/controller unit, as shown in Figure 5. A custom printed circuit board in the link will control the adjacent roll and pitch actuators. Wiring between modules is thereby limited to power and serial command/data lines, providing a simple and highly maintainable system. Based on experience with the architecture of the Ranger arms, which are similarly modular and disassembled with a single fastener, this manipulator would be fully capable of evolutionary growth to a system which is self-repairable on-orbit, with failed units being changed out autonomously by another manipulator.

The interchangeable end effector mechanism is mechanically identical to the capture/release mechanism

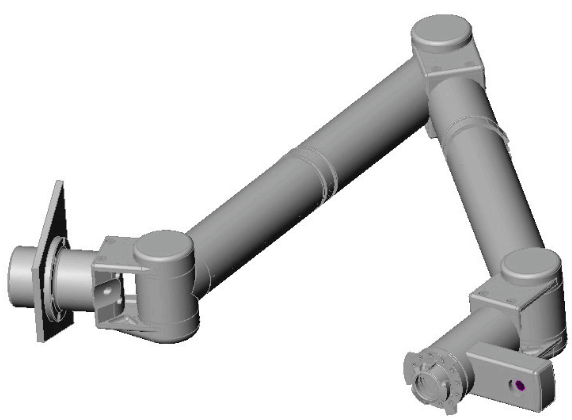

Figure 4. Conceptual design for the MODSS dexterous manipulators. *This design is a six degree-of-freedom serial manipulator, composed of three standard pitch-roll modules and links to bring total shoulder-tool plate length to one meter.*

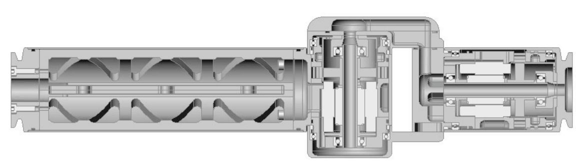

Figure 5. Pitch-roll actuator module for MODSS dexterous manipulators. *Volume to the left of the pitch joint houses local servo-level control electronics.*

on Ranger TSX, where a single insert followed by a 90° roll will lock the end effector on a tool post prior to arm release, or will latch the arm to the end effector prior to tool post release. This ensures that no inadvertent release of end effectors is possible. Instead of the two concentric mechanical drives on Ranger TSX, the MODSS system will use electrical contacts to supply power and command/data to self-actuated end effectors. This reduces system mass and maximizes the flexibility of the system, while minimizing constraints on the design of the end effectors.

After a detailed design process, the estimated mass for one of these dexterous manipulators was 7 kg. While end effector mass will vary based on complexity, an estimate of 2 kg was used for each end effector carried. The same manipulator concept, redesigned to incorporate longer joint links and electrically actuated brakes in each joint, would be used for the grapple manipulator to allow attachment to and control of the target spacecraft. This version of the manipulator was estimated to mass 15 kg.

B. Spacecraft bus

Extensive experience with operational simulations of space robotics has led the SSL to develop the concept of dual dexterous manipulators, mounted on a small volume at the forward end of the spacecraft and with wide separation from support systems such as thrusters or solar panels. A third manipulator provides the grapple link between MODSS and the target spacecraft. While all versions of Ranger incorporated a fourth manipulator for maneuvering video cameras for a variety of views, that approach will not be feasible within the mass limitations of this system. Instead, a number of extremely lightweight video cameras will be located around the vehicle, and used for both machine vision of the work site and for relaying operational information to a ground monitoring facility.

The deployed configuration of the MODSS vehicle is shown in Figure 6. The solar arrays incorporate alpha joints for sun tracking during orbit-fixed attitudes, and provide 150 W of power for onboard systems. This is felt to be adequate for most operations, although neutral buoyancy simulation testing will be necessary to more adequately document power requirements. The manipulators stow along the surface of the spacecraft, and three end effectors are carried for each dexterous manipulator. Residual volume is readily available for mission-specific payloads.

The system mass allocations for the complete vehicle are shown in Table 1. The current mass estimate of 91 kg allows 9% development growth margin for the design limit of 100 kg, This system includes 7.2 kg of hydrazine monopropellant, for a total mission ΔV of 230 m/sec.

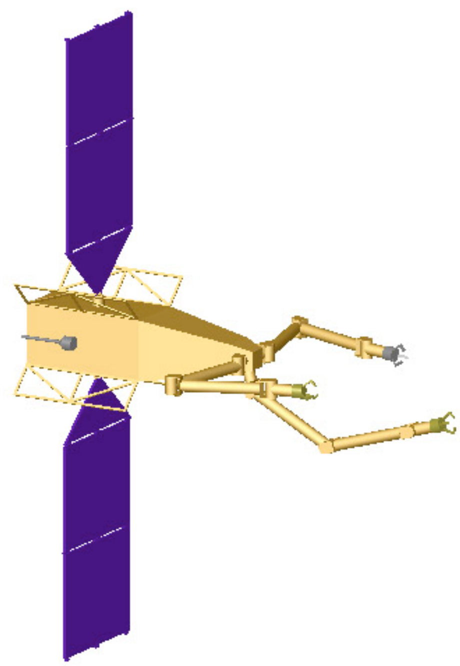

Figure 6. Miniature On-orbit Dexterous Servicing System. *Free-flying spacecraft bus with two dexterous manipulator, grapple arm, and solar arrays.*

C. MODSS Applications

Small Dedicated Launch Vehicles - While MODSS was designed for a planned rapid-response launch vehicle with a 100 kg payload, any servicing missions on this class of launch vehicle would be severely limited by the lack of payload margin for maneuvering propellant and replacement parts. Given a dedicated launch on existing small launch vehicles, such as an Orbital Sciences Pegasus or Taurus or SpaceX Falcon 1 vehicle, the range of potential applications of MODSS broaden greatly. Using the additional Pegasus payload to add propellant to the hydrazine-based orbital maneuvering system would allow MODSS to reach significant national assets, such as GPS satellites. The larger payload capacity of a Taurus- or Falcon-class booster would allow MODSS access to geostationary or higher orbits, including a mass allocation for replacement parts or consumables resupply of the orbital assets.

Secondary Payload Applications - The small size of MODSS also makes it feasible to launch as a secondary payload on the EELV series of launch vehicles. Although details of the EELV Secondary Payload Adapter (ESPA) interface have only recently been finalized, the current MODSS conceptual design adheres in all respects to the ESPA constraints. A 200 kg ESPA payload limit will allow MODSS to circularize in geostationary orbit with 28 kg of logistics mass. Additional mass capabilities for secondary payloads will proportionally increase the allocation for servicing logistics, or allow consumables for extended MODSS operations once on station.

This is perhaps the most exciting of the current possibilities for near-term servicing demonstrations, as the use of secondary payload accommodations provides an essentially "free" GEO servicing launch. The logical next step is to validate the MODSS design concepts by producing a prototype, and developing operational experience with it through neutral buoyancy simulations. The SSL MODSS design exercise indicates that, even with a conservative sequential development approach, MODSS could be ready for initial space flight testing in 42 months at a price of approximately $20M.

Based on the promise of the MODSS concept, the Defense Advanced Research Projects Agency (DARPA) sponsored a six-month seed grant with the University of Maryland to address the significant issues related to the study. Specifically, the goals for this study were to develop and test a prototype robotic actuator module, and to investigate the potential of highly modular and self-reconfiguring systems for operational assembly and servicing tasks in space. An overview of the results of this study is presented in the next two sections of this paper.

Table 1. Component masses for Miniature On-orbit Dexterous Servicing System.

MODSS Component	Mass (kg)
Dexterous Manipulators	2@7
Grapple Arm	15
End Effectors	4@2
Pan/Tilt	2
Power Systems	24
Avionics	6
Bus Structures	10
Propulsion System	5
Propellants	7
Margin	9
Total	**100**

III. Robotic Manipulator Miniaturization

The overall goal for the miniaturization task was to demonstrate the technology that would result in a space-qualifiable robot manipulator with all of the same capabilities as the existing Ranger arms, but reduced in mass by a factor of 8-10. The fundamental design concept was to develop a six degree-of-freedom (DOF) serial revolute manipulator, composes of three 2 DOF roll-pitch actuators in a single module and physical links to connect the modules into an arm of the selected length. Modules (actuator pairs and links) would be connected via an androgynous interface mechanism (AIM), a standard robot-compatible interface to facilitate self-reconfiguration in the modular robotic analysis of the next section. Based on this paradigm, a number of "Level 1" requirements were developed for the lightweight manipulator prototype; those specifically dealing with manipulator design issues are listed here along with a brief explanation of the rationale for each.

- *6 degree of freedom manipulator* - While the modular robotic "toolkit" concept developed in the next section can be used for almost any activity, the most straightforward implementation would be a classical serial revolute manipulator. This allows the demonstration of a number of needed space operations tasks, while leveraging past experience in the Space Systems Laboratory.
- *Serial manipulator* - The requirement for serial linkages in each arm is due to the need to limit branching (and prevent looping) of the serial data bus. The serial manipulator represents the simplest functional branch in the project taxonomy.
- *< 10 kg (22 lbf)* - The original thought experiment leading to this project was to examine the Ranger dexterous arms, and determine what the potential mass reduction would be for manipulators with similar capabilities. Preliminary design estimates pointed to the 10-kg region as an ambitious, but achievable goal. This represents a reduction in mass from Ranger technologies by a factor of 8, while maintaining most of the Ranger capabilities. A preliminary survey of microsats and small satellites showed that this category of robotic system was reasonable as an augmentation to those classes of spacecraft.
- *> 30 inches in length* - Robotic systems have application on spacecraft in a variety of scales, from centimeters to hundreds of meters in length; in fact, one of the potential benefits of the proposed modular system is to be able to address much of this size range based on the use of standard components. By setting a requirement for a meter-scale six-link development manipulator, we eliminated the potential for "cheating" by accomplishing the target mass reduction by simply scaling down the system. The specific value of 30 inches was chosen as a compromise between building a Ranger-scale (54 inch) arm for direct comparison to past operational performance on that system, while keeping the overall moments on the shoulder actuators small enough to make 1-g testing viable.
- *Design tip force ≥10 lb* - This is a critical parameter, as applied force limits strongly drive the actuator design. If one controls both sides of the ORU interface, in principle the required actuation force could be as small as desired. Practically, this trend is limited by interferences, friction, and differential thermal expansion across the mounting interface. It was felt that 10 pounds represents a force level which is feasible for a miniature actuator, yet still permits the actuation of most "real-world" interfaces. Further increasing the tip force to ~25 lb would allow contingency servicing of interfaces assembled on the ground and not initially planned for on-orbit servicing, but this higher force level would have strongly driven the overall design if used as the requirement.
- *Total manipulator power (control power + actuator power + control system) ≤ 100 W at 28 V* - Small satellite applications for robotic systems will be severely limited in both mass and available power. With modern

photovoltaic systems, 100 W corresponds to additional array area approximately 0.5 m on a side, which was felt to be an acceptable impact on the host spacecraft. This was also a reduction from Ranger power requirements by a factor of approximately 8-10, which is in line with the mass reduction target.

- *Electronics integrated inside the actuator modules* - The only practical way to implement the goal of modularity, including self-reconfiguration, is to develop "smart" components. By closing servo-level loops locally, there is no need to reconfigure these control levels (other than modifying gains) as the application configuration changes. To keep the system capable of physically building new robotic systems from component modules with a single manipulator, power and data interconnects will be integral to the androgynous interface mechanism (AIM) attachment system, and there will be no power and data umbilical running on the outside of the manipulator.
- *Manipulator is reconfigurable on-orbit (using a second manipulator)* - This enables self-repair of the robotic system, as well as an increase in manipulator capability. This requirement necessitates the development of a single-point interface for the second manipulator to mate/demate the AIM mechanism while maintaining control of the component(s) removed. By current plans modules are both interchangeable and reversible; for example, it may be desirable that an actuator module be usable in both pitch-roll and roll-pitch configurations. This requires that the AIM allow mating and removal from either side of the interface, and either end of an individual module.
- *Evolutionary extension to flight* - If the lightweight modular reconfigurable robotics system works well in the ground-based testing planned for this program, the next logical step would be a low-cost, near-term flight demonstration. Component design and selection for the test articles will be made so as to not preclude simple upgrading to flight hardware. This is particularly true for electronics design, where components selected will be constrained to those with flight-certified or radiation-tolerant versions available.
- *Capable of either 1-g or underwater operations for ground testing* - Initial testing of the module (in Phase 1) and the integrated arm (in Phase 2), based on current analysis, can be readily accomplished in 1-g. This dramatically simplifies development testing, as well as initial operational testing. Complex entities, such as the configurations to be eventually selected for Phase 3 investigations, may well require neutral buoyancy capability or other technologies to accomplish gravity offset.
- *Power and data to/from end effectors will be provided from the manipulator via standard AIM* - This is basically a statement that the end effector changeout mechanism is an AIM, rather than a special-purpose mechanism. This will mean that a separate manipulator will be required to change end effectors. Should single-arm end effector changeout be required (as per Ranger), an interchangeable end effector mechanism (IEEM) module could be developed, attached to the arm by an AIM and then used for unaided tool interchange.
- *End effectors will be those necessary to accomplish the design missions of assembly, servicing, and maintenance, such as bolt drivers, parallel jaw mechanisms, stereo camera pairs, etc.* - This requirement is intended to mandate that the system not place significant constraints on the type or form of end effectors adopted for any particular mission. Unlike the Ranger end effectors, which are limited to two controlled degrees of freedom, the prior requirement adopting an AIM as a standard end effector interface will allow any arbitrary end effector capable of being powered and controlled by the system. For example, it is conceivable that a Robonaut-type anthropomorphic hand could be readily adapted to this system as a high-dexterity interface, and changed out for specialized interfaces as appropriate.

The basic concept of the lightweight modular actuator consisted of a brushless DC motor, compact harmonic drive for torque amplification, and incremental and absolute encoders for actuator control. A central wiring "tunnel" allows for simple, robust routing of the basic wiring of the actuator.

An exercise was conducted wherein the size of the brushless motor and harmonic drive were varied. The diameter and length of the actuator and the 1-g lift capacity of a manipulator made up of six identical actuators in each case were compared to determine optimal configuration. The differences in the candidate designs are summarized in Table 2.

Figure 7 plots the 1-g lift capacity of a 6-DOF manipulator made up of each candidate actuator against the estimated mass of the entire manipulator. The target weight limit of 22 lb (10 kg) for the manipulator is shown as a solid line. Based on this analysis, the Actuator 5 design was chosen for prototype development. The detailed design of a standard roll actuator is shown in the exploded diagram of Figure 8. A prototype roll actuator was built and tested, and modifications made to the design prior to the fabrication of the complete elbow module.

Following the successful bench testing of the roll actuator prototype, the outer housing designs were modified to produce an actuator mounted in the pitch orientation. Two more test actuators were fabricated and assembled as a pitch-roll 2 DOF actuator module. This unit is shown in Figure 9, with a 12 ounce soda can next to it to provide scale. This unit weighed 4 pounds; the corresponding elbow module from the Ranger dexterous Manipulator has a mass of 46 pounds. This clearly demonstrates that the MORPHbot actuator design supports the goal of an order of magnitude reduction in arm mass.

IV. Modular Self-Reconfiguring Robotic Architectures

With the successful validation of the MORPHbot actuator design, the MODSS servicer has been shown to be feasible at the ambitious 100 kg total mass mark. This enables the discussion of a variety of small dexterous robotics missions, including geostationary servicing missions launched as secondary payloads on current Atlas or Delta launch vehicles.

However, the MODSS application does not take advantage of one of the most important features of the MORPHbot architecture: the modularity.

Table 2. Results from candidate actuator designs for lightweight dexterous manipulator.

Candidate Actuator	Actuator Weight (lb)	Actuator Length (in.)	Actuator Diameter (in.)	1-g Lift Capacity (lb)
1	1.6	3.0	2.8	-1.9
2	2.3	3.6	2.8	0.2
3	2.5	3.6	2.8	1.6
4	2.9	3.3	3.2	5.7
5	2.4	2.7	3.5	9.0
6	2.9	3.0	3.5	10.2
7	4.1	4.3	3.6	19.9
8	3.2	3.1	3.6	6.6
9	3.7	3.4	3.6	16.1
10	3.8	3.0	4.3	24.5

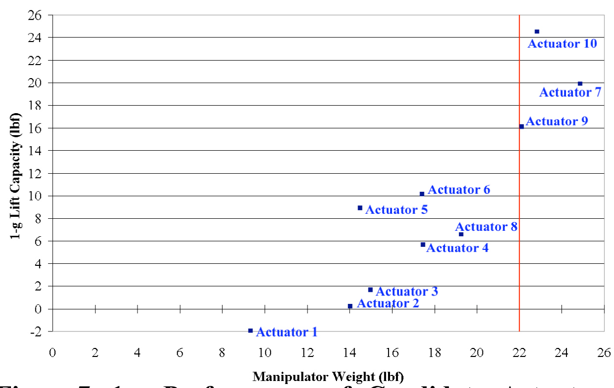

Figure 7. 1-g Performance of Candidate Actuators. *Analysis shows the 1-g payload of a canonical 6DOF manipulator using each actuator candidate.*

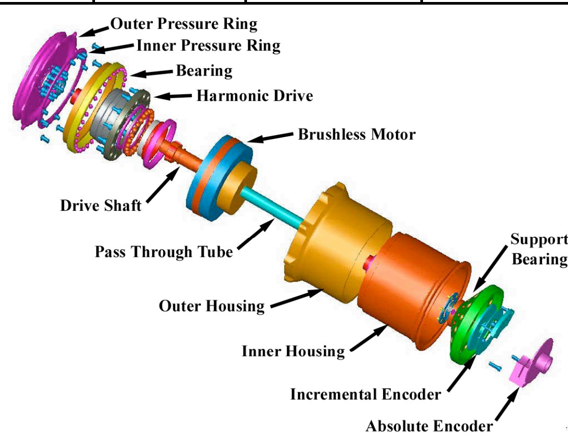

Figure 8. Exploded Diagram of Roll Actuator.

The architecture developed for the Ranger Telerobotic Shuttle Experiment incorporated modularity for ease of development and maintenance. The Ranger dexterous arms are designed around shoulder, elbow, and wrist modules. Each module includes the appropriate actuators, local motor controllers and processors, and structural interfaces. Modules are connected by a simple V-band clamp ring, and electrical interfaces (power and MIL-STD-1553B serial data communications) are automatically connected and disconnected along with the mechanical interface. This approach was adopted to allow each module to be operated independently for testing; however, the common mechanical and electrical interfaces also provide a simple mechanism for reconfiguration. Over the first four years of operation of the Ranger robotic system, the components have been operated in 22 unique configurations.

The only limitation to Ranger reconfiguration is the requirement for human involvement in the

Figure 9. Prototype Pitch-Roll 2DOF Elbow Module. *Pitch actuator design uses identical interior components to roll actuator with specialized outer housing components. Soda can included for scale.*

reconfiguration process. While one Ranger dexterous arm has successfully disassembled the other, the system of connecting the components and attaching the V-band coupler requires human dexterity.

For the MORPHbot study, the design goal was to create a modularity concept that allowed full self-reconfiguration. This would provide robustness for MODSS-type vehicles, and enable a new paradigm in operational space robotics; the auto-reconfiguring robot toolkit. To accommodate this goal, the UMd design team envisioned a system of heterogeneous modules with androgynous interface mechanisms (AIM) for interconnection, capable of being connected and disconnected with a single external manipulator. A tree-branching communications architecture was developed, to allow the use of multiple serial manipulators in the broadest possible assortment of configurations. A serial communicated protocol based on the IEEE-1394 ("Firewire") data bus was selected due to high bandwidth and robust hot-swappable capabilities of the network.

In addition to the physical details of the modular component architecture, a detailed analysis of the software and control capabilities of a reconfigurable MORPHbot system was performed. Some of the critical requirements for this system include:

- *Control modes include Cartesian tip position, joint position, teleoperation, supervisory control, and autonomous operations* - Standard operating mode for this systems will be full automation, and the software architecture under development will accommodate the necessary high-level planning and perception capabilities necessary for this. The supervisory control mode will allow for workarounds of unexpected problems, and the continuation of (potentially degraded) operations in the face of a diagnosed system fault. Teleoperation is primarily for ground development testing, and will allow parallel development of the robotic mechanisms and the autonomous control code.
- *Dynamically deals with changes in number of degrees-of-freedom and/or configuration* - The underlying vision of this research activity is that a new requirement for on-orbit operations will be dealt with by deciding upon a system configuration based on the modules available, build-up of entities to populate the system, and the performance of the task, followed by disassembly of entities until the next task comes along. As modules are physically interconnected to form branches, nodes, and entities, the goal is for the software to autonomous recognize the new configuration and adapt to accommodate that kinematic and dynamic configuration.
- *Dynamically deals with changes in end effector* - This requirement is really just a reiteration of the previous one, for the special case of end effectors.
- *Capable of self-diagnosing faults* - This is clearly required for a robust, reliable system. Faults might include mechanism, electronics, or software failures, as well as unexpected external constraints. The system must be capable of recognizing an off-nominal condition, diagnosing what the generic type and specific instance of the problem is, and either dealing with it directly, initiating autonomous response (such as replacement of a malfunctioning module), or appealing to a remote monitoring and control station for commands.
- *Prevents acting upon erroneous or illegal command from within or outside (either teleoperator or another vehicle) the vehicle* - Ranger clearly demonstrated the utility of built-in self-checking of command data streams. By having the robotic system monitor and censor illegal or unsafe commands, the remote controller and communications links are not part of the safety-critical system. This allows full concentration of safety functions internal to the robotic system, rather than split between local and remote sites. The end effect is a more robust and reliable system, with greater command flexibility.

The notional design of the androgynous interchange mechanism is shown in Figure 10. The requirements for the AIM system include mating and demating electrical contacts (control and actuator power buses and 1394 serial data) as part of the physical connection process. As the "androgynous" label would suggest, there is no limitation on the ability to reconnect modules in different configurations, including reversing a module if desired. The physical connection transfers the full rated load capacity of the actuators through a connection that generates sufficient preload that it exhibits a linear stress-strain relationship throughout the operating region.

The AIM includes a dedicated interface for the assembly manipulator to grasp the AIM to stabilize the attached MORPHbot module and actuate the AIM mate/demate mechanism. An AIM-AIM connection may be

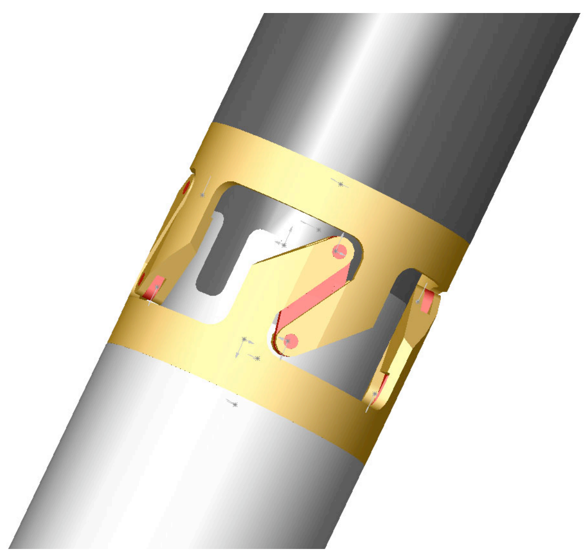

Figure 10. Androgynous Interchange Mechanism. *Overcenter latches provide preload to connection for uniform structural characteristics, while electrical contacts are automatically made internally.*

made with either side active, and one difficult requirement is that the connection must be capable of being disassembled from either side without regard for which side was active in the assembly process. This provides an assured path for disassembly, even if one side of the AIM is frozen in place.

The MORPHbot architecture is based on a number of classes of components, which are built up in acceptable network configurations to create a robot optimally capable of performing a specific task or set of tasks. MORPHbot components come in three basic categories:

The most basic class of MORPHbot components is the *module*, which provides manipulator capabilities. There are no constraints on the order, complexity, or orientation of these modules in an assembly. Each module contains a local processor for communications, control, and built-in self test. Typically modules have at least two AIM connection points, although end effectors (a subcategory) only have one AIM interface and occupy the end location in a chain of modules. There are a wide variety of possible module types, which include:

- 1 DOF roll actuator
- 1 DOF pitch actuator
- 2 DOF pitch/roll actuators
- 2 DOF pitch/yaw actuators
- 3 DOF wrist module
- 6-axis force-torque sensor
- Prismatic actuator
- Static arm links (various lengths)

The "body and brains" of any entity built up of MORPHbot parts are in the *node* elements. These units provide for mechanical interconnection, and typically carry sufficient connections to serve as branch points for the attachment of multiple serial strings. As such, they also contain hubs for communications networks and higher-level computational systems. Some nodes are perform specialized mobility functions. Typical varieties of MORPHbot nodes include:

- Mini-node (computation and branch point only)
- Standard node (computation, branch point, and power systems)
- Extended operations node (additional power and branch points)_
- Cable walker node (mobility mode using tensioned suspension wires)
- Wheeled node (planetary surface mobility)
- Thruster node (microgravity free-flight mobility)

Auxiliary services to nodes are supplied by *packs*. These are generally mission-specific, used to provide specialized functions ancillary to the MORPHbot entity itself. Examples of packs include:

- Battery pack
- Power generation pack (e.g., deployable solar arrays)
- Tool carriers
- Cameras and sensors
- Inspection devices
- Orbital replacement unit carriers
- Communications pack
- Navigation pack
- Spacecraft bus interface

The overall concept of MORPHbots is that modules, nodes, and packs can be brought together to form *entities*: complete independent agents for use in space operations. Typically, any given mission will involve multiple heterogeneous entities built up into a MORPHbot *system*, which would be used to accomplish the desired mission. The presence of reconfigurable robotic components on-site provides highly reliable robot operations, and allows the use of configurations ideally suited to the task at hand.

One conceptual example of the operational application of the MORPHbot concept is shown in Figures 11-13. Two serial manipulators built up of three pitch-roll actuator modules each are attached to a standard node, along with a camera-based sensor pack. As shown in Figure 11, this entity is walking along the truss of a space platform, performing inspection tasks. When a fault is found that requires maintenance, the MORPHbot depot is notified, and an additional entity is built up for the replacement task (Figure 12). The second entity walks to the activity site, and for this strut replacement task, joins together on-site with the original inspection entity to form a four-appendage robot capable of performing dexterous strut replacement while being positioned by two other manipulators (Figure 13).

One example of the complex configurations simple components can be built into is shown in Figure 14. This system is optimized for performing radial instrument changeouts on Hubble Space Telescope. Four simple 6DOF serial manipulators are mounted on a standard node, and provide mobility and positioning on EVA handrails mounted around HST. A pair of dexterous manipulators are used to perform the repair tasks, with a four meter

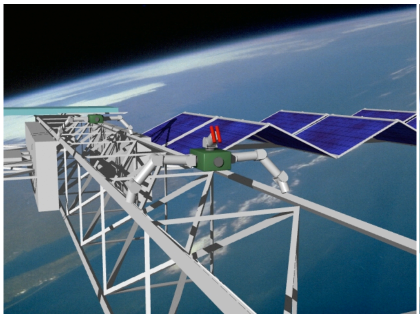

Figure 11. Inspection Robot Surveys Space Platform.

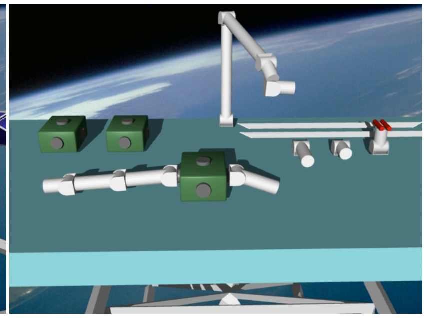

Figure 12. MORPHbot Depot Builds Up Repair Entity.

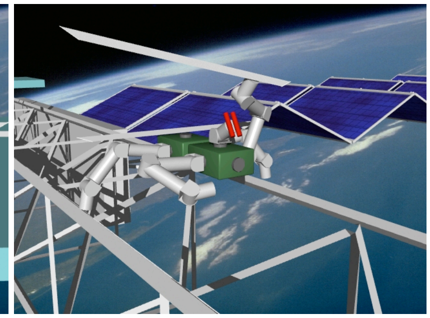

Figure 13. Entities Reconfigure On-Site to Effect Repairs.

positioning manipulator connecting the dexterous manipulators to the mobility platform to provide the 3m stroke required to remove the instruments, such as the wide field camera, from its positioning rails, and also to provide sufficient reach from the closest handrails to the maintenance site. Cameras are mounted on the mininode connecting the dexterous arms and on the mobility base for worksite monitoring. This entity would perform the orbital replacement unit (ORU) swap, although it would optimally be augmented by smaller specialized entities performing tasks such as opening and holding access doors or positioning auxiliary cameras for tight-tolerance insertions.

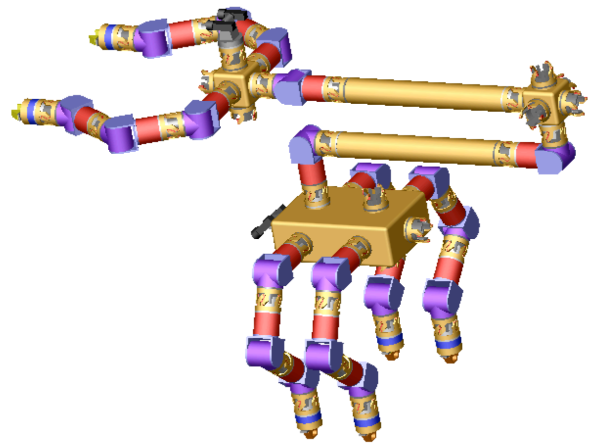

Figure 14. MORPHbot System For Hubble Space Telescope Radial Instrument Replacement. *System incorporates four 6DOF legs for walking/positioning on EVA handrails, 4 m positioning arm, and dual dexterous manipulators for ORU replacement task. can included for scale.*

V. Conclusion

Over the six months of this study, the University of Maryland successfully designed and prototyped a 2DOF actuator module that demonstrated a ten-fold reduction in mass from the Ranger servicing system. In addition, the modular nature of Ranger was extended into a concept wherein simple modules could be automatically reconfigured on-orbit to form robots ideally suited to each specific task. This MORPHbot concept shows great potential for future space applications.

Although funding for further MORPHbot development has not materialized, the underlying technology is being actively applied in a variety of uses. The lightweight actuator designs have been adapted for use in an exoskeletal anthropomorphic manipulator for shoulder rehabilitation, under a joint program by the University of Maryland, Georgetown Medical School, and the U.S. Army. This system provides unrestricted shoulder motion including following skeletal articulation of the shoulder joint, and will enter clinical trials in 2007. In parallel, the distributed computing and control architecture of MORPHbot has been incorporated into the SAMURAI (Sub-polar ice Advanced Manipulator for Underwater Research and Autonomous Intervention) manipulator, a deep submergence high dexterity manipulator developed for the NASA Astrobiology Program. The SAMURAI manipulator, capable of operating at 6000 m ocean depths, will be integrated into a Woods Hole Oceanographic Institution autonomous undersea vehicle for autonomous sampling of life forms around hydrothermal vents under pack ice in both the Arctic and Antarctic oceans in 2007.

Due to its lightweight components and reconfigurable adaptability, the MORPHbot concept has great potential across a wide range of potential space applications. From large space platform assembly and inspection to complex spacecraft maintenance and upgrades, MORPHbot components can be built up into highly capable robots ideally suited to specific tasks, then be disassembled to await the next requirement for a new configuration. The University of Maryland recently completed a study looking at autonomous selection of MORPHbot configurations based on genetic algorithms.[3] Due to the small size of the MORPHbot components, a MORPHbot depot could be installed internal to the International Space Station to augment the crew for routine maintenance activities. A second depot mounted externally on the ISS truss structure would be capable of many tasks currently requiring astronauts in extravehicular activity. Since the MORPHbot components have been designed to be capable of operating in Earth's gravity without external offload systems, MORPHbots would be equally applicable to robotic and human exploration of planetary surfaces, including construction and maintenance of human bases and in-situ resource utilization. The University of Maryland looks forward to continuing its development of MORPHbot technology for application across a wide range of future robotic missions.

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