Lessons Learned on the AWIMR Project

Rick Wagner and Hobson Lane

Abstract—**The Northrop Grumman Space Technology (NGST) Automated Walking Inspection and Maintenance Robot (AWIMR) project was one of many NASA Technology Initiatives for the Exploration Initiative, NASA's program for return to the Moon and Mars. AWIMR was intended to assist astronauts by moving about on the exterior of a crewed space vehicle, performing inspection and other tasks which might assist astronauts executing extra-vehicular activities (EVAs) or reducing the frequency and duration of these EVAs. Though the four-year AWIMR project was canceled after the first year (2005), a number of important lessons were learned that will apply to similar in-space robot projects in the future. We describe these lessons we learned and provide advice for future projects to develop space walking robots.**

I. INTRODUCTION

EXTRA-VEHICULAR activity (EVA) is expensive in both astronaut time and in mass of consumables, such as spare parts for space suits, expelled coolants, and life support gasses. Trade studies have shown that there are many benefits to using robots in space both in lieu of EVA and as assistants to astronauts performing EVA. These benefits include the reduction of mass for spare space suits, space suit spare parts, and space suit consumables. The payoff is also in the form of a reduction in astronaut time for the performance of some EVA tasks. For a complete analysis of the cost and benefits of using AWIMR to replace or supplement EVAs, see reference [2].

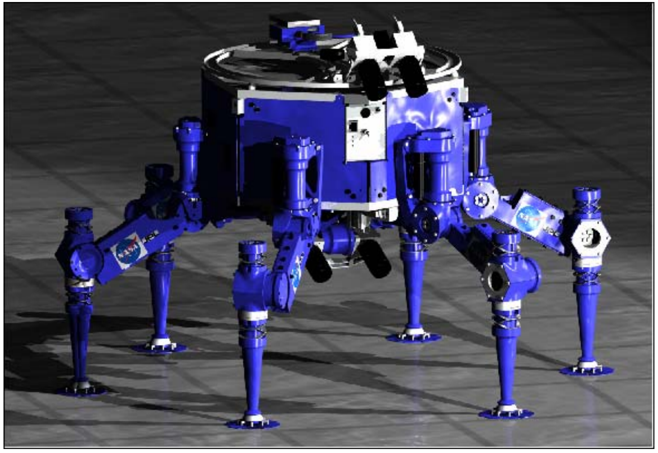

Figure 1: Rendering of a conceptual model of AWIMR.

AWIMR is intended to assist astronauts in space, outside space stations or crewed vehicles. By "in space" we mean not on a planetary surface: either in orbit or on a trajectory between orbits. The key distinction between in-space and planetary robotics is the absence of gravity, although propulsive or attitude control accelerations will be present. A vacuum environment (and attendant thermal considerations) is also characteristic of in-space robotics, as is relative freedom from particulate contamination.

The AWIMR project began in January 2005. Completed phase I tasks included requirements definition and subsystem design [2]. In addition, a prototype robot was operated in one gravity (g), and prototype grippers were built and tested. The customer was satisfied with program progress, but NASA funding constraints cut the program short in November, 2005. NGST filed two patent applications as a result of the research work, one for a new type of gripper (electrostatic) and one for a specialized gait for the "sticky" (gecko foot) type of gripper.

II. RELATED WORK

AWIMR builds on a long history of microgravity robotic locomotion research and development. Using two arms and a single "leg," NASA Johnson Space Center's (JSC) Robonaut is designed to interface with the same infrastructure and tools as space suited astronauts [4]. The Jet Propulsion Laboratory's (JPL) LEMUR I and LEMUR II prototypes were designed to use six legs for climbing difficult planetary terrain and spacecraft truss structures [3]. Carnegie Mellon University's (CMU's) collaboration with NASA on Skyworker also contributed to the body of "spaceclimbing" knowledge, with simulations and mechanism mockups of microgravity mobility, and robotic assembly in space [5].

III. PROTOTYPE AWIMR

AWIMR is intended to free astronauts for more important work by taking on a number of suitable tasks, including inspection for damage from micrometeorites and other mechanisms. This inspection would take the form of regular patrol or directed inspections. Simple repair work and astronaut assistance in repair are also feasible tasks [2][6]. Our study showed that 10 kg of robot and support equipment required for AWIMR can save many times that in EVA hardware.

Phase I (prototype for ground test) AWIMR has an axi-symmetric hexagonal layout with six limbs for locomotion and tool use (see Figure 1 and Figure 2). This mechanical design, by AWIMR team-mate, JPL's Brett Kennedy, allows omni-directional motion so that the robot does not have to rotate its body to change its locomotion direction.

The hexagonal equipment compartment contains batteries, power management electronics, motion control electronics, and communication equipment. Battery recharging is accomplished by docking to a charging station.[1]

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R. Wagner is with the Northrop Grumman Corp., Space and Technology Division (Phone: 310-813-5049; e-mail: Rick.Wagner@NGC.com).

H. Lane is also with the Northrop Grumman Corp., Space and Technology Division (e-mail: Hobson.Lane@NGC.com).

[1] One design trade not fully explored is the option of using drop-off batteries. This would free the robot to continue work while the dropped off

Teleoperation and configuration modes utilize an operator console connected to AWIMR by a digital radio link.

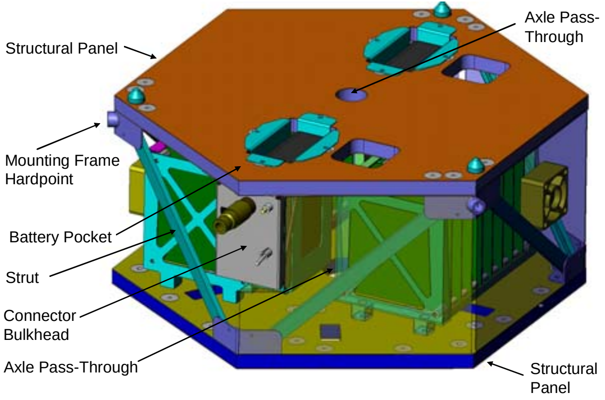

Figure 2: Prototype AWIMR (LEMUR II)structure design.

The two pairs of stereo cameras (Figure 3) rotate on an axle (note the axel pass-through hole in Figure 2). The upper pair of cameras is primarily used for navigation, and the lower set is intended for close-up surface inspection. The two pairs of cameras pan together about the body axle and tilt independently.

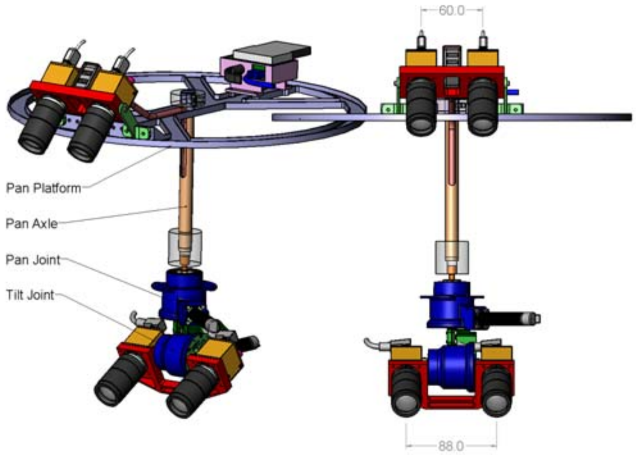

Figure 3: Camera system (dimensions in mm).

Realtime images are provided to the astronauts at the teleoperation console via the radio communication system. Each of the six identical limbs is designed for both locomotion and manipulation via an interchangeable end-effector interface at the knee joint (see Figure 4). Four brushed DC motors through multi-stage transmissions actuate the four rotary joints per leg. Optical 9-bit encoders provide joint position information, and six-axis force/torque sensors at the end-effector interface provide end-effector stress information.. The sticky foot incorporates a passive 3-degree-of-freedom ball joint to enable the end-effector to passively align with whatever it contacts.[2]

The power bus uses 24 volts provided by nickel metal hydride (NiMH) rechargeable battery pack. See reference [2] for descriptions of prototype AWIMR electronics and software architecture. Higher performance batteries, such as lithium ion, should be considered for flight use.

A docking station prototype for battery charging was produced and tested.

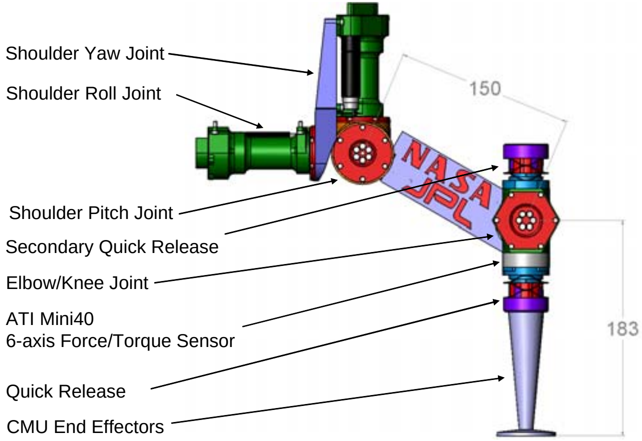

Figure 4: Limb design (dimensions in mm).

Gripper design and prototype hardware were developed by another team-mate Carnegie Mellon University (CMU), led by Dimi Apostolopoulos. The gripper approach is based on the biologically-inspired gecko foot, using hair-like microfibers. Our prototype gripper used dry adhesive polydimethylsiloxane (PDMS), which provides performance comparable to the synthetic fibrillar dry adhesive which was under development at the time. Photographs of the prototype gripper and components are shown below in Figure 5.

Figure 5: From top left, clockwise: Spherical joint mockup, flexible sticky foot, and prototype foot assembly gripping anodized aluminum.

We performed tests with the PDMS sticky material (as well as with a white silicone dry adhesive) on a variety of surface materials, including bare aluminum, anodized aluminum, Kapton thermal insulation, and a Space Shuttle thermal protection system tile. The testing was performed by

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battery was being charged. Such a feature would require at least two batteries and it would also increase power management complexity.

[2] With a form closure mechanical gripper (such as would be used for grasping an astronaut handrail), additional degrees of control would need to be accounted for in the locomotion algorithm.

pre-loading the sample and measuring the force required to pull it off the test surface. We also did some pull duration tests. While precautions were taken to keep the test apparatus and samples clean, whatever contamination was present did not seem to contribute any variability to the test results. Figure 6, below, shows some typical data obtained for one of the material samples we tested.

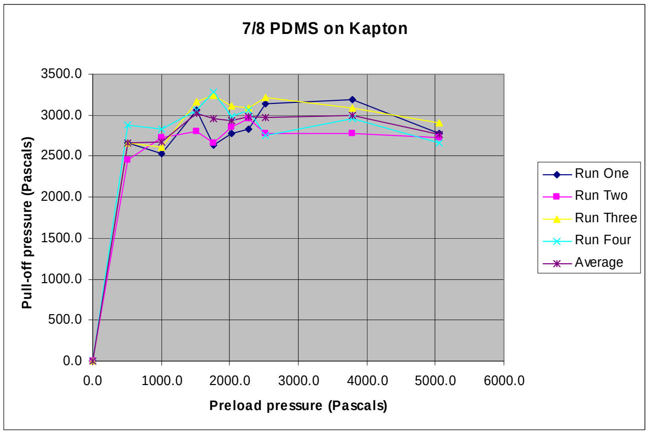

Figure 6: Example test data for PDMS on Kapton.

As mentioned above, we also did some testing with an electrostatic gripper. Surfaces tested with the electrostatic gripper prototypes include bare aluminum, Kapton insulation (aluminized and plain), carbon-impregnated Kapton, and solar cells. Typical axial (normal to the surface) data are shown below in Figure 7.

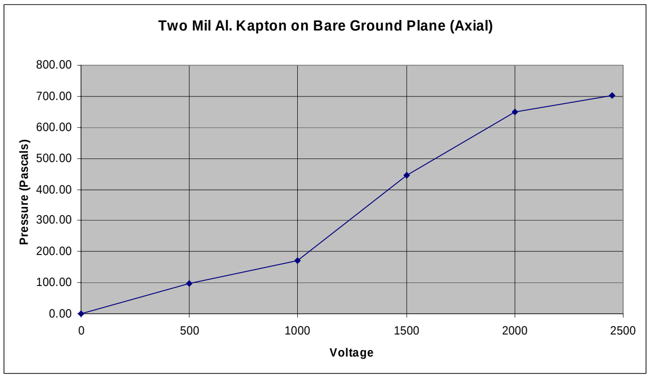

Figure 7: Example test data for an electrostatic gripper, two mil (0.002 inch) aluminized Kapton on bare aluminum. The aluminized side of the kapton was toward the foot (away from the bare aluminum test surface).

For the electrostatic gripper, shear force capability (not shown) was much higher than anticipated from normal force results due to surface molecular alignment effects. One potential advantage of an electrostatic gripper over a gecko (or sticky) foot is that it can be turned off[3] and will not potentially damage space vehicle surfaces from pull-off forces. We found that voltages in the range of 2,000 to 3,000 were suitable for space robotic locomotion.

IV. LESSONS LEARNED

A. *Task and Algorithm Iteration*

A space robot is part of a space system and is included in the system to meet the system's mission goals. Robot tasks are selected in accordance with a system view. Good space robot design requires iteration over robot tasks and robot algorithms to accomplish those tasks. Unlike purely computational algorithms, robot algorithms have a physical dimension [1].

1) *Task Trade Study*

A trade study should be performed to determine a space robot task set. The candidate task set is generated within a system context for task definition. Benefit assessment is performed for each task. The tasks then drive algorithm conceptual design, and the algorithms, in turn, drive hardware conceptual design. The hardware conceptual design then allows us to determine costs (mass, power, complexity, reliability) for the robot concept.

2) *Design to the Optimal Task Set*

The task set drives algorithm development which drives hardware design. At this point in the cycle, it may become apparent that some tasks are too costly, and we can then modify the task set and iterate to develop an optimal task set. For example, if one task involves the use of tools, then the robot will need to react tool forces, which will require special attention to the robot's mechanical interface to the space vehicle.

It will be necessary to address the balance of teleoperation versus autonomy. A metric might be percent autonomous operation (more autonomy reduces crew load). Another metric might be efficiency (speed of autonomous operations versus speed of teleoperation).

The task-driven algorithms will also drive the optimal amount and kind of sensing and control. For example, machine vision allows more flexible autonomy but increases computational complexity. Dynamic gaits allow greater movement efficiency but increase mechanical complexity.

Another consideration is general versus special purpose design. Special purpose design may be mass- and power-efficient for a smaller set of tasks, while a more general purpose design may be more efficient for a larger set of tasks, but may be higher in mass and complexity.

3) *CONOPS*

"CONOPS" is an acronym for conceptual operations (or concept of operations). CONOPS are operational scenarios generated for discovering requirements. Avoid space repair/inspection timeline surprises by refining the task set and algorithm development by performing CONOPS simulations. We found that locomotion speed is a lot more important than was originally assumed. A fast robot that can be available for timely EVA assistance is a big plus in terms of astronaut safety. These simulations ought to be a normal part of the task-algorithm-hardware design iterations.

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[3] Due to residual static electricity with the materials we tested, to fully "turn off" an electrostatic foot quickly requires a reversal of electrical polarity.

B. *Walking Locomotion*

If an untethered robot (absence of a tether is a big plus) should ever fail to maintain a positive grip on the space vehicle, it will drift away out of control, requiring the crew to either retrieve it or write it off.[4] One approach is to use mechanical grippers on astronaut handrails or other space vehicle features. This approach has a number of drawbacks, including mechanical and control complexity, and the need to drive the space vehicle design to provide graspable features.

The challenge of space walking is to balance forces and torques with a quasi-static gait. This is difficult to do without an easy means of "pealing" or releasing feet, but there are solutions involving force control that were found on AWIMR.

C. *Sticky Foot*

The sticky foot (AKA gecko foot) is a generalized zero-g locomotion enabler. If an in-space robot had to rely on mechanical gripping then every space vehicle would have to have a large number of strategically placed grip-holds (rails, sockets, knobs, or something).[5] With the sticky foot concept, virtually any space vehicle exterior is a candidate for walking access by a robot. This also applies to electrostatically sticking feet.

However, in addition to the advantages, the various types of sticky feet have disadvantages. Gecko feet require a significant pull-off force, or some as-yet-undefined peel-off mechanism. Figure 6 shows a very steep preload to pull-of force slope. However, that example represents a best case for walking margin. Other surfaces might result in preload margin problems.[6]

A sticky footed robot will probably need to avoid fragile surfaces such as thermal blankets and solar cells, yet an electrostatic foot might enable locomotion on those surfaces. However, electrostatic adhesion requires the added complexity of high voltage supply and control and is possibly susceptible to damage from sharp projections on the spacecraft surface.

D. *Navigation*

The simplest kind of navigation, dead reckoning, in which only joint angle sensing is used, is feasible for the simplest robot tasks that do not involve significant distances. However, AWIMR's primary task, routine autonomous patrol and survey of a space vehicle exterior, requires periodic registration to reduce uncertainty in position knowledge to an acceptable maximum. AWIMR's navigation vision system inherits barcode (or block code) position registration capability from LEMUR II [3]. We had not yet reached the stage where we would be able to test this capability, however, and as locomotion speed became a concern from our scenario and modeling activity, future space robotic programs requiring vision navigation should emphasize early capability demonstration, with emphasis on speed of computation.

Additionally, obstacle avoidance, as a consideration in path planning, is a capability that should be addressed early in the program. As space vehicles typically have a number of delicate appendages, cables, fluid lines, thrusters, or sensors that definitely need to be avoided, the path planning algorithms, running as a system with vision navigation, should be able to demonstrate both sufficient speed and margin for avoiding these obstacles.

E. *Docking Force*

The docking station prototype that was developed for AWIMR utilized the robot's body motion for the docking maneuver (Figure 8). The six sticky feet provided sufficient margin for electrical connector mating force, but there are contingency scenarios (such as from connector wear or damage) where the robot (without force feedback) could become unstuck from the space vehicle. Therefore, force feedback control, in addition to being a good idea generally, becomes necessary for safety in docking.

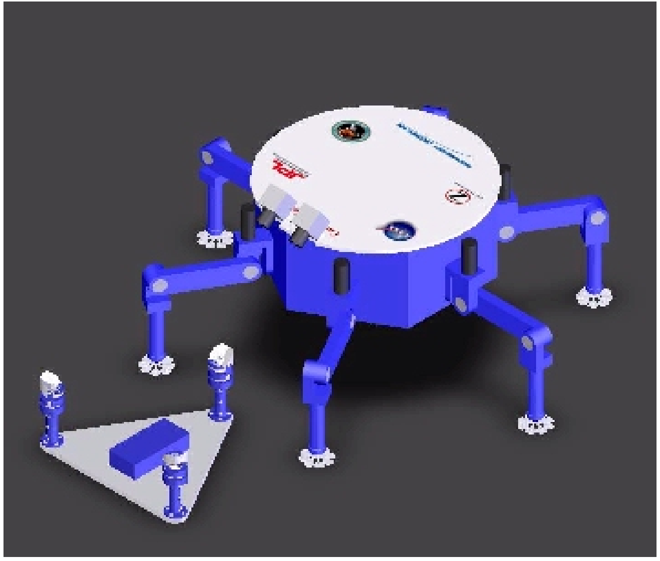

Figure 8: AWIMR and docking station concept model.

Some thought should be given to a docking station feature for positive mating, such as a screw drive interface to avoid reliance on mating tensile force supplied by the robot's sticky feet. Such a positive mating feature could also react propulsion forces to provide additional margin during space vehicle delta-V maneuvers.

As gripping in shear, both with sticky feet and with electrostatic grippers, provides greater force capability than with tensile loading, a special gripping interface plane pair,

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[4] A hybrid flying-walking robot (using gas jets for delta-V) is another approach that should be investigated. Another potential payoff is to use both free flying and walking robots and to provide an interface for the free flyers to dock to the walkers.

[5] In all fairness, any crewed vehicle will probably need a good number of handrails anyway for contingency astronaut EVA. A sticky footed robot might step on them or step over them.

[6] If the preload to pull-off force ratio is unitary, then there will be no margin for a hexapod robot tripod gait: preloading three feet might pull off the other three feet.

parallel to the direction of mating, is another possibility: four feet can provide robot body locating ability while two opposed feet on surfaces 90 degrees from the walking surface could help to provide docking reaction force.

F. Power Management

In zero (micro) gravity, joint motor power consumption is small for quasi-static locomotion. However, to achieve the locomotion speeds our scenarios indicated were desirable, dynamic gaits and control may be necessary. Increased robot speed will mean increased power consumption, but it will also mean that more surface area of the spacecraft exterior can be covered in a given time. Vision system processing, path planning, control processing, and RF communications will all consume power. As with all space system design, power in AWIMR is a scarce resource, and power considerations will drive algorithm design. A larger battery will allow longer duty cycle between charging station visits, but will take longer to charge. Minimizing the total mass of AWIMR, of course, is a strong design driver, and battery and power management hardware are major contributors to robot mass. Therefore, any future space walking robot project will need to optimize the power management system by taking into account the totality of operational scenarios. A strong driver may be the need to provide power margin for contingency operations, such as for astronaut assistance in EVA.

G. Business

The AWIMR project was a partnership among NGST (prime), JPL (prototype AWIMR hardware and software), NASA Johnson Space Center (JSC, zero gravity simulation and test) Carnegie Mellon University (CMU, gripper technology) and ZIN Technologies (docking station). This partnership was a collaboration among diverse university, government, and private organizations. As prime, NGST has significant experience in managing subcontracts, but this diverse mix of performers was unusual and required special attention to communication and managing expectations. Such collaborations in the future should explicitly manage communications. For example, expectations as to what and when design, software, or hardware handoffs are to occur should be communicated explicitly early in the project and updated regularly.

V. CONCLUSION

A robot to walk on the exterior of a space vehicle for inspection, repair, and astronaut assistance, provides such a great payoff in reduced EVA time that it might be properly considered an enhancing, if not enabling, technology for crewed space exploration, and therefore is likely to be revived as NASA's exploration initiative progresses. Although small by space system project standards, and of relatively short duration, the AWIMR project produced many interesting results and many lessons that can be applied to similar projects in the future.

ACKNOWLEDGMENT

We wish to acknowledge the contributions of our partners, including Dimi Apostolopoulos of CMU, Myron Diftler of JSC, John Heese of ZIN Technologies, and Brett Kennedy of JPL.

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