Teleoperated Modular Robots for Lunar Operations

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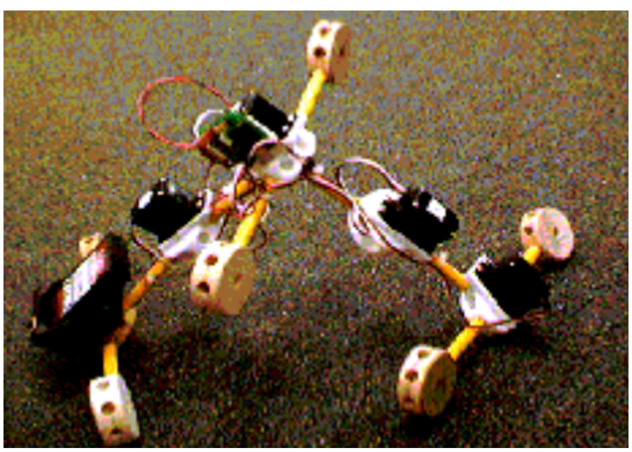
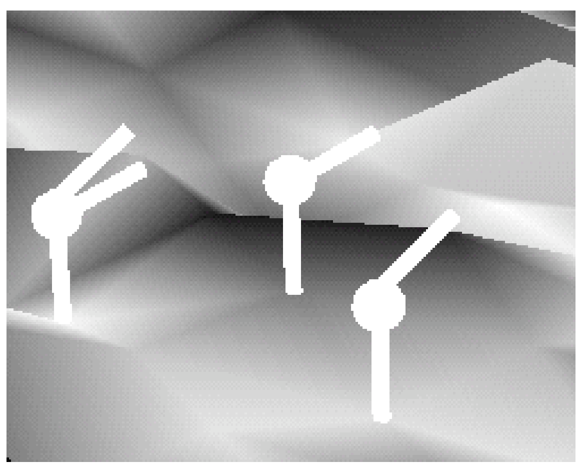
Solar system exploration is currently carried out by special purpose robots exquisitely designed for the anticipated tasks. However, all contingencies for *in situ* resource utilization (ISRU), human habitat preparation, and exploration will be difficult to anticipate. Furthermore, developing the necessary special purpose mechanisms for deployment and other capability is difficult and error prone. For example, the Galileo high gain antenna never opened, severely restricting the quantity of data returned by the spacecraft. Also, deployment hardware is used only once.

To address these problems, we are developing teleoperated modular robots for lunar missions. Teleoperation of lunar systems from Earth involves a three second speed-of-light delay, but experiments by [Globus 1981] and others have shown that interactive operations are feasible. Modular robots typically consist of many identical modules [Yim 1994] that can be reconfigured for different tasks providing great flexibility, inherent redundancy and graceful degradation as modules fail. Our design features a number of different hub and spoke modules to simplify the individual modules, lower structure cost, and provide specialized capabilities.

Hub and spoke modular robots are similar to tinker toys. Spokes can be purely structural or also carry data and power. Variable length spokes allow rapid construction of large robots. A variety of hubs can provide structure, computation, communications, power, joints, grippers, sensors, thermal control, simple tools, robot reconfiguration, and other capabilities.

Modular robots are well suited for space applications because of their extreme flexibility, inherent redundancy, high-density packing, and opportunities for mass production. Simple structural modules can, in principle, be manufactured from lunar regolith *in situ* by directed solar sintering at $1100^{o}C$ [Allen 1994] in a manner similar to commercial 3D printers.

Software to direct and control modular robots is difficult to develop. We have used genetic algorithms to evolve both the morphology and control system for walking modular robots [Hornby 2002] (leftmost figure). This robot was first evolved in a software simulator. Once implemented in hardware, the robot functioned without change to the evolved control system. The figure on the right is a simulated lunar teleoperations window.

We are currently developing software and physical simulators, including regolith simulation, to enable design and test of robot software and hardware, particularly automation software. Ready access to these simulators could provide opportunities for contest-driven development ala RoboCup (http://www.robocup.org/). Licensing of module designs could provide opportunities in the toy market and for spin-off applications.

[Allen 1994] Carlton C. Allen, John C. Graf, and David S. McKay, "Sintering Bricks on the Moon," *Engineering, Construction, and Operations in Space IV*, American Society of Civil Engineers, pages 1220-1229.

[Globus 1981] Al Globus, "Remote Teleoperation Earth to Moon - An Experiment," *Fifth Princeton/AIAA Conference on Space Manufacturing*.

[Hornby 2002] Gregory S. Hornby and Jordan B. Pollack, "Creating High-Level Components with a Generative Representation for Body-Brain Evolution," *Artificial Life*, 8:3.

[Yim 1994] Mark Yim. *Locomotion with a Unit-Modular Reconfigurable Robot*, PhD thesis, Department of Computer Science, Stanford University.