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## A Simple 5-DOF Walking Robot for Space Station Application

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### ABSTRACT

Robots on the NASA space station have a potential range of applications from assisting astronauts during EVA (Extra-Vehicular Activity), to replacing astronauts in the performance of simple, dangerous and tedious tasks; and to performing routine tasks such as inspection of structures and utilities. To provide a vehicle for demonstrating the pertinent technologies, we are developing a simple robot for locomotion and basic manipulation on the proposed space station. In addition to the robot, we have developed an experimental testbed including a 1/3-scale (1.67-meter modules) truss and a gravity compensation system to simulate a zero-gravity environment.

The robot comprises two flexible links connected by a rotary joint, with 2-dof "wrist" joints and grippers at each end. The grippers screw into threaded holes in the nodes of the space-station truss, and enable it to walk by alternately shifting its base of support from one foot (gripper) to the other.

Present efforts are focused on mechanical design, application of sensors, and development of control algorithms for lightweight, flexible structures. Long-range research will emphasize development of human interfaces to permit a range of control modes from teleoperated to semiautonomous, and coordination of robot/astronaut and multiple-robot teams.

### INTRODUCTION

We are developing a telerobotic Self-Mobile Space Manipulator (SM<sup>2</sup>) for use on trusswork like that which will form the backbone of Space Station Freedom. Our design criteria have been chosen to complement the capabilities of space-suited astronauts as well as the features of robots already designated for deployment on Space Station. The SM<sup>2</sup> has a simple, modular, 5-DOF design for economical implementation and easy maintenance. It has low mass and is capable of safe, independent locomotion from node to node on space station trusswork, without touching the trusswork struts. The SM<sup>2</sup> can

move autonomously, but can also be guided using various levels of telerobotic control - from high-level, goal directed commands to the lowest level of joint torque specification.

For example, under autonomous operation we envisage the robot "walking" along specified nodes on the trusswork, doing routine visual inspection, then reverting to low level teleoperation to allow an astronaut within the space station to examine and repair anomalies discovered during the inspection process. At levels of self-guidance intermediate between those just mentioned, astronaut control of semi-autonomous functions could be invoked to operate the robot to resupply and assist the Flight Telerobotic Servicer (FTS) or astronauts during EVA by bringing components or tools to a worksite. The SM<sup>2</sup> could be useful as an "active tether" by attaching to and positioning lights, cameras, or sub-assemblies handed to it during work at an EVA job site. During construction activities, the SM<sup>2</sup> should be capable of autonomous assembly operations with properly designed components.

The robot's low mass and compliant design will permit the SM<sup>2</sup> to move on space trusswork with minimal induction of truss vibration or disturbance to the space station's microgravity environment. These same factors, coupled with proximity sensing, also reduce the potential for the robot to accidentally cause injury to space station equipment or personnel. The SM<sup>2</sup> system will be equally suitable for the remote construction and maintenance of other large structures to be assembled in space, including sensing platforms and reflector arrays.

We are developing a one-third scale SM<sup>2</sup> system on a similarly scaled model of space station trusswork. Our testbed includes a system to compensate for earthbound gravitational effects as well as three bays of trusswork supplied by StarNet Structures that are similar to NASA's design. Its nodes are full size and geometrically derived from the NASA design, but the truss struts are foreshortened to reduce the basic cubic bay side dimension from 5 meters to 1 2/3 meters (See Figure 1).

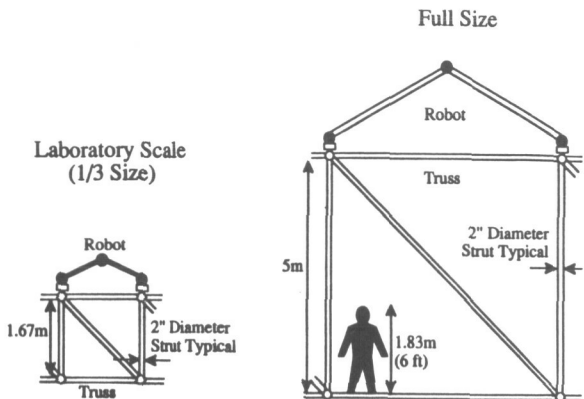


Figure 1: Overall dimensions of the truss and robot are scaled to 1/3 to permit experiments in the laboratory, while local dimensions (sizes of nodes, joints and grippers) are the same to keep local behavior similar, and mechanism size workable.

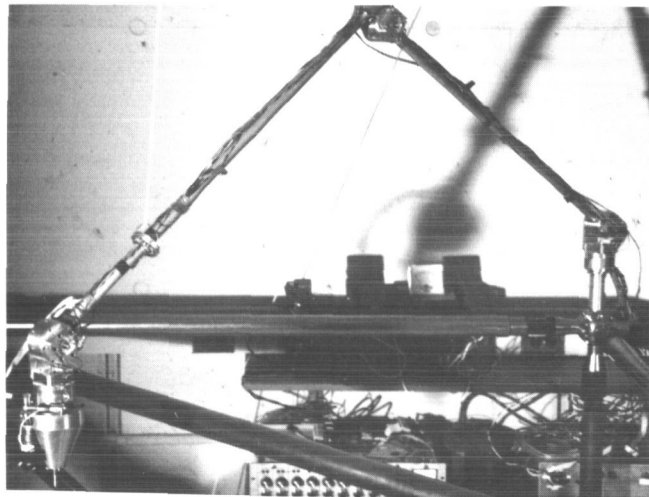


Figure 2: Photograph of the robot on 1/3-scale truss.

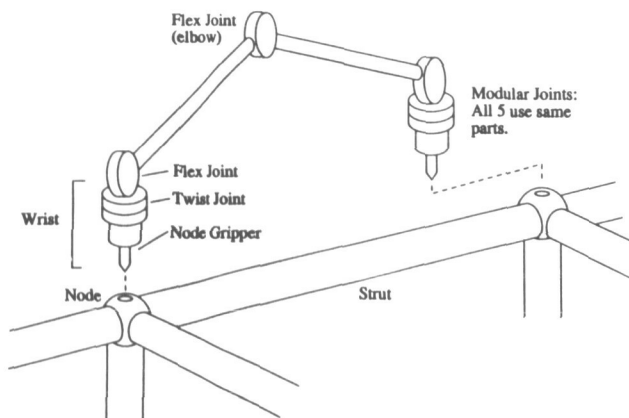


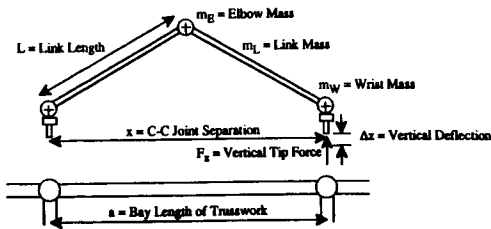
Figure 3: Schematic drawing of SM<sup>2</sup>

## ROBOT HARDWARE

The basic robot walker, shown in Figures 2 and 3, is a simple, 5-joint configuration which has the minimum size and number of degrees of freedom (dof) to permit walking on the space-station trusswork. The robot comprises a pair of slender links attached at an "elbow" flex joint, with 2-dof "wrist" joints and special grippers at both ends. The grippers screw into threaded holes in the nodes of the truss to attach the robot to the truss. The robot can span adjacent nodes which are 1.67 meters apart for our 1/3-scale laboratory robot, 5 meters for full scale. It walks by releasing one gripper, swinging to the next node and gripping; then repeating the process with the other foot. Although the robot has all its links in a plane at any time, its plane of operation can be rotated by the outboard twist joints so it can, in theory, access any unoccupied hole (26 holes per node at 45-degree spacing) of any node of the truss. With appropriate end-effectors, this configuration also permits limited manipulation capability.

The design for the laboratory robot is based on a hypothetical, full-sized, self-contained robot to be used on the Space Station; scaling rules were applied so the dynamic behavior - masses, stiffnesses, natural frequencies, linear speeds - of the scaled-down robot would be similar to that of the hypothetical one. As can be seen from Figure 1, overall dimensions of the truss and robot were reduced to 1/3, while local dimensions - of truss nodes, joints and grippers - were kept equal. This allows the testbed to be used in a laboratory of reasonable size, while mechanism are not unworkably small. Figure 4 gives some basic parameters for the scaled and full-sized designs.

The robot is designed for mobility in a zero-gravity environment, with simplicity and low mass as primary design goals. The robot is assembled from five, compact, self-contained, modular joints. As shown in Figure 5, each joint contains a DC motor, harmonic drive (60:1 or 100:1 reduction), and a potentiometer and incremental optical encoder for measuring joint angle. Joint torques are sufficient to move the robot's limbs at reasonable rates, but too low to support the robot's weight; thus it can operated only when gravitational effects are removed. Each joint weighs about 2.7 kg (1.2 lb.), and has a peak torque of 14 N-m (125 lb-in) (for 100:1 gearing) and peak speed of 5.8 radians/sec (100:1 gearing) The two links that connect the three flex joints are slender, thin-walled aluminum tubes having substantial compliance; the end-effector deflects nearly 150 mm (6 inches) under full joint torque when the robot is fully extended. The links of the 1/3-scale robot were designed to reflect the compliance of links in the full-size robot, where link mass is a significant factor. Possible improvements in the design include reduction of joint friction arising from motor brushes, bearings and gearing; and of joint backlash arising from bearing clearances. Both these factors aggravate control problems.



Parameter	Formula	1/3 Size	Full Size
Bay Length	a	1.67m	5.00m
Link Length	L	0.97m	2.91m
Link Tube Dimensions (OD x wall thickness)		19mm x 0.7mm	51mm x 1.0mm
Link Mass	$m_l$	0.11kg	1.23kg
Wrist Mass*	$m_w$	14kg	14kg
Tip Stiffness (@ $x=2l$ )	$k=3EI/(2L)^2$	5.64 kgf/m	5.67 kgf/m
Tip Force @ Max Joint Torque	$F_t$	0.92 kgf	0.92 kgf
Tip Deflection @ Max Joint Torque	$\Delta z=T(2L)^2/3EI$	148mm	148mm
Lowest Natural Frequency (@ $x=2l$ )	$\omega_n=\sqrt{k/m_w}$	2.19 rad/sec	2.20 rad/sec
Step Time (nominal for 180° step)	$t_{180}$	6.7 sec	20 sec

\*Estimated for self-contained robot with auxiliary manipulators.

Figure 4: Scaled parameters for full-size hypothetical robot and 1/3-size laboratory robot.

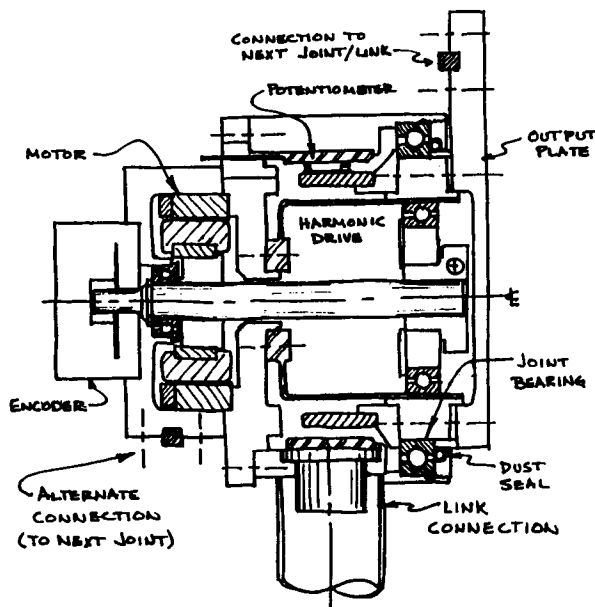


Figure 5: Joint is compact, self-contained, modular design. Joint includes a DC motor, harmonic drive reducer, position sensors and bearings.

We minimize mechanical backlash and friction, and enhance mechanical stability, with harmonic-drive gearing and four-point-contact joint bearings (Kaydon type X). Because the links are very light, we can assume the mass is concentrated at the joints, which simplifies control significantly by practically eliminating the high vibration modes associated with distributed link mass. Keeping the robot lightweight, in general, permits acceptably fast control with low torques, although joint friction is still about 10% of available peak torque.

The node gripper, the device that attaches the robot to the nodes of the trusswork, is a critical part of the design. Unlike a typical robot end-effector, it must be able to anchor the robot firmly to the nodes, because the robot's base of support shifts from one end to the other during walking; the robot depends on this attachment point to provide a precise, stable frame of reference. The node gripper includes a screw that engages the threaded holes in the nodes, a motor and gearing that drive the screw, and a potentiometer to sense the gap between the faces of the node and gripper. After the screw is fully engaged, an internal cam mechanism draws the gripper against the node with more than 1800 N (400 lb.) of force; this prevents twisting or rocking on the node, which would disturb the robot's frame of reference. In the future, we plan to develop other end-effectors for general manipulation or specific tasks such as assembly of trusswork.

## GRAVITY COMPENSATION SYSTEM

The zero-gravity environment at an orbiting space station has significant impact on the design and performance of a robot. The absence of gravitational forces permits a long, spindly robot to move relatively large masses with small forces and small consumption of power. In order to perform realistic experiments on earth, we have developed a gravity compensation system that balances the more significant gravitational effects. As shown in Figure 6, the cable supporting the robot is suspended from an overhead gantry that tracks the movements of the robot in the horizontal plane using an infrared camera and robot-mounted light source. The support cable, which attaches to a spreader beam above the robot, is routed through a system of low-friction pulleys to a low-inertia counterweight. Because of the lever arrangement, the counterweight adds only 10% to the robot's "vertical inertia." Discrepancies in the compensation forces due to friction and tracking errors amount to about 1% of the robot's weight in the vertical direction and 2 - 4 % in the horizontal. With the current system, the robot can walk reliably on the top face of the trusswork. Improvements are planned to provide better horizontal tracking (reduced side forces), to reduce friction in the counterbalance system, and to permit walking on the side faces of the truss and carrying payloads.

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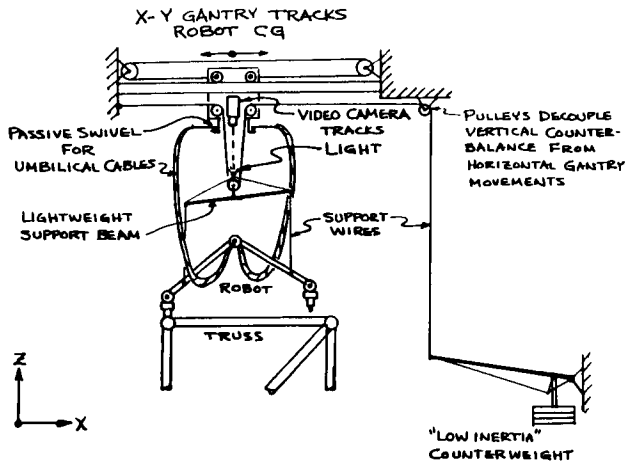


Figure 6: Gravity compensation system includes a passive counterbalance system for vertical support and an active horizontal tracking system.

## SENSORS

To enhance SM<sup>2</sup> system reliability and versatility, we strive for sensor redundancy both in the factors to be measured by sensors and in the utilization of these sensors' information. For instance, link deflection may be measured both by an internal optical system based on lateral effect diodes and by strain gages laminated to the link shell. During unconstrained limb movement, both these deflection measures - with their different ranges, resolutions, and response times - can be used for controlling limb position, while when both ends of the robot are attached to objects, these same sensors can measure the forces generated by deflection of the compliant links.

A small CCD camera head is located at each end of the robot. The video is necessary for fine human guidance during teleoperation of the robot and we try to make use of this wide bandwidth sensor for autonomous control, too. We would like to use vision for end-effector target acquisition and guidance, as well as for the direct estimation of the relative position of the two ends of the robot. The challenge for our robust use of machine vision for automatic end-effector guidance is the wide dynamic range of light intensities to be found in space. It may be impossible to simultaneously see aspects of objects illuminated by direct sunlight and in deep shadow. The contrast across shadow boundaries exceeds the dynamic range of most small imagers, so machine vision aids and algorithms must be chosen carefully. Optimally, new imaging sensor structures, with wider dynamic ranges can be fabricated using conventional VLSI techniques.

We make use of both potentiometric and incremental optical encoder information from each joint to measure joint angle and velocity. For most of the permissible rotation of each robot joint, potentiometer readout is directly proportional to joint angle, being linear to about .001 revolution (6.3 milliradians, equivalent to about 1 cm at the end-effector). By calibrating at the 90-degree positions, corresponding to the target (node) locations, our sensor accuracy at critical points is an order-of-magnitude better. However, sensor errors are overshadowed by structural deflections: elastic deflections in the links due to system dynamics and disturbances from the gravity-compensation system, and joint deflections due to backlash in the gearing and bearings. Such deflections are present to some degree even during calibration. The resultant positioning accuracy, about 1 cm, is marginal for the node-insertion task, hence our effort to use camera and other end effector-target related information.

Silicon accelerometers on the wrist (ankle) joints directly sense tip vibration and help smooth motion control at high response frequencies.

## CONTROL

SM<sup>2</sup> robot control issues are more fully discussed in reference 6 by Ueno and Xu, et al. Three factors make control of our robot difficult: the long reach of the robot (greater than 5 meters at full size), the low joint torques available, and the compliance of the structure. Small angular deflections, due to sensor errors, backlash and structural deformation, are amplified into significant linear deflections at the robot's end-effector. Because torques are low, we want to keep joints and links light. Friction in the joints becomes a significant nonlinearity that must be dealt with. Structural compliance further increases the uncertainty in tip-position measurements and permits high-amplitude, low-frequency (around 1 hz), as well as mid-frequency (around 20 hz) vibrations in the unanchored robot structure.

There has been a great deal of interest during the last 5--10 years in the control of flexible arms (references 1, 2, and 4). Most of this has been theoretically oriented, focusing on rigorous identification and control of simple arms often with exaggerated flexibility). Little work has been reported on application-oriented, multiple-joint systems. In contrast to most of the research in this field, our goal is not to study the control of flexible arms, but to obtain a working system. We desire to control a 5-joint, 3-dimensional robot that has substantial flexibility resulting from the necessarily lightweight design.

Control algorithms are borrowed from conventional, rigid-arm control with several modifications. We use P/D and PID controls with "gentle" input trajectories and low-pass filtering to minimize excitation. For locomotion, we employ a "coarse control" phase that uses acceleration feedback and low gains for a smooth,

stable motion to the area of the target node. Once the end-effector is close to the target, the mode switches to "fine control," using higher gains and integral feedback to minimize the static error.

Real-time control is implemented digitally on an Ironics M68020 single board computer on a VME backplane, running the CHIMERA II real-time operating system. Aside from supplying a high-performance real-time kernel, CHIMERA II provides a layer of transparency between the diverse hardware and the control software (ref 5). Selecting CHIMERA II as the real-time operating system over commercially available operating systems was also motivated by its powerful multiprocessing features, which allows us to distribute the control code over multiple processors if necessary. A Sun 3/260 host workstation is used for code development and graphical displays.

### HUMAN - MACHINE INTERFACE

Telerobotic control is currently based on a mouse-driven screen interface generated on a Sun 3/260. Using a hierarchical system of screen displays, an operator can choose between low-level joint position control and higher level end effector target designation. In the latter case, the computer derives and displays the sequences of end-effector motion for operator preview and approval, while in the former case, the operator directly specifies end-effector trajectories.

The challenge in design of a control station for the SM<sup>2</sup> robot is the non-anthropomorphic design and alternating base of support during locomotion. Dual hand controls and "state-of-the-art" helmet mounted virtual displays that are slaved to operator head movements are more appropriate for anthropomorphic robotic designs such as FTS, which has recognizable head and hand analogs. Similarly, since the SM<sup>2</sup> manipulator has no fixed base of support and alternates which end is attached to the space station trusswork, more conventional robot arm control interfaces are less than satisfactory. We are evolving our own human-interface control station both to satisfy our current control needs and to accommodate future requirements to coordinate the activities of multiple Self Mobile Space Manipulators working in harmony. Teleoperation is based on gestural control by an operator using a hand-held Polhemus 6-DOF pointer to guide the 5-DOF motion of the free end of SM<sup>2</sup> in Cartesian space. Computer mediation between the 6-DOF control and the 5-DOF robot protects against illegal motion commands, allows for scaling, indexing and calibrating robot motion, and selective axes isolation for task-specific motions (such as linear insertion in the absence of rotation, or rotational alignment without sensitivity to pitch or yaw movements of the controller.) We are developing a force reflecting hand controller that is articulated isomorphically with the SM<sup>2</sup> and that appropriately attaches, at alternate ends, to the control station.

### CONCLUSIONS

The one-third scale Self Mobile Space Manipulator currently walks on horizontal surfaces of bays of trusswork that are assembled in our laboratory. It walks by alternately attaching to adjacent nodes under various levels of telerobotic control - ranging from autonomous multi-step moves to low-level teleoperation. Our next goals include walking over the edges of the trusswork to demonstrate 3-D locomotion capability. We intend to extend the capability of our gravity compensation system to allow us to do simple parts transportation and manipulation tasks with SM<sup>2</sup>. We plan to do demonstration projects, in cooperation with NASA's Space Station contractors, to establish the capability of this design for solving the evolving inspection, maintenance and construction needs of Space Station Freedom.

### ACKNOWLEDGMENTS

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