Development of a 5-DOF Walking Robot for Space Station Application: Overview

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Abstract

Robots on the NASA Space Station have the potential to relieve astronauts of tedious and dangerous tasks; to minimize astronaut EVA (Extra-Vehicular Activity) time; and to reduce the load on personnel life-support systems. To provide a vehicle for demonstrating the pertinent technologies, we are developing a simple, five-joint robot that has the minimum size and complexity needed for locomotion on the space-station trusswork. The robot has grippers on its two feet which enable it to walk by attaching to the nodes of the truss and alternately shifting its base of support from one foot (gripper) to the other. The robot's mass is kept low to minimize the dynamic disturbances to space structures, and the potential for damage or injury. 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 permit testing in a simulated zero-gravity environment.

As the initial phase, we have concentrated on achieving primitive walking on the trusswork. We have developed the robot hardware and grippers; the real-time control hardware and software for precise, stable control of the highly flexible, 3-dimensional robot; and a gravity compensation system. This paper presents an overview of the project.

1 INTRODUCTION

We have undertaken a research project to develop technologies that will enable the use of mobile robots on the Space Station and other space structures. In our laboratory at Carnegie Mellon University, we are developing a 1/3-scale version of a robot that will walk, autonomously or under human control, on the truss structure of the Space Station; and perform tasks such as transport of tools and materials, inspection of equipment and structures, and assembly of trusswork and equipment. Present efforts are focused on the development of robot hardware and controls for primitive movements, and of the gravity compensation system to provide a simulated zero-gravity environment for experiments in the laboratory.

The need for robots in space arises from several factors. First, during EVA, astronauts are limited to short shifts and become fatigued quickly. Robots, on the other hand, given an adequate power supply, can work continuously without fatigue or boredom. Second, robots may be allowed to do jobs that are too dangerous for humans; the use of simple, relatively low-cost robots, such as we are developing, minimizes the risk. Third, using robots in place of humans eliminates or reduces the need for human-support facilities: air, water, food, sleeping and exercise areas, waste-treatment equipment, air conditioning, etc.

Our objective is to provide the technology for a simple, lightweight, relatively low-cost robot for use on the Space Station. It is intended to perform relatively simple locomotion, transport, manipulation and inspection tasks, and assist astronauts in more complex tasks. Enhanced performance could be obtained by using these simple robots in teams. The lightweight design would minimize the disturbance to structures, and the injury potential to equipment and personnel. Below is an overview of our research effort, which can be roughly divided into five areas: robot hardware, sensing, controls, human/machine interface and gravity compensation.

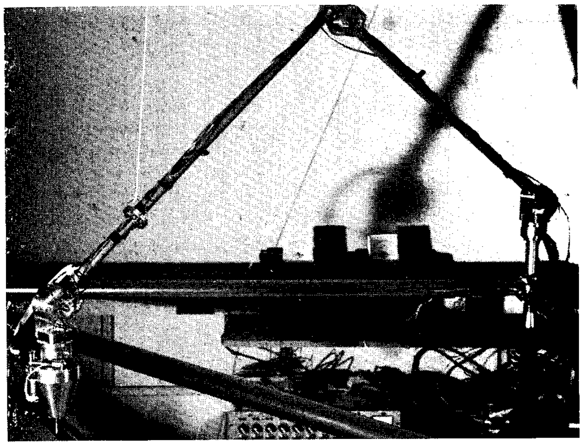

Figure 1: Photograph of the robot on 1/3-scale truss.

2 ROBOT HARDWARE

The basic robot walker, shown in Figures 1 and 2, 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 to anchor the robot. 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.

As a starting point, we designed a hypothetical, full-size, self-contained robot to be used on the Space Station. Then a 1/3-size laboratory robot was designed and built using scaling rules to keep the dynamic behavior—masses, stiffnesses, natural frequencies, linear

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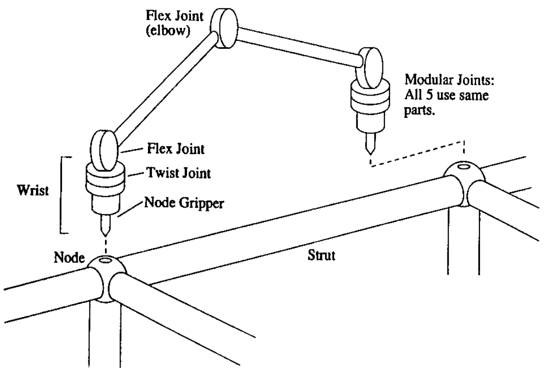


Figure 2: Primitive robot walker has five modular joints, two slender links and two grippers for attachment to truss nodes.

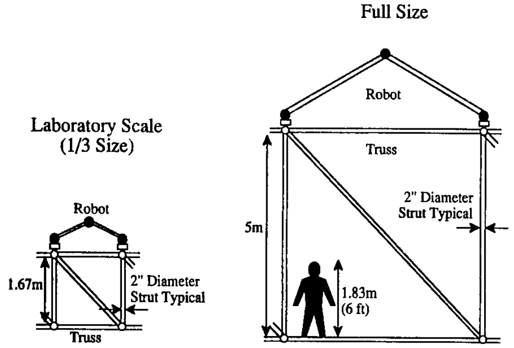
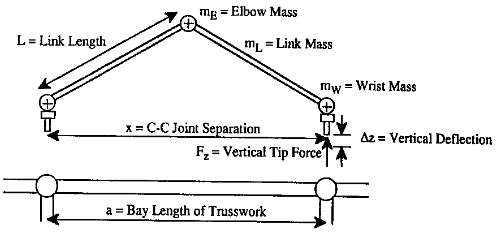


Figure 3: Overall dimensions of the truss and robot are scaled to 1/3 to permit experiments in the laboratory, while local dimensions (sizes of nodes, joints and grippers) are the same to keep local behavior similar, and mechanism size workable.

speeds—of the scaled-down robot similar to that of the hypothetical one. As can be seen from Figure 3, 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 mechanisms are not unworkably small. Figure 4 gives some basic parameters for the scaled and full-size designs.

The robot is designed for mobility in a zero-gravity environment, with simplicity and light weight as primary design goals. It 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 for measuring joint angle. Joint torques are designed to move the robot's limbs at reasonable rates, but not to support the robot's weight; thus it can operate only when gravitational effects are removed. Each joint weighs about 0.55 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 are designed to reflect the compliance of links in the



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 × wall thickness)		19mm × 0.7mm	51mm × 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_z	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.

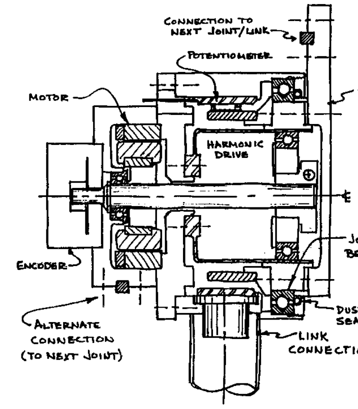


Figure 5: Joint is compact, self-contained, modular design. It includes a DC motor, harmonic drive reducer, position sensors and bearings.

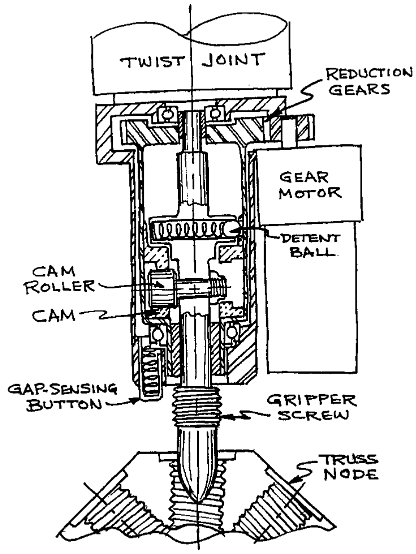


Figure 6: Gripper is designed to anchor robot firmly to nodes of truss: cam mechanism generates over 1800 N (400 lb.) of hold-down force. Sensors allow automatic gripping cycle.

full-size robot, where link mass is a significant factor.

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 (Figure 6) 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.

3 SENSING

Because the sensing available has a great impact on control of the system, we use only sensors that would be feasible in a space-station environment. In particular, we do not use any external tip sensing such as optical tracking from a remote camera, which is typically employed for the control of flexible arms [2]. Currently we rely primarily on potentiometers in the joints which are 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 substantially better (limited by 12-bit A/D converters). 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.

A potential solution to this problem is the use of relative end-point sensing. For example, we are developing a visual servoing system whereby a tip-mounted camera provides an image of the target such as the truss node; an automatic vision system processes the image to provide error signals to servo the end-effector to the node. Other sensors, such as infrared-ranging or mechanical sensors (e.g. "whiskers"), may also prove useful for locating a target.

4 CONTROL

Control of the robot motion is difficult due to three factors: 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 structure.

There has been a great deal of interest during the last 5–10 years in the control of flexible arms. Most of this has been theoretically oriented, focusing on rigorous identification and control of simple arms, often with exaggerated flexibility [1, 2, 4]. Little work has been reported on application-oriented, multiple-joint systems. In contrast, our goal is 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.

Our approach to the control problem begins with the mechanical design. We selected harmonic-drive gearing and four-point-contact joint bearings (Kaydon type X) to minimize friction and backlash. Still, joint friction is about 10% of the available peak torque. 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.

The currently used 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. Offset torques (currents) are applied to compensate for system friction, assumed to be ideal Coulomb friction. 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. Controls and experimental results are discussed in detail in a companion paper [6].

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 [5]. Aside from supplying a high-performance real-time kernel, CHIMERA II provides a layer of transparency between the diverse hardware and the control software. 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.

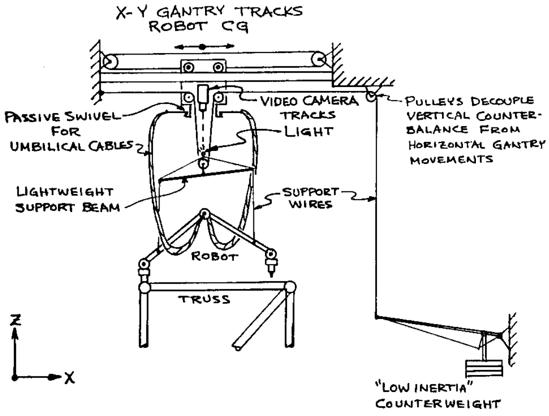


Figure 7: Gravity compensation system includes a passive counterbalance system for vertical support and an active horizontal tracking system.

5 HUMAN/MACHINE INTERFACE

We are developing a video-screen interface for operator inputs and information display. The mouse-driven interface allows the operator to select the mode of control (from autonomous walking to teleoperation) and to simulate or execute commanded motions. In the autonomous mode, the operator specifies a step or sequence of steps for the robot to follow. For teleoperation, we have begun experiments with gestural control using a Polhemus 3SPACE system [3]. Robot commanded position is derived directly from the position of a 6-dof stylus. Processing is needed to remove the extra dof; filtering of commands and/or generation of appropriate trajectories from inputs may improve system performance.

6 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 7, a 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 of payloads.

7 CONCLUSION

We are developing a simple, 5-dof, 1/3-scale, laboratory version of a robot intended to walk on the trusswork of the Space Station, and perform tasks such as inspection, parts transport and simple manipulation. We have designed and built the robot and a gravity compensation system to permit simulated zero-gravity experiments, developed servocontrols for primitive movements, and begun developing operator interfaces. During the next year, we plan to refine the robot hardware, controls, and gravity compensation system; experiment with more advanced human interfaces, including force-feedback capabilities; and add manipulation capability to the mobile robot.

References

[1] T.E. Alberts, W.J. Book, and S.L. Dickerson. Experiments in augmenting active control of a flexible structure with passive damping. In *AIAA*, Reno, Nevada, January 1986. Georgia Institute of Technology.

[2] R.H. Cannon and E. Schmitz. Initial experiments on the end-point control of a flexible one-link robot. *International Journal of Robotics Research*, 3(3):62–75, Fall 1984.

[3] Scott S. Fisher. Telepresence master glove controller for dextrous robotic end-effectors. *Journal of the Society of Photo Optical Instrumentation Engineers*, 726, 1986.

[4] F. Pfeiffer and B. Gebler. A multistage-approach to the dynamics and control of elastic robots. In *Proc. 1988 IEEE International Conference on Robotics and Automation*, pages 2–8, Philadelphia, Pennsylvania, April 1988. Computer Society Press.

[5] David B. Stewart, Donald E. Schmitz, and Pradeep K. Khosla. Implementing real-time robotic systems using chimera ii. In *IEEE International Conference on Systems Engineering*, Pittsburgh, Pennsylvania, August 1990.

[6] Hiroshi Ueno and Yangsheng Xu et al. On control and planning of a space station robot walker. In *Proc. of 1990 IEEE International Conference on Systems Engineering*, Pittsburgh, Pennsylvania, August 1990.