ISRAM '94- Fifth International Symposium on Robotics and Manufacturing) August 1994

DESIGN, CONTROL, AND APPL1CATIONS OF A SERPENTINE ROBOT, PART I: DESIGN, FABRICATION, AND CONTROL

THOMAS S. LEE and TIM OHM
lee@telerobotics.jpl.nasa.gov
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, 91109

SAMAD HAYATI
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, 91109

ABSTRACT

The design, fabrication, and control of a 12 DOF serpentine robot is described. The serpentine robot is used for application in JPL's Remote Surface Inspection project and as a research tool in redundant manipulator control.

1. Introduction

One of our goals was to develop technology to inspect 1 crook, hard-to-reach locations. The JPL experimental facility contains a mockup of the Space Station truss structure that is cluttered with different types of objects such as an Orbital Replacement Unit (ORU) and a thermal radiator. The tasks to be performed range from visual insp ection by maneuvering inside of narrowly confined areas and detecting anomalies to temperature and gas leak detection. One such scenario is moving behind a radiator panel and searching for electrical damages. 'There are also some light manipulation tasks which are required to diagnose, service, and repair devices attached to the space structure.

At JPL, a highly redundant robot inspection system consisting of 20 DOF will be utilized to perform some of the required rc.mote inspection tasks. The idea is to attach a smart end-effector tool that has a long-reach serpentine feature at the end of a conventional robot. Figure 1 shows this configuration. Note that the 7 DOF of Robotic.s Research arm is mounted on a 1 DOF mobile base. The larger manipulator can be thought of as a global positioning device, while the serpentine robot can be viewed as a fine manipulator being restricted to operate in a local region. In this paper, the design, fabrication, and control of the serpentine robot is described. (see Figure 2).

2. Background

Work in serpentine robotics dates back approximately 30 years. Namely, the Japanese companies such as Toshiba, Mitsubishi, and Hitachi have done a lot of work in this area

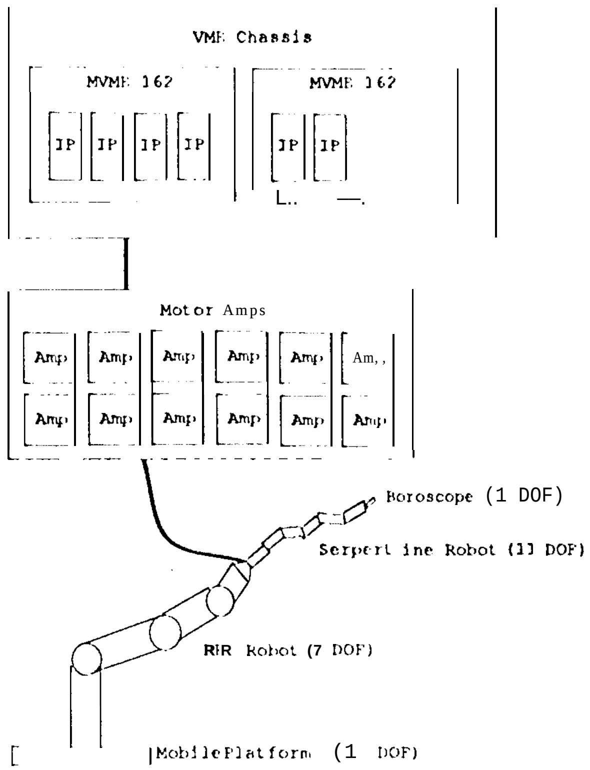

Figure 1: Overall Inspection System and the Hardware Architecture

for application in the nuclear power industry. Hirose [2] of Tokyo Institute of Technology developed a number of snake-like mechanisms, for example, a crawling mechanism which utilizes oblique swivel joints. Asano [3] built Toshiba's Self Approach System in 1982. A camera was mounted on the tip of this 16 DOF tendon-driven mechanism to perform inspection. In the Unites States, notable works include Anderson and Horn [4] who built a 16 DOF tensor arm for Scripps Institute of Oceanography in 1964. Chirikjian and Burdick [5] of Caltech built a 30 DOF variable geometry truss manipulator to validate hyper-redundant arm control algorithms.

3. Final Mechanical Specifications of the Serpentine Robot

- 3-1) Mechanism with Total Weight of 5.6 lbs
- Extended Reach : 34.5", Diameter of the Robot: 1.5"
- Through-Hole Inside for Cables: 5/16"
- Total of 12 Degrees-Of-Freedom (DOF)
  - -- 5 Pitch DOF (–60° to 600), 5 Yaw DOF (–60° to 60°)
  - - 1 Roll DOF (- 180° to 180°), 1 Borescope DOF (- 100° **to 100°)**
- DOF Velocity : 60 degrees/second

The serpentine robot was designed to be utilized as a smart end-effector tool. The serpentine robot would be picked up by a base robot when additional dexterity is

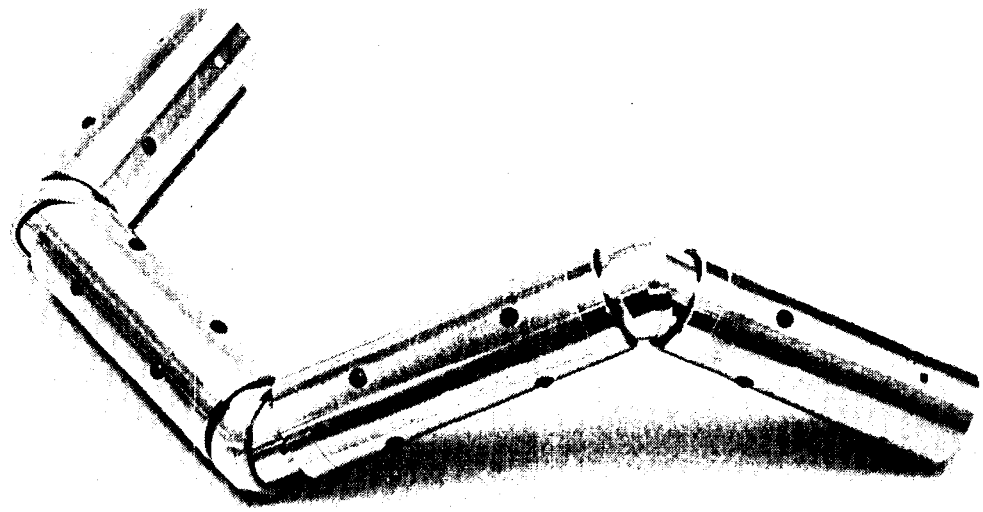

Figure 2: The JPL Serpentine Robot

required to perform the task. in this paper, only a few of the design issues will be discussed, For more details, please refer to [6].

4. Serpentine Robot Design

Since the serpentine robot is to be attached at the end of another robot, weight and size needed to be minimized. Miniature, yet high torque motors were needed. MicroMo's 2 watt DC motors were chosen. Based on ironless core technology, these products have the feature of high efficiency with low mechanical time constants.

'1'o achieve high torque, each axis has a very high gearhead ratio. The axes of the first two base joints have a gearhead ratio of 3333:1, and the axes of the rest of the joints have a gearhead ratio of 1111:1 (high gear ratio was achieved by building our own custom planetary stages). Two redundant motors which are mechanically coupled turn each axis and provide double the torque of one motor. The gear-tra,ill is non-backdriveable. Maximum torque at each DOF is 90 in-lb.

The joint design needed to be compact. If the conventional method of mounting the motors on the joints were adopted, the serpentine robot would have had a bulky design. A patented design owned by the NEC Corporation was chosen. This design allows all motors to be mounted inside of the joint housings.

The original design is an active universal joint based on work by Ikeda and Takanashi [7] of the NEC Corporation. Our mechanism was made more compact by modifying their joint assembly design. The basic idea is illustrated in Figure 3. The oblique swivel joint assembly has two shafts, with each shaft attached to a half-sphere at an oblique angle. The two half-spheres arc joined together to rotate freely with respect to each other. This arrangement is contained inside a universal joint with each shaft joined to one side of the frames that make up the universal joint. The motors rotate

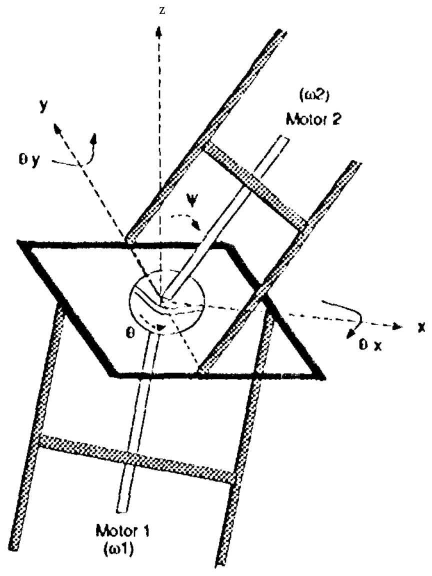

Figure 3: Oblique Swivel Joint Assembly

the two shafts thereby actively changing the orientation of the universal joint. Both motors are controlled simultaneously to change the orientation. Now consider the Spherical coordinate system. When the motors are rotated in the same directions, the joint assembly makes a motion along the ψ direction. If the motors are rotated in opposite directions, then the joint assembly makes a motion along the θ direction. The motions along the ψ and θ directions make up the 2 DOF movement of the joint. Note that when the shafts are collinear ($\psi = 0$), a degeneracy (singularity) occurs.

The oblique swivel joint can simply be considered as a two-axis joint having yaw (θ_x, a rotation about its X axis) and pitch (θ_y, rotation about its Y axis) motions. Let ω_1 and ω_2 be the angular velocities of the two motors at the joint. Let $\dot{\theta}$ and $\dot{\psi}$ be the relevant angular velocities in the Spherical coordinate system as discussed above in Figure 3. Finally, let $\dot{\theta}_x$ and $\dot{\theta}_y$ be angular velocities about X and Y axes respectively. We want to find the angular motions about the X and Y axes caused by the motions of the motors. That is, we transform the motor velocities as follows:

$$(\omega_1, \omega_2) \rightarrow (\dot{\theta}, \dot{\psi}) \rightarrow (\dot{\theta}_x, \dot{\theta}_y)$$

First, we compute the intermediate angular velocities:

$$\dot{\theta} = K_1(\omega_1 + \omega_2)$$

$$\dot{\psi} = K_2(\omega_1 - \omega_2)$$

where K_1 and K_2 are some constants.
We integrate $\dot{\theta}$ and $\dot{\psi}$ for the following transformations:

$$\theta_x = ATAN(-s\psi\ s\theta, c\psi)$$

$$\theta_y = ATAN(s\psi\ c\theta, c\psi\ c\theta - s\psi\ s\theta\ s\theta_x)$$

we then difference the obtained θ_x and θ_y with the previous θ_x and θ_y to obtain the desired results.

5. Additional Features of the Serpentine Robot System

The mechanism was designed to be mechanically modular -- the joints can be easily added or subtracted. Visual data is acquired by using of a flexible borescope embedded inside of the serpentine robot housing. User interface will be done by interacting with a SGI/IRIS graphics menu. The motors are controlled remotely from externally located VMEbus hardware.

All the above features are described in more detail in [6]

6. Control: Via Point Fitting Algorithm (VPFA)

An obvious method of motion planning for the serpentine robot is to utilize some sort of a "follow-the-leader" algorithm. The idea is to first let the tip of the serpentine robot to move in such a way it does not collide into any of the obstacles. To avoid collision with the obstacles for the rest of the serpentine robot's body, we direct the rest of the links to follow the task space path that the tip has propagated through. in this section, we briefly describe one such motion planning algorithm.

Consider a serpentine robot with N joints. Each joint has 2 DOF and is capable of angular motions with respect to its X and Y axes. Given a set of N_{via} via points (VP_1,..., $VP_{N_{via}}$) in Cartesian task space that the tip of the serpentine robot has propagated through, we decompose the motion planning problem into two subproblems: (1) select Joint Frame Move Points (JFMP) which are a series of N-point sets for the origins of the robot joint frames to propagate through; then (2) solve for the pitch and yaw angles at each joint to fit the selected JFMP points.

The JFMP points can be selected by propagating backward from the last via point ($VP_{N_{via}}$) where the tip is located toward the first via point (VP_1). We designate a particular via point as a JFMP point for the corresponding joint if the via point's accumulated Euclidean distance (i.e., $\sqrt{x^2+y^2+z^2}$) from the tip position is close to the accumulated sum of appropriate link lengths. For example, the JFMP for the last joint N is the position of the serpentine robot's tip. The JFMP for the next to the last joint (N-1) is marked when the accumulated Euclidean distance from the tip point is close to the length of the last link. The JFMP for the joint (N-2) is marked when the accumulated Euclidean distance is close to the sum of the lengths of the last two robot links. This procedure continues until all N- JFMP points $((X_N, Y_N, Z_N), (X_{N-1}, Y_{N-1}, Z_{N-1}), ..., (X_1, Y_1, Z_1))$ are selected from the via points. We now proceed to the fitting portion.

We start fitting from the base joint (i.e., computing the corresponding θ_x and θ_y angles at the base frame). Let the JFMP point associated with the base frame be (X_1, Y_1, Z_1). Here we simply solve a problem of computing the required angular rotations to place a point $(0, 0, \sqrt{X_1^2+Y_1^2+Z_1^2})$ to (X_1, Y_1, Z_1). The solution of this problem is as follows:

$$\theta_x = ATAN(-Y_1/Z_1) \tag{1}$$

$$\theta_y = ATAN((c\theta_x X_1)/Z_1) \tag{2}$$

$$\theta_1 = \theta_x, \quad \theta_2 = \theta_y \tag{3}$$

To compute the next set of θ_x and θ_y, we position our reference frame to have

(X_1, Y_1, Z_1) as the new origin, and reorient the next JFMP point which is (X_2, Y_2, Z_2) to be referenced with respect to the orientation of the new reference frame. First compute a vector associated with (X_2, Y_2, Z_2). That is,

$$V_2 = (X_2 - X_1,\ Y_2 - Y_1,\ Z_2 - Z_1)$$

Then multiply a rotation matrix to the vector V_2. That is,

$$V_2' = RotX(\theta_1)\ RotY(\theta_2)\ V_2$$

V_2' is the vector referenced with respect to the frame of the second link. Then once again, we use a similar set of equations as equation (1), (2), (3) above to fit to V_2'. θ_3 and θ_4 are then found. The next JFMP point is computed as follows:

$$V_3' = RotX(\theta_1)\ RotY(\theta_2)\ RotX(\theta_3)\ RotY(\theta_4)\ V_3$$

The procedure continues until all angles are computed.

An IRIS/SGI graphics simulation program has been written. The VPFA algorithm has been validated by testing it on the IRIS machine.

7. Conclusion

We arc! in the process of implementing several control algorithms for the serpentine robot. In the meanwhile, control experiments are being performed to resolve' any instability problems associated with high gear ratios.

8. Acknowledgements

The research described in this document was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We would like to thank Nobuaki Takanashi for providing the information on the patented mechanical design.

[1] Hayati, S., et. al, "Remote Surface Inspection System," *Robotics and Autonomous Systems*, Vol 11, No. 1, pp. 45-59, May 1993.

[2] Hirose, S. et. al., "Design and Control of a Mobile Robot with an Articulated Body", *The International Journal of Robotics Research*, Vol. 9, No. 2, April 1990.

[3] Asano, K., et al., "Multijoint Inspection Robot," *IEEE Transaction on Industrial Electronics*, Vol IE-30, No. 3, pp. 277-281, 1983.

[4] Anderson, V., Horn, R. C., "Tensor-arm Manipulator Design," *ASME Transaction*, vol. 67-DE-57, pp. 1-12, 1967.

[5] Chirikjian, G., Burdick, J., et. al, "Kinematics of Hyper-redundant Robot Locomotion with Applications to Grasping," *Proceedings of the IEEE International Conference on Robotics and Automation*, 1991.

[6] Lee, T. S., et. al, "A Highly Redundant Robot System for Inspection," *Proceedings of the AIAA/NASA Conference on Intelligent Robots in Field, Factory, Service, and Space*, League City, Texas, March 1994.

[7] Ikeda, H., Takanashi, N., "Joint Assembly Movable Like A Human Arm," United States Patent Number 4,683,406, July 28, 1987.