Design and Sensor-Based Control for Hyper-Redundant Mechanisms

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Research Objective

Toxic materials in DOE sites pose a significant threat to DOE personnel who must inspect these locations. Working in confined spaces further complicates the situation especially when the workers must wear heavy and cumbersome protective suits. A robot or conventional mechanism can clearly bypass the danger and perhaps expedite the characterization process because the person is removed from the site and neither the site nor the person require preparation. However, conventional robots are not suitable for these inspection tasks because they are not flexible enough to pass through and into target DOE inspection sites. This effort is developing an articulated probe, called a *hyper-redundant mechanism*, which is a snake-like device that can exploit its many internal degrees of freedom to thread through tightly packed volumes transmitting images and data from remote locations inaccessible to conventional robots and people. This effort contains two parts: mechanism development and control of the device.

Research Progress and Implications

One of the challenges in designing a hyper-redundant robot is to make it small enough so it fits through narrow holes and openings and yet be strong enough so it can lift itself and maneuver in three dimensions. Prior work was either limited to the plane or can lift only a small fraction of itself. The design goals for the snake robot included maximum torque-to-weight to allow cantilever support of the snake; minimum envelope diameter to fit through small openings; minimum achievable radius of curvature, resulting from short links with maximum angular travel between links; and rugged construction. Secondary goals included minimum backlash and compliance in the structure; and "reasonable" speed of motion.

From the outset, an “almost” modular design with all links identical was chosen for simplicity of design, fabrication and assembly. This is sub optimal in the sense that the joints near the fixed end or base of the robot will generally have much higher loads than those near the proximal end or head. In the proposed effort, we promised to deliver two two-degree-of-freedom joints and then decide on how to build a hyper-redundant robot. We actually were able to design for six joints. A six joint device is a hyper-redundant robot in its own right, but the choice six joints for this robot rather arbitrary when one realizes the real manipulation capabilities depend also on the degree of travel in each joint.

Instead of going with the bevel gear design, we opted for a simpler actuated universal-joint (U-joint) design was selected for its simplicity and ruggedness. In this design, U-joint "crosses" are connected to one link with a pitch pivot joint, and to the next with a yaw pivot joint. The pitch and yaw joints are always orthogonal, and intersect along the link centerlines; this leads to simple kinematics. See Figure 1 The pitch and yaw joints are actuated by linear actuators in the two links.

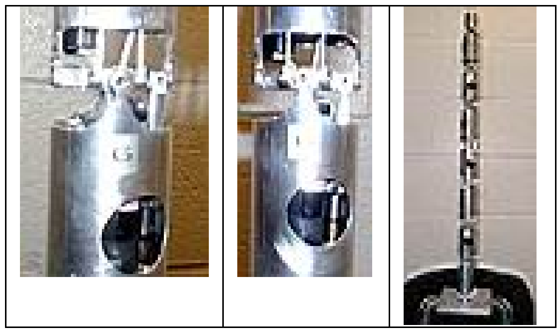

Figure 1 Two Views of Actuated Universal Joint with Orthogonal Degrees of Freedom

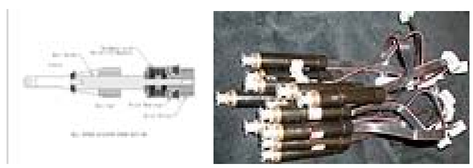

Figure 2 We Use a Ball Screw Design with Conventional Actuators

Links are configured such that the axes at each end of any link are parallel; thus, one link will have pitch joints at both ends actuated by its two linear actuators; the next link will have two yaw joints. This arrangement facilitates packaging of the two linear actuators side-by-side in the link. Ball screws were chosen for the linear actuators because of their high efficiency (compared to lead screws) and effective speed reduction. The screws are fixed in bearings mounted to the links, while the nuts drive clevises connected to the crosses of the U-joints. The screws are driven by brush-type, permanent-magnet, DC motors which can be operated with simple, pulse-width-modulated (PWM) electronics. For compactness, the gearmotor and ball screw are placed side-by-side with a small toothed-belt drive connecting them. Each actuator is mounted to the link through a steel flexure that accommodated the slight lateral movement of the screw as the joint angle changes. . See Figure 2

A novel feature of this design is the overload mechanism or "snubber." It is designed to absorb the kinetic energy of the links and motors when the mechanical stops are reached, and to accommodate imposed loads on the snake without damage to the actuators or structure. Belleville spring washers--4 series sets of 3 parallel-stacked washers--are mounted in the "snubber housing" such that the ball screw can move axially by 1mm if the preload value is exceeded. The thrust load of the screw is taken by a custom-made, 4-point-contact bearing that is integrated into the snubber housing.

Each link is 41.7mm in diameter, 96.0mm long (pivot-to-pivot), and weighs about 240g. The ball screws are 6mm diameter with 1mm lead, are rated at 700N, and are connected to the crosses at 14.7mm from the pivot. Motors are Maxon RE-13 (13mm diameter) gearmotors with 16.58:1 planetary gear reducers and 16-count encoders (64 counts per revolution with quadruature decoding). These develop about 38mNm of continuous torque; this translates to 380N of force at the ball screw (well below the rated load), considering the 2:1 belt drive and transmission efficiencies. The snubber mechanisms are preloaded to about 600N to protect the ball screws and bearings from overload; no displacement occurs until this load value is reached, so the normal stiffness of the structure is not compromised. Motor no-load speed at the nominal 12V input is 8900RPM, which corresponds to 5s time to travel the full 22.4mm of screw travel. Joint angular travel is about +/-55 degrees.

Tests of the joints showed that the actuators can produce 4.5Nm of torque at 12VDC (0.40A). That is, each ball screw produces 307N at 14.7mm radius on the U-joint cross. Based on the expected 5.08mNm at 0.40A, theoretical output would be 1060N with 100% transmission efficiency. This indicates that overall drive efficiency is only (307N/1060N) 29%, much lower than predicted (48%). We will investigate this to see if significant increases in efficiency and output torque are possible.

The torque about a joint needed to "cantilever-lift" (lift when extended horizontally) a single joint, assuming its center-of-mass (COM) to be at its geometric center, is 0.113Nm. The torque to lift n joints is n-squared times this. Given 4.5Nm available joint torque, the snake should then be able to cantilever-lift 6 joints. Tests on the complete snake robot confirm this capability. This ability is important to allow the snake to achieve arbitrary configurations working against gravity.

We have not demonstrated fixed base probing on an already existing JPL snake robot because the range of motion of this device is not sufficient. However, considering the significant advances in mechanism design, well beyond the original planned deliverable schedule, we are still in excellent shape.

We have also constructed a feeding device for the hyper-redundant robot. The feeder is a mechanism that “pushes” the hyper-redundant robot through an opening into its environment. The belief here is that the hyper-redundant robot should not “waste” its internal degrees of freedom outside the inspection site just to get inside. Instead, the feeder has one degree of freedom that serves its job of inserting the snake into the inspection site. Since we did not have the hyper-redundant robot built at the time of designing the feeder, the feeder design allows for a variety of snake robot shapes and sizes. The feeder also serves a secondary purpose as a storage and carrying device for the hyper-redundant robot. See Figure 3

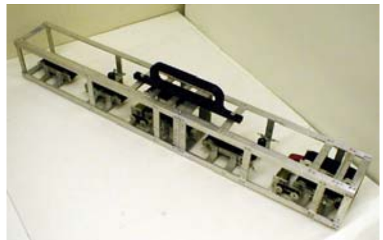

Figure 3 Feeding Device for Hyper-redundant Mechanism

Planned Activities

At present we have a 7-link, 14-actuator snake assembled and working. The U-joint cross at one end is mounted to a fixed base. Joint actuators are individually controlled by 14 switches, allowing the robot to be moved into arbitrary configurations. Ultimately we need to have the hyper-redundant robot under computer control so that the tip can be moved to the desired position and orientation while the body of the robot obeys constraints of the environment, etc. To this end, we are leveraging support from the Office of Naval Research to develop an electronics "bus" system that will carry power and signals between the actuators and sensors on the snake to a control computer. Hard wiring to all 14 actuators and encoders would require (14 x 8) 112 conductors and was deemed unfeasible. The plan is to use an I-squared-C bus on the snake to connect micro-controllers on the actuators to the control computer. The technology is available, but packaging the required components (H-bridge, decoder chip, PIC micro-controller plus passive components) to fit within the link envelope, and providing interconnects between controllers, are challenging problems.

In the remaining two years, we are going to re-build another snake robot to contain on-board sensors and a camera. We are also going to construct a simple joystick interface that will enable any person to drive the head of the robot around. In the third year, we will integrate our path planning algorithms onto the snake robot and provide demonstrations of it threading through tightly packed spaces

Finally, we seek to receive feedback from other DOE sites so as we can tailor our design to their specific needs.