Design and Sensor-Based Control for Hyper-Redundant Mechanisms

Howie Choset, choset@ri.cmu.edu
Carnegie Mellon University
Tel: 412-268-2495 / Fax: 412-268-3348

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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.

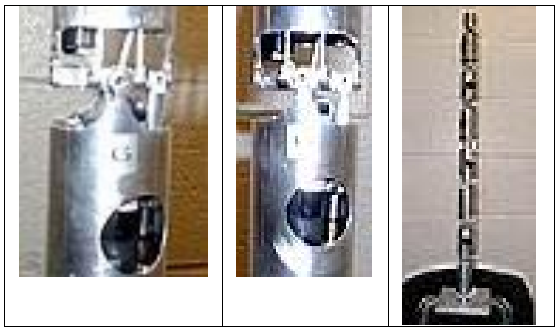

Figure 1 Two Views of Actuated Universal Joint with Orthogonal Degrees of Freedom

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

In the last six months, we spent considerable amount of time developing circuitry for the snake robot. Each bay now has its on-board microprocessor (Figure 3) which can receive power and signal information from a unique bus system that we developed. This bus uses

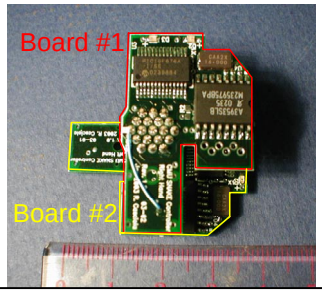

Figure 3 Electronics board installed at each bay

the I2C protocol, which gives our system incredible modularity. Now, we can add a variety of sensors and other devices. See Figure 4 to get a view of the boards installed onto the robot.

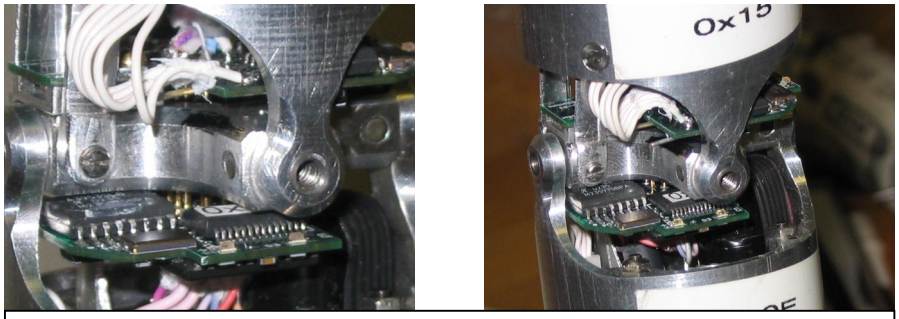

Figure 4: Circuit Board Deployed on Snake Robot Joints

With the circuitry on the snake, now the device is truly a robot. It is also worth noting that this is the first snake robot, of its size, where both the actuation and the electronics are all on-board. Now, we are able to save "key" positions that the robot can move to and in the future integrate it with the path planning algorithms that we are developing.

In terms of path planning, we have continued our efforts in using the roadmap based approach for the follow-the-leader method proposed in the original work. However, it has become clear that we need the head of the snake to cover a surface, so we began developing algorithms that allows for coverage. In particular, we developed an approach that allows the head of the snake robot to move laterally, as opposed to a follow-the-leader fashion. Next year, we will integrate this with a coverage algorithm.

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. Now, our robot can be computer controlled, as opposed to control via switches. Before we move on to full blown computer control, we are going to update both our mechanical and electrical systems to be more robust. In particular, our electronics currently sits at the joint on a moving part. This will most likely be the source of electronic failure after repeated use. Therefore, we plan to redesign the circuit so it will fit into a fixed location inside the housing within a link. This will entail some minor redesign of the mechanism.

We are going to put a sophisticated pan-tilt camera system at the end of the snake robot so the user can gain a virtual presence of the remote environment being sensed. We are also developing a novel user control interface so someone, not necessarily with a PhD, can easily drive the robot around with little start-up training.

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