IDEA

Innovations Deserving
Exploratory Analysis Programs

Highway IDEA Program

Bridge Inspection with Serpentine Robots

Final Report for Highway IDEA Project 56

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EXECUTIVE SUMMARY

Every bridge in the United States must be inspected at least once every two calendar years if it spans more than twenty feet. The unfortunate reality is that these federally mandated inspections require extensive rigging and traffic control. This rigging and traffic control alone consumes 40% to 50% of the inspection budget. Rigging and traffic control are so excessive because the inspector has to see all locations of the bridge, which are often hard to reach on large bridges. This research will develop an innovative technology that resolves these shortcomings. Instead, an inspector sitting in a truck on the bridge roadbed will control a *serpentine* robot that can "view" the entire bridge through a sensor suite deployed at the end of the robot. This system would reduce the cost of bridge inspection, increase the safety factor, provide better views of the bridge, improve the quality of information, and as an added benefit, decrease traffic delays that are a result of such an operation. The main challenges addressed in this project were to design a new prototype and develop control strategies to move a serpentine robot through the trusses of a bridge.

IDEA PRODUCT

Hyper-redundant robots have their name because they posses many more internal degrees of freedom (motors) than are necessary to position and orient their end-effectors. A point in the plane has two degrees of freedom, and a point in space has three degrees of freedom. A rigid body in three-dimensions has six degrees of freedom: x, y, z, and the angles the object makes relative to these three axes.

A conventional robot has six joints to specify the object's position and orientation. The human arm has seven degrees of freedom to position the hand, so has one degree of redundancy. This extra degree of freedom allows you to grasp an object and wiggle your arm between the shoulder and hand while keeping the object in the same orientation, thus you have many choices for how to reach something. If your elbow were in a cast you would lose the redundant degree of freedom and have a harder time reaching things.

Hyper-redundant robots are particularly useful because they have many redundant degrees of freedom, which cause flexibility. This flexibility allows them to reach through tightly packed volumes. Probing is done without actually touching the environment, needing only support itself at its base point. The flexibility and the shape of the robots cause it to resemble a snake, so they are often called serpentine robots. The flexibility is the motivating feature of these robots, but the redundancy allows them to deal with motor failures also. Just as when your elbow is in a cast you can still use your arm, a serpentine robot can work quite well in spite of simultaneous failures in some of its joints because so many of them are redundant.

In bridge inspection, using these robots can yield great savings. Rigging for the inspector to use requires 40-50% of the time of the inspection, a serpentine robot would require a small fraction of this rigging for its inspection. Along with this direct savings, we will be able to record everything the serpentine "sees" for future reference. Because the inspector will be on the roadbed in a van monitoring the inspection, the safety will be increased over the normal scenario where they are on scaffolding, scaling the bridge, or in a snooper bucket doing the inspection. There will also be savings in planning an inspection. The robot can optimize its path across the bridge such that time is used more efficiently.

Although these robots were considered specifically for bridge inspection in this contract, it is apparent that serpentine robots can be used for other kinds of inspection from jet engines to urban search and rescue (USAR). These robots are not limited to inspection though; they can be used in bridge painting, welding, and other applications where light forces are required in crowded environments.

This investigation focused on a serpentine robot that has its "tail" fixed to a base so that it is more like an elephant's trunk. Our vision is that a Snooper truck or crane will hold the base of the serpentine robot and provide the course movement around the bridge. The serpentine robot would then provide the fine movement to cover the bridge with. This is much like the elephant using its legs to provide the coarse walking motion to get close to a bag of peanuts, and then using its trunk to do the fine work of grabbing them.

CONCEPT AND INNOVATION

There are three major challenges in implementing serpentine robots: the physical design, the sensor deployment and finally the control algorithms. Each of these areas is highly dependent on choices made in the other two.

PHYSICAL DESIGN:

The physical design is challenging because the joints of the serpentine robot that are located near the base of the robot must be strong enough to support the entire weight of the robot. As the robot gets longer, the stresses get higher and the power required for movement gets larger. This need for strength and power creates a difficult design loop because both power and strength require larger motors and a larger cross-section. These larger dimensions in turn increase the weight, causing a need for even larger motors and cross-sections. This becomes a difficult optimization problem, especially since cross-sectional area is a variable that should be minimized.

Our novel joint exhibits reachability, flexibility and stability, while at the same time it has the added feature of a compact yet hollow assembly. The joint connects two cylindrical members which we will call bays. For the sake of explanation, assume that we fix one member and we observe how the joint moves the other bay. Figure 1 shows the reachability and the flexibility of our joint. Note that the single free end is shown in two different positions.

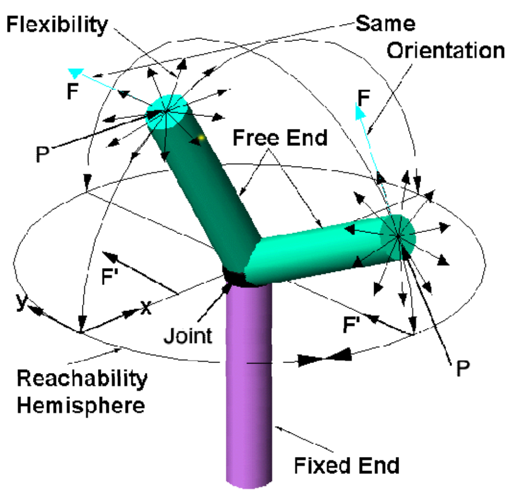

Figure 1: Flexibility of Joint

Note that a point P on the axis of the free end is able to reach a complete hemisphere. Moreover, starting from any point on this hemisphere point P can move in any desired direction tangent to the hemisphere. Even though the joint has a compact and hollow assembly it is very strong and can withstand high loads. Moreover, it has a high mechanical advantage, i.e. small motors are needed.

Many joints have two degrees-of-freedom, but they cannot be used as a serpentine robot joint. This is due to the fact that there is relative twist between the members, which will destroy any electrical connection going along the body of the robot. This relative twist can be cancelled by introducing a third actuator that keeps the orientation constant. However, controlling this third actuator is complex, plus it will add extra cost to the joint. Another solution is to introduce more mechanisms but this is complex to build and expensive. On the other hand, we have designed a mechanism that cleverly utilizes only two actuators to extract two serpentine-friendly degrees-of-freedom yet maintain the same orientation. So wherever the free end is on the hemisphere, all the projections of F onto the plane normal to the fixed bay stay parallel. This feature ensures that there is no relative rotation or twist between the two members. This feature is critical for serpentine robot design.

The joint has a hollow assembly that allows electrical wires to pass inside the joint. This feature is important since it protects the wires inside the joint assembly from any rough environment. Hence the joint has an enveloped

design. Finally, the joint does not allow relative twist along the axis between the two members of the joint. This will protect the wires from being twisted, avoiding failure.

The goal of the invention is to provide a joint assembly that is suitable for building serpentine robots. Hence the joint should be light, compact, strong and easily controllable. Our joint exhibits innovations in all of these categories. The joint we designed is compact with 0.925 inches cross-sectional radius using off-the-shelf components. Given this small cross-sectional diameter, it is strong. This is due to an angular bevel gear train that connects the two members of the joint. This gear train allows the actuator to be positioned along the axis of the joint but transfers forces at the periphery of the mechanism, creating a high mechanical advantage proportional to the radius of the robot. The gear train also minimizes the stresses and torques on the joint components. So the joint is able to produce high forces and resist high loads that are critical in all types of serpentine robot tasks. Moreover, this gear train transfers rotational motion between the two members with a constant ratio. This constant ratio is unlike other connecting mechanisms, such as universal joints that were used in previous joint designs. This constant ratio makes the joint easy to control and simplifies the inverse kinematics of the joint. In other words, given any configuration of the joint, it can be easily transferred to motor rotations.

SENSING:

Sensors are important for a few reasons. First, the robot's ultimate purpose is to sense the bridge as a part of the inspection. Secondly, if the geometry of the bridge is not known at the beginning, the robot will need to sense the bridge to build up the database so it can more easily figure out an optimal path across the bridge. Third, the sensors are needed for localization, which is how the robot knows where it is in the world based on its immediate surroundings.

Prior work in serpentine robots can be seen as a pre-cursor to our own. In the prior work, the sensing was limited to sensors to detect the internal state of the robot, i.e. joint angles, or force sensors for free crawling snakes. At best a small camera has been mounted on the front of a snake. Our goal is to increase the sensing capability from simply mounted camera to one with pan, tilt capability. We would like to have sonar distance sensors for use in mapping and localization. If a small and affordable laser range finder were to become available, that would be of great utility also. Integrating these sensors into the path planning and mapping capabilities of the robot is a very important step in our project.

PATH PLANNING:

Path planning is the next major goal. To be of the greatest utility, the serpentine robot must have some degree of autonomy. This autonomy can come in many different forms. We have enumerated a sequence of sub-goals that achieves our ultimate goal of autonomous exploration.

The first sub-goal is tele-operated mode. In this mode, a person will direct the head of the snake while the planner coordinates all of the internal degrees of freedom to achieve the desired motion of the head. A planner is necessary here because it is impossible for a human to achieve purposeful movement with the serpentine robot by controlling each joint angle independently.

The second sub-goal would be semi-autonomous mode where the operator would specify a high level plan for coverage and the serpentine robot would be able to complete the detailed coverage using its own planner. Finally, in fully autonomous mode, the serpentine robot would be able to plan a path across a bridge it has never seen before.

Serpentine robots are difficult to control because they have many degrees of freedom, which are not intuitive for humans to control. To achieve purposeful motion computerized control strategies are essential, unfortunately the coordination of these numerous joints is not handled well in traditional robot motion planning theory. In this work, the robot will use a roadmap, a geometric structure used in the robotic motion planning field, to plan the paths for the robot which guarantee its sensors "see" all locations of the bridge with the sensor suite. Typically, the roadmap can be derived from a CAD model of the bridge, but if no such model exists, then the serpentine can construct the roadmap, as it inspects the bridge, from sensor data.

Inherent in the path planning problem is the solving of inverse kinematics problem. A kinematics problem involves taking the joint angles and using them to figure out the end point of the serpentine robot. This is a tedious but straightforward problem that leads to one single answer. An inverse kinematics problem is much harder, and has an infinite number of solutions for a serpentine robot. Take the example where your finger is touching a point on the table, notice that you can still wiggle your arm; this shows that there are an infinity of joint angles that will place your finger to the same point on the table. At first, it would seem that having an infinity of solutions to the inverse kinematics problem would make it *easier* to find a solution as compared to the forward kinematics problem where there is only one solution. Unfortunately, this is a situation where biology easily solves the kinematics problem but conventional math theory does not. The kinematics theory works out so that it is harder to find one of the infinite number of solutions of an inverse kinematics problem than to find the single solution to a forward kinematics problem.

We use a roadmap to generate a sequence of inverse kinematics problems and are able to solve these problems easily because of the way we model the problem. So, this roadmap is the key to simplifying what would normally be a very difficult problem. First, we will describe a planar roadmap and then upgrade it to three dimensions. The roadmap used in this work is defined in terms of a distance function $D_i(x)$, which measures the distance from a point x to the closest point on object C_i, In the planar case, generalized Voronoi graph (GVG) edges are simply the set of points equidistant to the nearest two obstacles. By definition, the end points or "nodes" of the GVG edges are boundary points $D_i(x) = D_j(x) = 0$ and meet points $D_i(x) = D_j(x) = D_h(x)$ for at least one obstacle h. In the Voronoi diagram literature, meet points are called Voronoi vertices, but we use the term meet points because GVG edges terminate (and meet) at them. The planar GVG is the collection of all GVG edges described above. Figure 2 shows the GVG with its meet points as heavy points at the intersections.

With the GVG that we generated, we can use a follow-the-leader approach to serpentine robot path planning. In this process a path is generated for the head of the snake, and the body simply follows along. The path we use is based on the GVG roadmap since it represents the path that is furthest from all the obstacles. All the bays of the serpentine robot are identical, so if the head is able to position itself then the rest of the body can follow it. Follow the leader is not always the most efficient strategy for movement, however it is the easiest to calculate and is a necessary sub-routine for all other path planners.

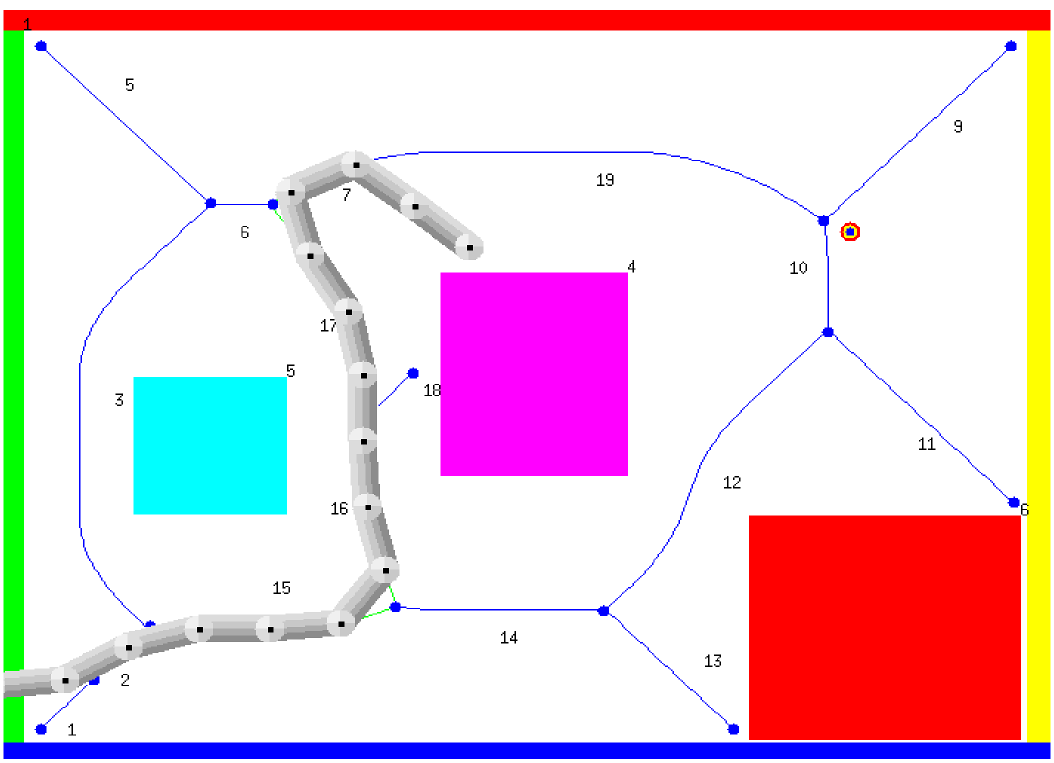

Figure 2: Planar Snake Simulation

One of our first contributions in computational geometry deals with computing geometric structures in man-made environments. This is difficult because man-made structures posses many symmetries that conventional geometric algorithms cannot handle. We overcame this problem and perhaps have identified a new fundamental method for constructing geometric structures in man-made structures.

The extension of the GVG into the next dimension is logical. Rather than the GVG being the set of all points that are equidistant from the nearest two obstacles in two dimensions, now it is the set of all points equidistant to the nearest three obstacles in three dimensions. A sample GVG in a three dimensional environment is shown in Figure 3.

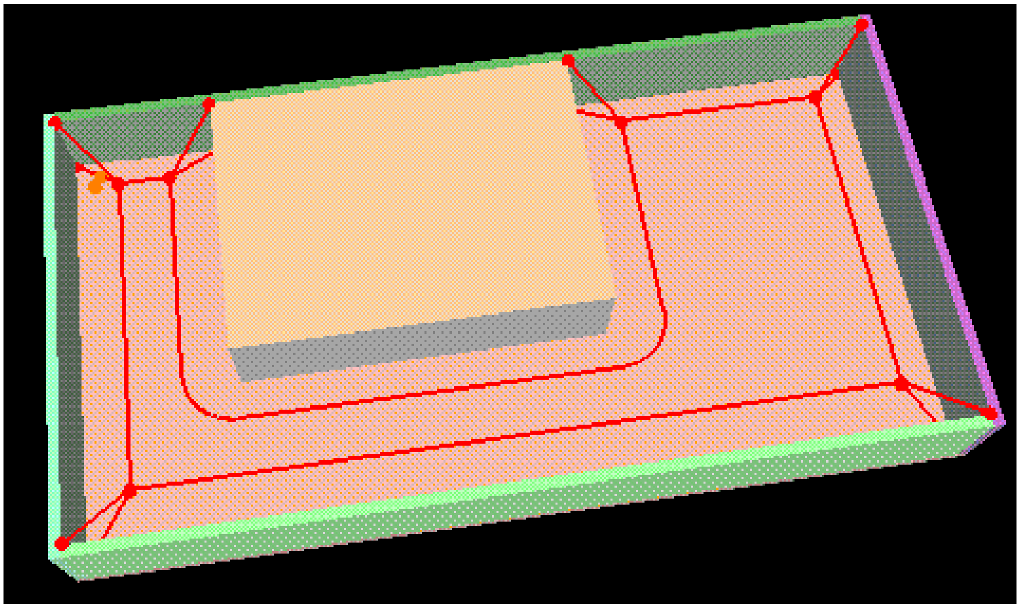

Figure 3: GVG in three dimensions

We know that a robot can maneuver in certain areas easier than it can in others. We have extended upon prior work to give a better measure of this maneuverability. This concept, called work space density, states that depending on the location of the base of the serpentine robot, certain areas of the workspace are more easily reached than others. This makes sense if you again think of your arm, it is much easier to manipulate items that are located at about 75% of arms length than it is to manipulate items that are a few inches from your shoulder. This is because to reach near your shoulder, your elbow is at its joint limit so is not as useful for manipulation. Serpentine robots have the same problem reaching near their own base. Figure 3 shows the workspace density for a planar serpentine robot. The dark red shows places of high maneuverability while light blue means low maneuverability. The dark blue shows places that are not reachable by the serpentine robot. Notice for a serpentine robot, the region of highest maneuverability is just inside of its maximum reach. This maneuverability is actually a measure of the percentage of configuration space that maps to a given work space position. This knowledge can be used to pick better locations for the serpentine robot's base to be held so that it does not need to be moved as often.

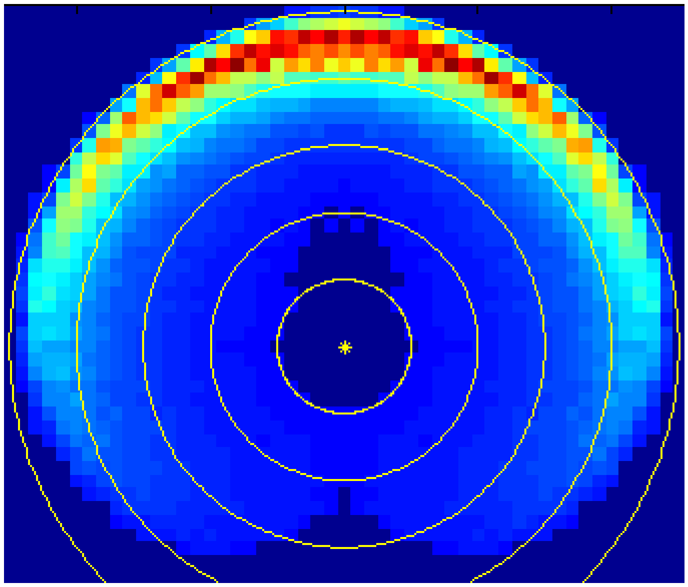

Figure 4: Workspace Density

INVESTIGATION

The research group developed a prototype joint for this project, and has developed plans for a second-generation prototype to expand upon the knowledge gained. The theory for planar probing was expanded and simulators were implemented. Finally a three dimensional simulator was created so that an operator can drive a serpentine robot through a virtual environment.

The prototype joint shown in Figure 4, was built as a proof of concept design but will soon be replaced by the second generation. This joint was built entirely with off-the-shelf components at a very low cost. Because we were optimizing for cost, the joint is much larger than the final product will be.

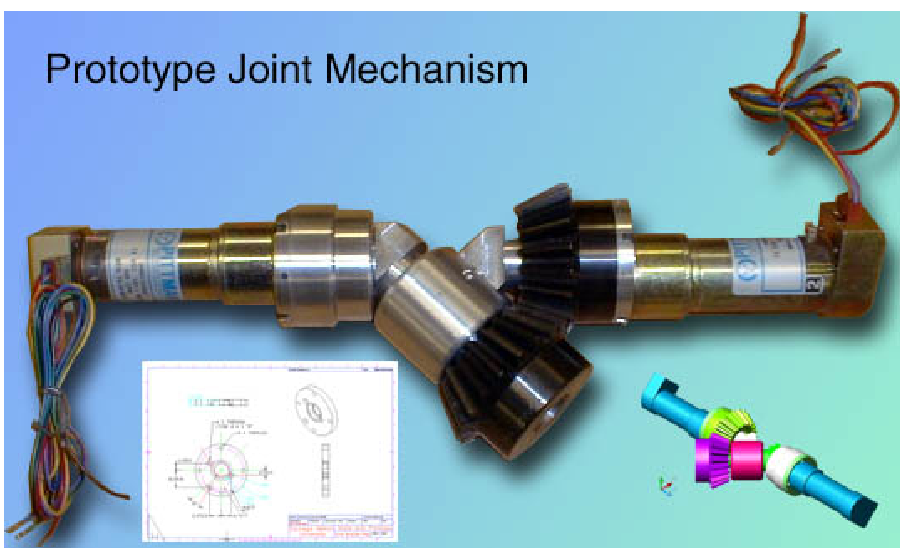

Figure 5: Prototype Joint Mechanism

The three-dimensional simulator is a very important part of the robot design because it serves as a testing ground for the human-computer interface. To achieve our first sub-goal of tele-operation, we are refining a simulator that allows the operator to use a joystick to control the serpentine robot. By moving a cursor inside the image from the

robot's camera the operator guides the motion of the head of the snake. The robot follows the cursor and calculates all of the joint trajectories automatically.

Even at this early stage of development, the simulator has taught us some very valuable things. Although simple, these items mean the difference between a usable and unusable interface. The first is the camera view from the serpentine robot. As the serpentine robot probes through an environment the camera goes through many orientations, at some points the camera is upside down, at other times it is rotated at other angles. This can be very disorienting for the user, even if the area being viewed is well known. Boroscope operators that inspect jet engines exemplify this. Even though they are very skilled and do these inspections frequently, they often get disoriented during the inspection because they lose all sense of direction. With a serpentine robot, the joint calculations can be done very quickly so that the up direction can be known and then the camera image can be digitally rotated so that the user always sees the world right side up. It is hard to impress how much this simple thing changes the interface for the better. Although no formal survey was done on this effect, we set our simulator in each of two modes of operation: rotated and unmodified. We then noted the ease of use in each mode. Those people using the rotated view were much better at driving the serpentine robot. Along with the rotated view the robot can display a coordinate frame on screen so that the current orientation can be better visualized.

The simulator also showed the need for a second camera for efficient operation. The serpentine robot mounted camera is good for close-up viewing, but a secondary camera that is placed at a distance from the operation gives another perspective that is useful for the high-level motion planning. Figure 5 shows the JPL serpentine robot doing a mock inspection. The photo shows how the second view that this picture represents adds nicely to the view of the camera mounted on the serpentine robot as viewed on the television.

Figure 5: Serpentine robot completing a model bridge inspection

PLANS FOR IMPLEMENTATION

We have identified a sequence of major milestones that will result in automated robotic bridge inspection. Our ultimate goal is to design and build a self-powered and self-locomoting serpentine robot that we can deploy anywhere on the bridge. Once deployed it will crawl along the bridge autonomously collecting inspection data. The state of the art in robotic computing, power, and actuator technology is not ready for this vision. We believe that a penultimate goal of a dual robot system: one part Snooper crane the other part serpentine robot, is worthy because it has practical implications for bridge inspection and addresses many issues geared towards our ultimate goal. In this dual robot system, the inspector can position the head of the snake robot via a joystick interface from a remote location, i.e. one that is not in a Snooper bucket or rigging specifically deployed under the bridge for the inspector. Cameras and other sensors at the tip of the serpentine robot can provide the inspector with all the data he needs. In fact, image-processing algorithms can run in concert with the inspector during the inspection process.

Putting this dual robot system together is a major challenge unto itself. Therefore we are going to focus as our antepenultimate goal of construction of a 12 degree of freedom serpentine robot and furthering our motion

planning of serpentine robots. Since we are also interested in paint deposition, we will also continue to develop coverage algorithms that guarantees a paint applicator passes over all points over the bridge. This piece of path planning technology can also be used in further automating the bridge inspection process.

Mechanism design will next create an actual snake using the multiple copies of the joint designed in this work. This will involve challenges in computer interface and wiring that were not present in the first prototype since there were only two degrees of freedom in the first prototype. Path planning will continue in automating the inverse kinematics problems so that the robot can develop its own joint trajectories in real time. Having this new snake robot will give us a test bed on which to implement our algorithms. Finally we will develop our human interface to allow bridge inspectors to give high-level commands to direct the inspection. Again, having the complete snake will allow us to move from the simulated robot to a real one.

CONCLUSIONS

Robotic automation will reduce the costs and time of bridge inspection, which is immediately apparent given that rigging and traffic control alone consumes 40%–50% of the inspection costs. This cost is a result of rigging and safety devices that are necessary to allow the inspector to see the entire bridge. We want the inspector to see the entire bridge, but not from a Snooper truck nor from complicated rigging. Instead, our goal is to have a robot provide these images, thereby removing the inspector from the rigging and snooper bucket and allowing him to inspect a bridge from the safety of the bridge roadbed.

Bridge inspection requires a special type of robot, one that has many redundancies. Redundancy means extra. Robot mechanisms that have redundant degrees of freedom have more flexibility. This added flexibility allows a robot arm to perform pick and place operations in multiple different ways. A factory designer may exploit redundancies in conventional robot arms to ensure safe operation of the robot and a tighter packing of work cells in the ‘relatively open’ factory environment. For example a robot arm can pick up an object in either elbow up or elbow down configurations. A hyper redundant mechanism, as its name suggests has many, many redundancies. It can exploit these extra degrees of freedom to thread through complicated structures and approach all points on a structure. This mechanism is particularly well suited to bridge inspection because a bridge offers an intricate structure to be inspected.

The many degrees of freedom that give serpentine robots their power also create their greatest challenge: how to design them and how to plan motions for them. We have provided the deliverables outlined in the proposed work: advances in three-dimensional motion planning for serpentine robots and a new prototype serpentine robot joint. These are just two small steps towards developing the ultimate dual mechanism bridge inspection device. The next step is to build a multi-degree of freedom serpentine robot using the joint constructed and designed under this grant. Such construction will offer new challenges in electric mechanical and computer design. We feel that a 12 degree of freedom prototype mechanism must be constructed before developing the dual mechanism system concept. We are now seeking funds to construct this mechanism.

Finally it is worth noting that bridge inspection is just the first step to bridge painting. Instead of passing a camera or other inspection device over all points of the bridge, we can use serpentine robots to pass a paint applicator over all points of the bridge. Currently the Principal Investigator, on another project is developing control strategies for auto body painting. In the United States, it takes three to five months to program a conventional non-redundant robot to paint a car body. The principle investigators work will automate this process so that it will take three to five days. We hope to integrate our car painting research with our serpentine robot bridge inspection work in the future.

INVESTIGATOR PROFILE

Dr. Howie Choset is an Assistant Professor in Mechanical Engineering and Robotics at Carnegie Mellon University, where he directs the Robotics Sensor Based Planning Lab. Professor Choset's research spans three categories (1) motion planning for serpentine robots (2) sensor based exploration and (3) coverage path planning.

While at Caltech, he did a significant portion of the hardware and software development for the Caltech Hyper-redundant Manipulator. More recently, the Naval EOD Technology Division contacted Professor Choset for his expertise in serpentine robots and how they apply to disarming bombs without disassembly of the bombs. Also, Dr. Choset was consulted by JPL scientists for their serpentine robot; currently, the JPL Serpentine robot is on loan in Professor Choset's lab at CMU. Recently, NSF awarded Dr. Choset its prestigious Career Award for basic work in sensor based motion planning, with a focus on serpentine robots. Recently, Professor Hirose, inventor the first serpentine robot, invited Professor Choset to deliver a talk at his MITI-organized workshop on “Super Mechano Systems,” which includes serpentine robots and configurable robots.

GLOSSARY

Coverage: The systematic process of passing a sensor over all points of an object or area.

Degrees of Freedom: The least number of variables required to define the state of an object or mechanism.

End-effector: On a conventional robot, this is where a tool would be placed. On a serpentine robot, this is the end of the bay furthest from the base.

Forward Kinematics Problem: Given the joint angle of a mechanism, how to find the position of the end-effector.

GVG: The acronym for a road map known as the Generalized Voronoi Graph. It represents the set of all points equidistant from the nearest n objects in n dimensional space.

Hyper-redundant Manipulator: A robot that has many more degrees of freedom than the minimal six required to position and orient an object in space.

Inverse Kinematics Problem: Given the position and orientation of an end-effector, how to find the joint angles that are required.

Kinematics: A field of study dealing with constrained motion.

USAR: Acronym for Urban Search and Rescue.