The KSI Tentacle Manipulator

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Abstract

Robotic tentacles provide an interesting alternative to conventional rigid-link robotic arms; in certain situations, they may even be more capable. Kinetic Sciences Inc. has developed a hybrid electric-pneumatic tentacular robot called the KSI Tentacle Manipulator. It has variable compliance, can bend independently in two or more regions, and can extend to more than five times its contracted length. In total, the Tentacle has six degrees of freedom—or seven with the addition of a distal wrist-rotate joint. The Tentacle's unusual kinematics and inherent compliance demand new approaches to control. Three schemes are considered here: joystick-based teleoperation, inverse kinematics-based tendon length control, and machine vision-based fine position control. Under control, the Tentacle has broad potential in many applications, including teleoperated vacuuming and spray washing (for nuclear hot cell decontamination), general materials handling, agricultural harvesting, robotic refueling, and endoscopy. The KSI Tentacle is protected by U.S. Patents 5,181,452 and 5,317,952.

1. Introduction

The conventional robotic manipulator essentially mimics the bone and muscle structure of the human arm: i.e., rigid links connected by actuated joints. Arms with pivoting joints are very successful, but they aren't the only class of manipulator found in nature. One particularly intriguing variation is the tentacle.

2. Natural Tentacles

From octopus legs and elephant trunks, to snail eye-stalks, prehensile monkey tails, and human tongues, tentacles are common in the natural world.

Although their physical size and composition vary significantly, tentacles share a set of functional properties that are fundamentally different from those of jointed arms. Table 1 provides a comparison.

Table 1: Tentacles vs. Jointed Arms

Tentacles	Jointed Arms
• Flexible over entire length	• Flexible at joints only
• Can usually retract or elongate	• Accomplish elongation and retraction by bending at joints
• Often prehensile (capable of a wrapping grasp)	• Crudely prehensile (need a hand)

These functional differences mean that for certain tasks, tentacles are better than arms. Specifically, tentacles could be better for:

1. Tasks which require extreme dexterity
2. Tasks where compliant contact of arm with environment is required (e.g., around people)
3. Tasks where a soft, prehensile grasp is required
4. Tasks where compact stowage is advantageous

3. Robotic Tentacles

Since natural tentacles are better suited to certain tasks than natural arms, it seems logical that robotic tentacles might be better at certain tasks than robotic arms. Not surprisingly, various tentacle-like robots have been proposed or built in the past. (For examples, see [1,2,3].) Kinetic Sciences Inc. has its own contribution to this group.

4. The KSI Tentacle Manipulator

Kinetic Sciences Inc. has developed an innovative tentacular robot [4], superficially resembling tentacles found in nature. See Figure 1.

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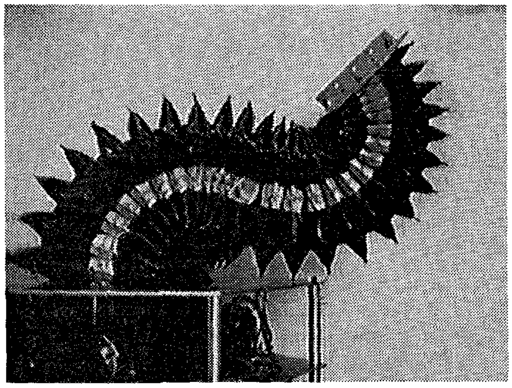

Figure 1: The KSI Tentacle Manipulator

The KSI Tentacle Manipulator is powered by a hybrid system of pneumatic bellows and electric motors. It can extend, contract, and bend independently in two (or more) regions along its length.

Contraction and bending of the manipulator is accomplished with tendons threading cable guides, providing a total of six degrees of freedom. Assuming a five-dimensional task space (three positions plust wrist pitch and yaw), the six tendon Tentacle is a redundant manipulator.

5. Tentacle Components

The Tentacle's main physical components are: a bladder, six tendons, and a motor deck housing six tendon servo winches. The gear motor servo winches are in the proximal base of the robot; no actuators are in the body of the arm. Optionally, a gripper and rotating wrist unit can be attached to the distal end of the manipulator. Separate from the Tentacle is a motor controller housing the electronics which run the Tentacle's servo winches. The Tentacle connects to the controller via an umbilical tether. The following sections consider these components in more detail.

5.1 Bladder

A patented pneumatic/hydraulic bellows actuator [5] forms the body of the KSI Tentacle. The shape of the bladder segments has been computer-optimized to exhibit negligible shear stress in the membrane, allowing the bladder to be manufactured from non-stretchable (i.e., non elastomeric), impermeable, flexible materials. The bladder's properties are manifested in the Tentacle's extension capabilities and overall stiffness.

5.2 Tendons

The six tendons control the Tentacle's shape and extension. They are made of flexible, 1/16" diameter stainless steel control cable. Each tendon originates inside a servo winch housed in the motor deck. It then threads along the length of the bladder through brass or nylon cable guides which are attached to the side of the bladder. The tendon finally terminates in a ferrule either halfway or all-the-way along the bladder, depending upon whether the tendon's influence is on the proximal or distal portion of the bladder.

5.3 Motor Deck

The motor deck is in the proximal base of the manipulator. The motor deck's primary function is to contain the Tentacle's servo winches and wiring. Packaging the electrical and mechanical components inside a protective box makes the Tentacle as a whole fairly robust, since bladder, tendons, and motor deck exterior are the only parts exposed to the environment.

5.4 Servo Winches

The servo winches (a KSI proprietary design) reel the Tentacle's tendons in and out in controlled fashion. The winches are completely self-tending; i.e., they manage the cable wrapped on the winch drum without the possibility of fouling—even if there is no tension on the wire.

Each servo winch is an integrated unit comprising DC gear motor, proprietary winch mechanism, and ten-turn potentiometer. The potentiometer is calibrated to provide feedback of the actual length of cable spewed out the winch (i.e., the tendon length). As an added sensor option, each winch can be equipped with a load cell to measure the tendon's tension.

5.5 Wrist/Gripper Unit

The basic Tentacle lacks the ability to rotate. KSI is currently designing a wrist/gripper unit to fit on the Tentacle's distal end. This unit will provide a seventh degree of freedom (i.e., wrist rotation), and give the Tentacle the ability to hold objects, manipulate tools, etc. The wrist/gripper unit will be tendon-driven via Bowden cables to keep the weight of its actuators from negatively impacting the robot's payload capacity. The actuators will be housed in the motor deck. The Bowden cables will wrap in a loose spiral around the Tentacle's body, free from any danger of binding or entanglement.

5.6 Motor Controller

The Tentacle's motor controller contains the circuit boards which control the servo winch motors. These boards (also a KSI custom design) accept position commands (e.g., from a joystick or directly from a D/A converter) and servo the motors to make the signals from the feedback pots match the commanded position. The motor controller connects to the Tentacle via an umbilical cable.

6. Tentacle Characteristics

The KSI Tentacle has a unique set of characteristics, including impressive extensibility/ retractability, multiple bending regions, and controllable compliance. The Tentacle can raise a 20 lb load vertically at a speed better than 2 in/sec, and maneuver a 10 lb load anywhere in its workspace. Table 2 specifies the Tentacle's horizontal lifting ability at different extensions. In a prehensile grasp, the Tentacle's ribbed vinyl pneumatic bellows surface can hold an object as small as 3.5 inches in diameter.

6.1 Extensibility/Retractability

The KSI Tentacle can extend more than five times its contracted length. By comparison, the elephant trunk or octopus leg has only 10 to 15 percent extension capability.

6.2 Multiple Bending Regions

The KSI Tentacle is capable of two (or more) independent regions of bending, each of which can curve more than 90 degrees in any direction. Each bending region is controlled by the combined absolute and differential lengths of three tendons (six tendons total). Figure 2 illustrates some of the unusual configurations a two-stage Tentacle can achieve.

Theoretically, a Tentacle can comprise any number of bending stages; however, practical considerations along the lines of cable interference and friction have not been fully characterized. All the same, we feel that three or four stage Tentacles are fully realizable.

6.3 Compliance Control

A pneumatic structure, the Tentacle's body is inherently compliant. This compliance provides some protection against collisions: both for the robot and for objects in the robot's environment. The Tentacle's compliance is determined by the pressure difference across the bladder: the higher the internal pressure, the stiffer the robot. Thus, the Tentacle's compliance can be controlled by modulating the air pressure in the bladder. Currently, we manually set the operating pressure on a pressure regulator; active compliance control remains a subject for future investigation.

Table 2: Tentacle Horizontal Lifting Abilities

Horiz. Length Extension (in)	Payload (lbs)
8	30
20	20
40	10

7. Tentacle Kinematics

The Tentacle's kinematics are complex. Even without a wrist rotate joint, the Tentacle's distal end can hold a fixed position and orientation in space, while the rest of the Tentacle's body assumes many different spatial configurations.

The Tentacle's unusual nature (continuous morphology, kinematic redundancy, and ability to extend/retract) requires non-traditional approaches to kinematics and inverse kinematics [6,7,8]. For control purposes, the inverse kinematics issue is particularly important. Here the fundamental question is this: to achieve a given position and orientation of the end effector, how long should each of the tendons be?

We are currently investigating an inverse kinematics technique based on cascaded spline arcs. The idea is as follows: given a desired end-effector position and direction, define a spline composed of two arcs. The first arc starts at the Tentacle base and ends at a knot somewhere in space. The second arc starts at this knot and ends at the desired end-effector position and direction.

Because the end of the second spline defines an end-effector position and direction (which requires only five degrees of freedom), and because the Tentacle has six degrees of freedom, there will in most instances be an infinite number of knot positions which will give the same end effector position and orientation. We propose to define a unique knot position using a redundancy variable. This redundancy variable can be specified in order to avoid collisions, to maximize the Tentacle's dexterity, or to meet physical limitations (e.g., cable tension minimization).

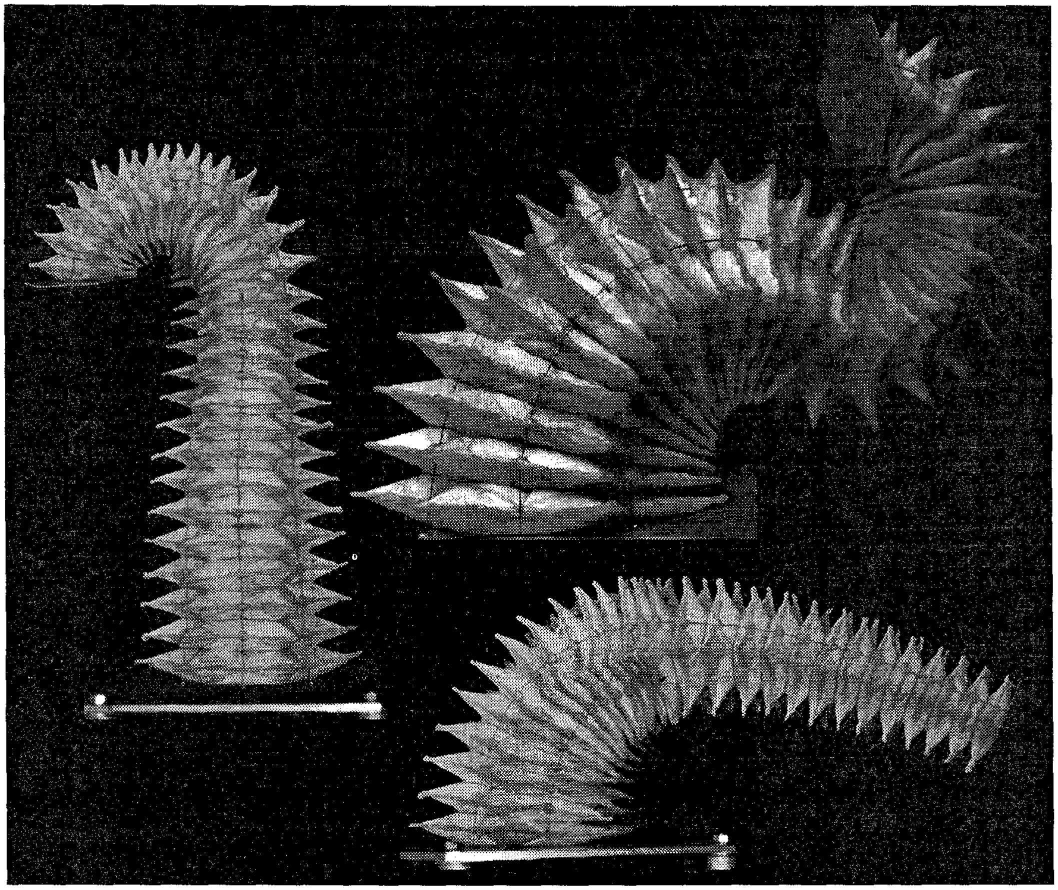

Figure 2: Representative Tentacle Configurations

Once the spline's configuration is totally determined, the six tendon lengths can be calculated. This mapping will be defined using functional approximation based on experimentally derived examples of observed splines as a function of tendon lengths.

The cascaded spline arcs approach looks promising, but, like other inverse kinematics-calculating techniques, it ignores load effects. A testament of the Tentacle's inherent compliance, for a given set of tendon lengths, loads applied to the end of the Tentacle will cause changes in position and orientation. This fact compromises precise control of the robot.

8. Tentacle Control

There are several ways the Tentacle can be controlled, including joystick-based teleoperation, inverse kinematics-based tendon length control, and machine vision-based fine position control.

8.1 Joystick-Based Teleoperation

Teleoperated control of the Tentacle is accomplished by an operator handling two identical joysticks (one each for the Tentacle's proximal and distal regions) while the operator watches the Tentacle move. The operator guides the Tentacle's position and orientation, compensating for load effects. A block diagram for this control scheme appears in Figure 3.

The joysticks are designed to provide approximate spatial correspondence to the Tentacle, thereby solving the inverse kinematics problem geometrically. Each joystick generates three signals: one for each tendon in its half of the Tentacle (i.e., proximal or distal).

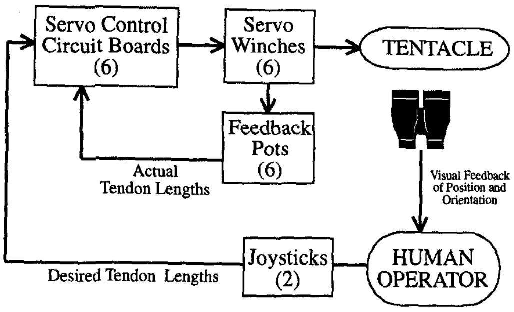

Figure 3: Joystick-Based Teleoperated Control Block Diagram

Figure 4 shows an example of a Tentacle joystick. The joystick independently tilts (to direct orientation) and slides up and down (to direct extension).

Spatial correspondence between joystick and Tentacle means that as the joystick moves, the tendon lengths adjust more-or-less correctly relative to each other.

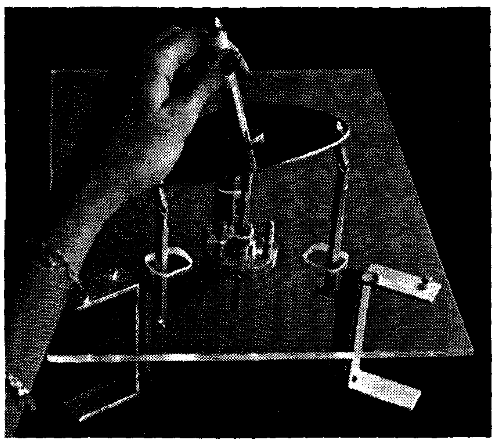

Figure 4: Spatially Corresponding Joystick

8.2 Inverse Kinematics-Based Tendon Length Control

An inverse kinematics-based tendon length control scheme is shown in Figure 5. Note that a human operator is optional, as operation can be directed by the computer.

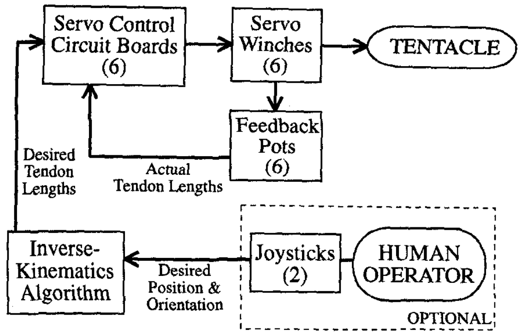

Figure 5: Inverse Kinematics-Based Tendon Length Control Block Diagram

End effector loads on the manipulator will still cause deviations from the expected position and orientation, however, due to the compliance of the bladder. Because feedback is of tendon lengths only and not of end effector position/orientation (what we ultimately want to control), this scheme can only position the manipulator approximately when the manipulator is supporting unknown loads.

8.3 Machine Vision-Based Fine Position Control

In order to position the Tentacle accurately, independent of load, a real-time means of measuring the Tentacle's position and attitude and conveying this information to the controlling computer is required. The KSI Eagle Eye Vision System provides the means.

"Eagle Eye" is a machine vision system that tracks special optical markers, calculating their position and orientation (and identity) relative to a video camera at a rate of several frames a second. Thus, an Eagle Eye marker on the Tentacle and a suitably-aimed video camera is all that is required to effect fine position control. Alternatively, for docking operations, a camera can be mounted on the Tentacle's wrist, and an Eagle Eye marker on the object to be grasped.

With inverse kinematics and direct control of tendon lengths, we can position the end of the robot crudely, and then use feedback provided by Eagle Eye to iteratively adjust the tendon lengths until the Tentacle is exactly where it should be. A block diagram for this control scheme appears in Figure 6.

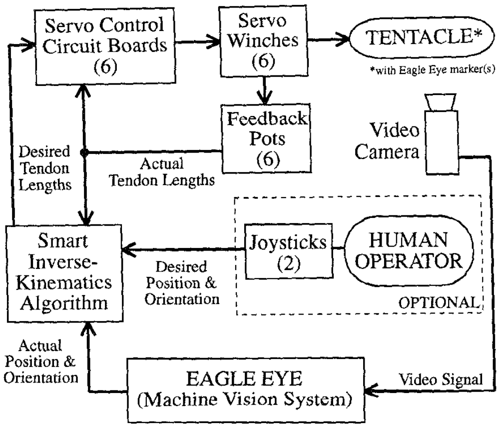

Figure 6: Machine Vision-Based Fine Position Control Block Diagram

9. Tentacle Applications

The Tentacle has broad potential in many applications. KSI has recently sold a Tentacle to Battelle Pacific Northwest Labs at the DOE Hanford site in Washington State. The application is nuclear decontamination of a hot cell by vacuuming radioactive detritus from the floor. (See Figure 7.) The Tentacle may also find application there in spray washing.

Other possibilities include general materials handling, agricultural harvesting, and robotic refueling; we are currently proposing to scale the Tentacle down for application in endoscopy. The possibilities are limited only by the imagination.

10. Tentacle Advantages

The advantages of the KSI Tentacle are as follows:

1. Lightweight (high power-to-weight ratio)
2. Little precision machining required
3. Low cost
4. Variable compliance
5. Extreme dexterity

11. Conclusions

The KSI Tentacle Manipulator provides a practical alternative to conventional rigid-link robotic arms; and may actually have broader applicability. Though the Tentacle's kinematics are unusual, various control schemes are viable, from simple teleoperation to sophisticated position and attitude control via the KSI Eagle Eye Vision System.

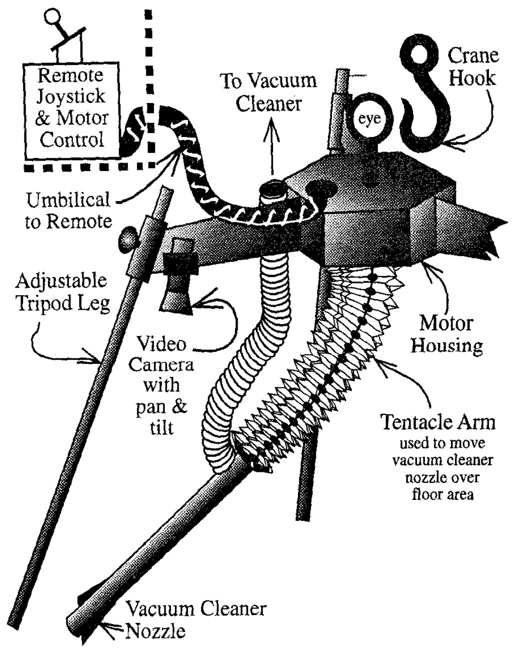

Figure 7: Tentacle Vacuuming Application

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