Robotic Manipulators Inspired by Cephalopod Limbs*

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ABSTRACT

This paper connects the investigation of the biomechanics and behavior of an octopus in the performance of a wide range of dexterous manipulations to the creation of octopus arm-like robots. This is achieved via the development of a series of octopus arm models which aid in both explaining the underlying octopus biomechanics and in developing specifications for the design of robotic manipulators. Robotic manipulators which match the key features of these models are then introduced, followed by an overview of the development of inverse kinematics for the circular (constant) curvature model.

Index Terms — Biological Inspiration, Robotics, Robot Manipulator Design, Inverse Kinematics

1. Introduction

Tongues, trunks, and tentacles demonstrate an amazing variety of abilities by which animals dexterously manipulate and interact with their environment. For instance, giraffes wrap their tongues around high tree branches to strip off leaves. They can also use their tongue to delicately pick leaves while avoiding the spiny thorns of acacia tree branches. Elephant trunks are amazing appendages that are strong enough to knock over trees, yet agile enough to pick straw off the ground. Squid have ten arms, two of which are tentacles. Tentacles are specialized arms used specifically for quick-strike prey capture. The other arms on the squid, which are similar to octopus arms, allow the creature to perform more general prey/object manipulation and locomotion.

These biological manipulators serve as a source of inspiration for the design and application of robotic manipulators [1]. For instance, a search-and-rescue robot equipped with "octopus arms" could efficiently navigate a rubble pile, search for victims in crevices and analyze structural integrity in a collapsed building. The variable stiffness observed in elephant trunks would allow a similar robot to grasp and handle payloads of varying dimensions and fragility (e.g. rocks and humans). Manipulators designed with redundant degrees of freedom have the capability to navigate around obstacles while performing end-effector tasks as deftly as the giraffe tongue avoids thorns while picking the leaves.

However, it is no small task to create robotic manipulators that replicate the abilities of biological manipulators. Thus far, researchers have designed and built a number of robots that try to duplicate the behavior exhibited by tongues ([2]), trunks ([3], [4], [5], [6], [7]), and tentacles ([8], [9], [10], [11]) to varying degrees of success.

It is important to note that it is rarely practical to build robotic devices with "biological designs." In most cases, present technology does not possess the materials and actuators to allow for it. Biological systems are composed of biological components, which are quite different from the components available for robotics systems. Additionally, evolution (the biological design process) is less concerned with optimal performance than with merely competing successfully within an economic niche. Evolution also has the constraint of being limited to the modification of existing systems, which has the possibility of creating innovative, but sub-optimal designs ([12], [13, p. 20-38]).

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Instead, the value of biology to engineering (and engineering to biologists) lies in creative inspiration and the practice of system modeling. For instance, a musculature model provides biological insight into the operation of an arm by showing the complex relationship between muscle forces and the resulting deformation and movement of the arm. The insight from this complex relationship can also provide information as to control strategies, actuator arrangement, and design of robotic manipulators. A number of models that allow kinematic or dynamic analysis of tongue, trunk, and tentacle-like robots have been proposed. These include [14], [15], [4], [16], and [17].

Through the use of models, this paper discusses biological investigations into the structure and behavior of octopus arms and relates these investigations to the design of robotic manipulators that possess properties similar to octopus arms. This work is being conducted as part of the multidisciplinary and multi-institutional *Soft Robot Manipulators and Manipulation* project funded under the DARPA BIODYNOTICS Program.

Section 2 provides an overview of the fundamental biological research that is taking place. This research includes investigations led by Dr. William Kier at University of North Carolina, Chapel Hill, NC on the morphology and biomechanics of octopus arms, and investigations led by Dr. Roger Hanlon at the Marine Biological Laboratory, Woods Hole, MA on octopus behavior.

The project also features basic biological research led by Dr. Binyamin Hochner at the Hebrew University of Jerusalem, Israel on the neural control of octopus, and consequent modeling efforts being performed at the Weizmann Institute, Israel led by Dr. Tamar Flash, and at Brooklyn College, NY led by Dr. Frank Grasso. Section 3 summarizes these models, which are based upon observations obtained from the biological investigations.

A key goal for the project is to use insights from the biological investigations to design and apply biologically inspired soft tentacle robots. The main design efforts are led by Pennsylvania State University under Dr. Christopher Rahn and Dr. Qiming Zhang. Section 3 also summarizes some designs for implementing key aspects of the biology-based models in robot hardware.

Given a finished manipulator, efficient control algorithms coupled with intuitive human-operator interfaces are required for effective deployment. This aspect of the project is led by Dr. Ian Walker, Dr. Darren Dawson, and Dr. Christopher Pagano at Clemson University, SC. Sections 4 and 5 focus on one design model in particular and present novel inverse kinematics which enables the design and construction of a tendon-driven, variable stiffness robotic manipulator/testbed.

2. Octopus Arm Biology

The amazing range of abilities octopus arms demonstrate result from their unique musculature, which allows them to function without a distinct skeletal support system. Behavioral studies of these creatures reveal the unique way in which they utilize their musculature to perform a wide variety of tasks.

A. Octopus Arm Morphology (Muscular Hydrostats)

Biological skeletal support systems generally fall into two categories. The first category features skeletal systems composed of hardened elements such as the bones of vertebrate animals or the exoskeleton of arthropods. The elements in a traditional hard skeleton provide attachment points for muscle and constrain muscle motion to a desired direction. These skeletal supports also provide lever and pivot points that amplify the resultant force, speed, or displacement of muscle activity.

The second category features hydrostatic skeletons. This kind of skeletal system can be found in polyps and vermiform animals (e.g. sea anemone, earthworm). Hydrostatic skeletons rely on flexible fluid-filled cavities that are constrained by connective tissue to conform to a given shape, typically cylindrical. These skeletons utilize the constant volume principle to produce movement. When the radial muscles situated around the cavity contract, they reduce the diameter of the cavity which forces the cavity to elongate to maintain constant volume. Similarly when the longitudinal muscles contract, they reduce the length of the cavity which causes the cavity to increase in diameter.

In most cases, these skeletal support systems are the means by which forces produced by muscle contraction are transmitted to produce movement. However, there are a number of biological structures that are almost entirely composed of muscle that operate without distinct skeletal support. Tongues, elephant trunks, and octopus arms are examples of such structures, dubbed muscular hydrostats in [18]. The arrangement of the musculature in these structures tends to be densely packed with fibers oriented in three general directions: (1) perpendicular to the long axis, (2) parallel to the long axis, and (3) oblique around the long axis [18].

For the octopus arm, the perpendicular muscle fibers are packed in a transverse arrangement, alternating horizontally and vertically. The parallel muscle fibers are set in longitudinal bunches around the center of the arm. These bunches are grouped antagonistically along the top and bottom of the arm and the left and right side of the arm. Additionally, the oblique muscles are arranged in antagonistic bunches (right-handed and left-handed helixes) along the periphery of the arm.

Muscular hydrostats, like traditional hydrostats, rely on the constant-volume principle to produce motion. However, unlike traditional hydrostats, there is no distinct fluid-filled cavity in muscular hydrostats. Instead, the hydrostatic fluid is contained within the muscle cells, which means that muscular hydrostats could in effect be modeled as hyper-redundant traditional hydrostats. More chambers of hydrostatic fluid gives muscular hydrostats appreciably more localized movement control than traditional hydrostats have.

Unilateral elongation can be performed by contracting the transverse muscles while relaxing the longitudinal muscles. This muscle actuation configuration reduces the cross-sectional area of the arm causing a corresponding increase in length. The alternating horizontal and vertical arrangement of the transverse muscles adds a degree of control, allowing the arm to flatten itself in a particular direction. Unilateral shortening can similarly be performed by contracting the longitudinal muscles while relaxing the transverse muscles. This muscle actuation configuration reduces the length of the arm causing the cross-sectional area to increase in response.

More complex arm bending and stiffening actions can be produced by combining activity of the transverse and longitudinal muscles. One way that the arm can be bent is by contracting the longitudinal muscles on one side of the arm while also contracting the transverse muscle. Contracting the transverse muscles causes the arm to resist the increase in diameter (and corresponding decrease in length) that contraction of the longitudinal muscles would otherwise cause. This resistance provides the structural stability required for bending. The degree and strength of the bend can be modulated by the level of contraction of both the transverse and the longitudinal muscles. Stiffness without motion can be accomplished by contracting the transverse and the longitudinal muscles so that the forces they exert on the shape of the arm balance out. Thus, while the arm is in a static configuration, the tension in the muscles will make the arm stiffer and more resistant to external forces.

The oblique muscles can be used to twist the arm along its long axis. The direction of this torsion depends on how the oblique muscle is helically arranged. Contraction of the muscle that is arranged as a right-handed helix causes counter-clockwise torsion in the arm; whereas, the opposite is true for contraction of the left-handed helix muscle. These oblique muscles may also play a part in elongation and stiffening of the arm.

Localized motion is the result of localized control of the muscles in the octopus arm. Varying the pattern and coordination of the muscular activity in the arm allow the specific direction, degree, strength, and point of bend to be freely modified. Additionally, localized extension/retraction, torsion, and stiffening allow the octopus to produce an impressive array of motions and behaviors with its arm. In this way, the muscular-hydrostat system is more flexible and adaptable than most other musculoskeletal systems.

Performing such complex local muscle control requires considerable neural capacity. The nervous system of an octopus is quite diffuse, with most of its neurons being found outside of the brain. More than twice as many nerve cells are found in the arm nerve cords than in the brain, which suggests that much of the control processing for octopus arms is distributed and lies within the arms [19, p. 246-7].

Feedback for control must be guided by a sensory system. In octopus arms, much of the tactile sensory system lies in the suckers. Further analysis of the morphology of the suckers on octopus arms (and synthesis of artificial suckers) is currently underway at Brooklyn College[1].

To demonstrate that high-level behaviors are made possible by this unique muscular structure, models based on the musculature of the octopus have been formulated to artificially simulate these behaviors. These models can also be used to aid in the design of a robotic manipulator with similar properties. More information about the morphology of cephalopod limbs can be found in [18, 19].

B. Octopus Arm Behavior

Octopi demonstrate an impressive variety of behaviors using their arms. The arms can perform a variety of reaches, pulls, sweeps, arm tip wraps, rotational twists and grasps. These basic behaviors can be combined to perform more complex behaviors, such as locomotion and feeding. While octopi often use their mantle cavity to propel themselves through the water,

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[1] More information on this research can be found at http://academic.brooklyn.cuny.edu/userhome/psych/fgrasso/.

they will also use their arms to "walk." The octopus performs a walking motion by reaching its arms out, grasping points in the direction of motion, and pulling itself toward those points. Grasping is accomplished either by adhering with its suckers to a surface, wrapping its arm around a stable object, or a combination of these two actions.

Octopi have several feeding behaviors. For example, to capture a shrimp, the octopus dynamically reaches its arms out with a rolling action toward the shrimp. Then, the portions of the arms that come into contact with the shrimp immediately wrap tightly around the shrimp to ensure a stable grasp. An "elbow" or bending point is formed along the arm about halfway between the location of the shrimp on the arm and the location of the octopus mouth, enabling the octopus to easily put the shrimp in its mouth [20]. The flexibility of choosing a bending point anywhere along the arm is an ability unique to muscular hydrostats. Such an ability, if duplicated, would create a highly adaptable robotic manipulator. Some initial investigations into continuous backbone robots with variable bending locations are given in [21].

Observations of octopus arm behavior suggest that the suckers are very important in octopus task performance. The suckers provide not only adhesion, but also contain a wide variety of tactile and chemosensory receptors. The suckers are also remarkably dexterous and under some conditions can even be used to independently locomote the octopus. An object can also be moved along the octopus arm by being passed from sucker to sucker. This knowledge of octopus behavior leads towards consideration of a manipulator designed with a single preferred grasping side.

As discussed in the previous section, the arms contain significant neural mass. This enables them to perform reflex actions, such as bringing food to the creature's mouth without any input from the brain. Also, much of the proprioception (self-sensing) system required for manipulation seem to be within the neural system in the arms, and not relayed back to the brain [20]. For instance, octopus seem unable to perceive weight differentiation among objects they manipulate [19, p. 233-237]. When they are given cylinders of differing weight, the arm obviously compensates for heavier cylinders with increased muscle tension, however researchers are unable to train them to choose a heavy cylinder over a light cylinder or vice versa.

These observations suggest the presence of a distributed control system in the form of low-level motor programs which reside in the arms neural mass. Presumably the brain of the octopus need only send (relatively) higher level signals to the arm, and the neural system within the arm breaks it down into lower level actions. This relationship between the octopus arm and brain provides is similar to the relationship between an octopus-arm robotic manipulator and a human operator.

3. Octopus Arm Modeling

Forming a model of how the octopus' arms convert muscle contractions to useful behavior provides the following useful insights. First, it helps validate the theory of how muscular hydrostats are capable of movement without a distinct skeletal support structure. Second, it provides further insight into how the animal's neural control systems utilizes the musculature to perform actions. Third, a model connects biology to engineering, allowing the development of a robotic manipulator which observes key aspects of the biological model.

Due to the complexity of the octopus arm, a number of simplified modeling approaches have been proposed which together provide a series of tradeoffs between accuracy and complexity. Complex, fully soft models attempt to describe the action of each muscle fiber as it interacts with others in an arm. The cylindrical extension model assumes an arm can be divided into a series cylinders varying in radius connected end to end. This model clearly illustrates the mechanical principles behind the operation of a muscular hydrostatic skeleton. Models based on a flexible backbone provide octopus arm dynamics, like soft models, but assume an extensionless system to simplify the model's complexity. Finally, circular curvature models provide a simple description of an octopus arm while making somewhat restrictive assumptions about the arm's shape.

Each proposed model provides insight into the biomechanics of the octopus' arm and suggests an accompanying implementation for a robotic manipulator. The following paragraphs examine some of the proposed models.

A. Soft model

One method for modeling muscular hydrostats is to model the arm as a collection of constant-volume cylinders. Each cylinder can exert force radially, changing its diameter, or axially, changing its length, in much the same way the transverse and longitudinal muscles in an octopus arm act. The forces generated by each cylinder can be derived from measurements of the muscle properties of squid [22]. These cylinders are grouped and surrounded by a "skin" of connective tissue to form an arm.

A second approach is to model the arm as a set of cubes connected end to end, each of which can be bent in two directions, again modeling the longitudinal and transverse muscles in an octopus arm. Simulations with this model reveal that a simple sequential contraction of transverse muscles in a bent arm produces the characteristic arm roll that octopus often use when reaching [20].

However, the complexity of these models introduces two challenges. First is the ability to regulate the position of the arm to a desired position. Second is the difficulty in developing a mechanical system composed entirely of soft, constant-volume actuators. Neither of these challenges have as of yet been solved.

B. Cylindrical model

An alternative is to model the arm as a series of constant-volume cylinders joined end-to-end [22]. This model provides insight into how muscular hydrostats convert small displacement, high force muscle tissue contractions into high displacement, low force arm movements. This forward dynamics model, using constants obtained from measurements of squid musculature, accurately predicts the motion of a squid's tentacle during a prey strike. While this model provides excellent insight into the behavior of the muscular hydrostat, it essentially describes a single prismatic joint in robotic terms. Therefore, it does not describe the full function of a useful robot.

C. Flexible backbone

Another approach is to model the arm as a constant-stiffness rod, which bends due to discrete or continuous forces applied to it. With sufficient simplifying assumptions, a dynamic model can be developed [23]. One of the most limiting of these simplifying assumptions, with respect to octopus arm behavior, is the assumption that the constant-stiffness rod is incapable of extension, retraction, or torsion. Another limit of this

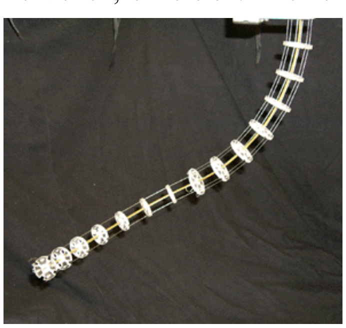


Figure 1: Tentacle Manipulator

Figure 2: Elephant Trunk manipulator

model is that the dynamic equations have only been solved for the two-dimensional case; extension to three-dimensions has proven to be extremely challenging.

This model provides a reasonable, if limited, model for an octopus arm and also a model for constructing a robot based on a flexible rod. The Tentacle Manipulator (shown in Figure 1) was constructed and controlled at Clemson University following this model [23]. The core of the manipulator is a thin continuous elastic rod, while pairs of remotely actuated tendon-cables simulate muscle. Unfortunately, the restriction of the model to two dimensions limits its practical application.

D. Circular assumption

The model that currently has the most practical application is based on the assumptions that the arm bends in constant curvature sections without torsion. Using these assumptions, the system can be simply modeled as series of revolute and prismatic joints, which allows the forward kinematics to be defined using the traditional Denavit-Hartenberg technique [4], [27]. This is advantageous because it facilitates the use of traditional robot control algorithms.

The novel Elephant Trunk robotic manipulator (shown in Figure 2) at Clemson University was controlled based on this model. The trunk is comprised of 32 degrees of freedom in 16 small links. There are four sections with two controllable degrees of freedom each. The sections are actuated with two pairs of antagonistically arrayed cable-tendons. The kinematics for the trunk are derived in [4].

Recently, the novel continuum robot Air-Octor (shown in Figure 4) was also designed based on this model. This design is novel in that it provides a combination of pneumatic and tendon actuation for controlled bending and extension as well as a double skin concept which provides a smooth continuum exterior for environmental interaction. The tendon configuration in this manipulator has also been modified so that there are three cables per section, rather than four as in the Elephant Trunk. To control this manipulator the kinematics had to be extended to handle extension and retraction and adapted to deal with a three tendon configuration [24], [25], [27]. The hardware realization and the kinematic derivation are discussed in more detail in the following sections.

4. Air-Octor Physical Description

The prominent design feature of the Air-Octor manipulator is a pneumatically pressurized central chamber sealed by aluminum end caps. This pressurized chamber acts as a continuously deformable backbone that provides the structural rigidity necessary to make the manipulator useful. Essentially, this central chamber is analogous to the transverse muscles in the octopus arm. One of the advantages of this design is that it frees up a large amount of space in the center of the manipulator that would otherwise be made up of a solid backbone structure. The space within the central chamber provides room for the routing of wires or hoses that may be needed to accommodate sensors or payloads.

An outer tube is fitted over the central chamber to provide protection for the central hose and a smooth durable surface with which to perform whole-arm manipulation. Protection is needed as holes or tears in the central hose would destroy its effectiveness as a flexible backbone. Cable guides are attached to the interior of the outer tube to route three individual tendon cables straight along the length of the manipulator. The cables are then anchored to the aluminum end cap at the end of each manipulator section. These cables are analogous to the longitudinal muscles in the octopus arm.

The primary motion of the manipulator is controlled by a tendon (cable) servo system. Standard DC motors actuate the tendons via a spooling system. The three tendons are arranged antagonistically about the manipulator section in a 120-degree configuration as shown in Figure 3. This antagonistic arrangement is necessary because the cables can only exert a pulling and not a pushing force. A pulling force on one of the cables causes the manipulator section to bend in the direction of the pulling cable. The combination of the three cables allows the manipulator section to be bent in any direction. The cable configuration used gives the manipulator section two degrees of freedom in bending.

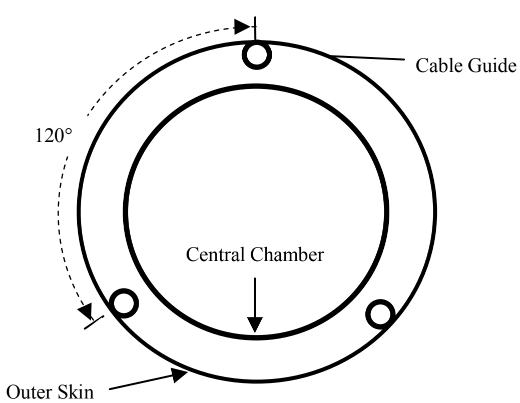


Figure 3: Cross-sectional schematic of the skin and tendon configuration.

Figure 4. The two-section Air-Octor.

The "soft construction" of the manipulator provides a third degree of freedom. Through appropriate actuation of the three tendon-cable motors, the manipulator can be made to retract and extend. The total length of the manipulator when fully retracted is approximately 10 cm, which gives the manipulator a 5:1 retraction ratio. This extension/retraction motion is improved with the addition of an electro-pneumatic servo pressure regulator to the system. The addition of the servo pressure valve allows for control of the overall compliance of the manipulator by varying the pressure of the central chamber. This is analogous to stiffness modulation via muscle contraction in the octopus. Further detail can be found in [26].

5. Air-Octor Kinematics

Two aspects relating to the kinematics are discussed in this paper. First, a model is developed which relates

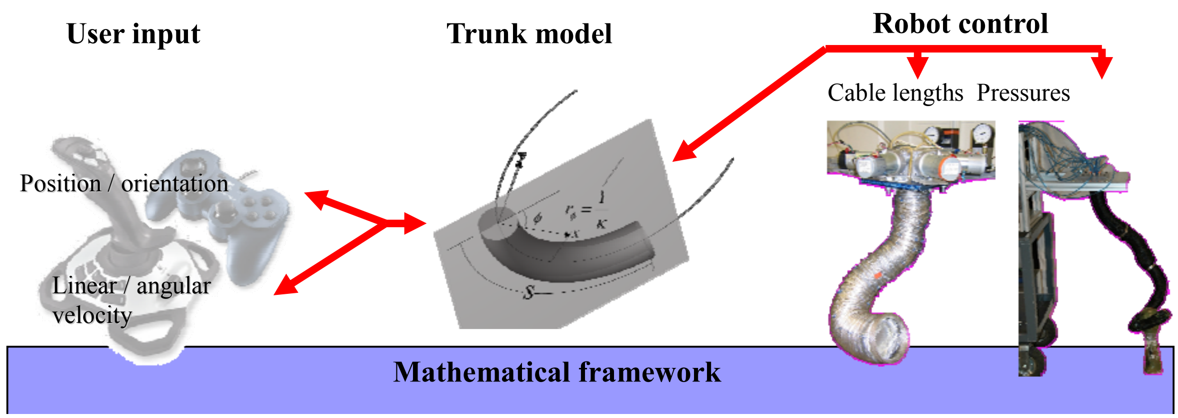


Figure 5. Controlling robot shape based on user input using a model

actuator values, such as cable lengths or pneumatic pressures, to the position of the trunk's tip. Second, manipulator-specific physical limitations, in particular material length limits, are modeled and discussed. The following two sections discuss each of these two topics in turn.

A. Kinematic model

Kinematic development of the trunk proceeds in three steps, as illustrated in Figure 5, and extends earlier work [4] by correctly modeling trunk orientation and by allowing trunk extension. First, this paper introduces a simple model of a continuum robot, namely an arc of a circle, defined by three parameters. Second, this paper presents a two-step process of modeling the trunk using classical D-H methods followed by geometrical transformations relating D-H parameters to trunk parameters. Finally, a modular mapping between trunk parameters and actuator values, such as cable lengths or pneumatic pressures, is illustrated by equations which map to three different types of trunks.

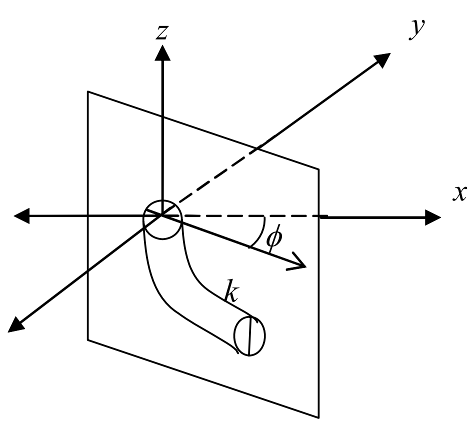


Figure 6: Manipulator variables ϕ and k. The variable ϕ gives the rotation in the xy plane.

The model used for the trunk, as discussed in the previous paragraph, is quite simple. A continuum robot, also termed a trunk, is divided into sections based on the actuator arrangement of the trunk. For example, a two-section trunk, such as Air-Octor pictured in Figure 4, contains three cables which actuate the bottom half of the robot and three more which actuate its top half, resulting in a two-section design. Each trunk section is then modeled as an arc of a circle as illustrated by the three-section trunk shown in Figure 7. This modeling assumption, upon which this kinematic analysis is based, is derived from a mechanical analysis which demonstrates that continuum structures bend in constant-curvature arcs due to the equal distribution of forces produced by the materials which compose the robot [23]. For example, pneumatic pressure in Air-Octor and OctArm or spring tension in the Elephant Trunk causes these robots to bend in constant-curvature (fixed-radius) arcs. The arc is defined by its arc length s, curvature κ, and angle of curvature ϕ as illustrated by Figure 6.

This trunk model can then be used to relate trunk parameters s, κ, and ϕ to trunk tip position $\underline{x}$ via a two-step process. First, a "backbone" composed of traditional rigid-link prismatic and revolute joints models the shape of the trunk in terms of rotations θ_i and trans-

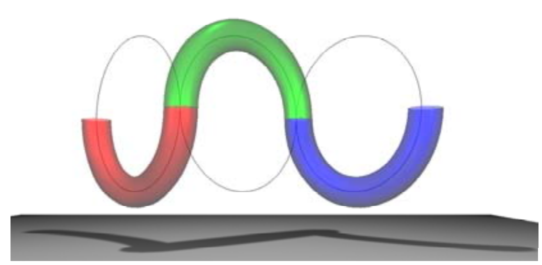
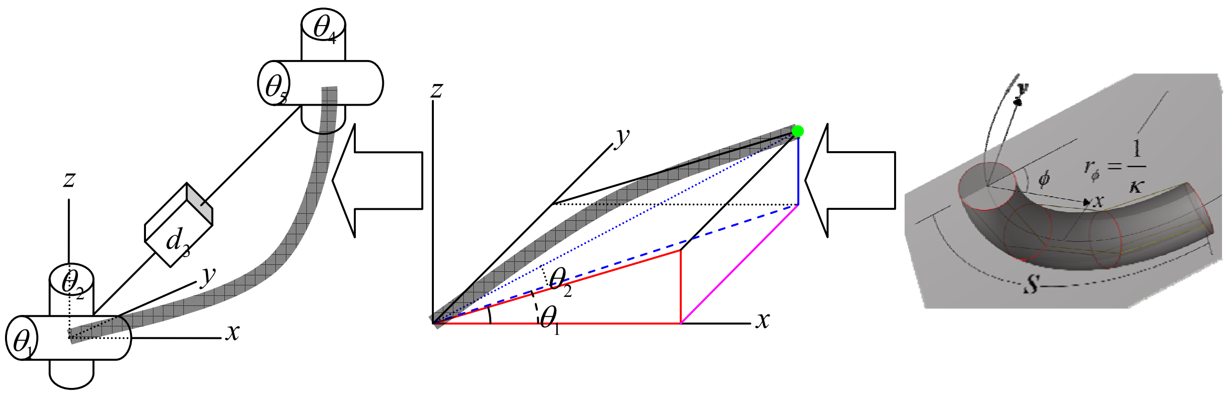


Figure 7. A three-section trunk, modeled by arcs of three circles.



(a) (b) (c)

Figure 8. Algorithmic flow, consisting of (a) a D-H table modeling trunk as prismatic and revolute joints, (b) geometric transformations between D-H table and trunk parameters, and (c) a modular mapping to trunk actuators, such as cable lengths or pneumatic pressures.

lations d_i. Specifically, as illustrated in Figure 8(a), two rotations of θ_1 and θ_2 orient the local coordinate frame to point to the tip of the trunk. Next, a translation of d_3 moves the local coordinate frame to the trunk tip. Finally, two more rotations of θ_4 and θ_5 orient the local frame to point along the tangent to the trunk. These rotations and translations can then be mapped to trunk parameters s, κ, and ϕ using plane geometric methods based on the triangles and rectangles shown in Figure 8(b). Substituting these transformations into the homogenous transformation matrix $\mathbf{A}$ produced by the D-H table then yields the tip orientation and position of

$$\mathbf{A} = \begin{bmatrix} \cos^2\phi(\cos\kappa s - 1) + 1 & \sin\phi\cos\phi(\cos\kappa s - 1) & -\cos\phi\sin\kappa s & \dfrac{\cos\phi(\cos\kappa s - 1)}{\kappa} \\ \sin\phi\cos\phi(\cos\kappa s - 1) & \cos^2\phi(1 - \cos\kappa s) + \cos\kappa s & -\sin\phi\sin\kappa s & \dfrac{\sin\phi(\cos\kappa s - 1)}{\kappa} \\ \cos\phi\sin\kappa s & \sin\phi\sin\kappa s & \cos\kappa s & \dfrac{\sin\kappa s}{\kappa} \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

as detailed in [27].

Since the trunk model is very general, it can be applied to a wide range of continuum robots. To adapt the model for use with a specific robot, only relationships between the trunk parameters and actuator values need to be developed, taking advantage of the foundation laid in mapping trunk parameters to tip position. This is illustrated by developing mappings for three differing continuum robots. Reference [4] develops this relationship for a robot actuated by four cables, spaced at 90° intervals about the trunk. A more common actuation strategy is to employ three cables spaced at 120° intervals. A series of geometric transformations [24], [25] can be used to determine the relationships between cable lengths and trunk parameters as

$$\begin{bmatrix} s \\ \kappa \\ \phi \end{bmatrix} = \begin{bmatrix} \dfrac{nd(l_1 + l_2 + l_3)}{a}\sin^{-1}\left(\dfrac{\sqrt{a}}{3nd}\right) \\ \dfrac{2\sqrt{a}}{d(l_1 + l_2 + l_3)} \\ \tan^{-1}\left(\dfrac{\sqrt{3}}{3}\dfrac{l_3 + l_2 - 2l_1}{l_2 - l_3}\right) \end{bmatrix} \qquad (1)$$

where $a = \sqrt{l_1^2 + l_2^2 + l_3^2 - l_1 l_2 - l_2 l_3 - l_1 l_3}$, n specifies the number trunk segments, defined as *the number of cable guides + 1*, and d gives the radius of the trunk. For pneumatic actuators, examining the limiting case as $n \to \infty$ yields $s = \dfrac{l_1 + l_2 + l_3}{3}$ and identical expressions for κ and ϕ.

Computing linear and angular velocities through a Jacobian, which enable joystick control of trunk shape, is then straightforward. Standard techniques can be used to compute the Jacobian of the D-H table, while computing the Jacobian of the geometrical transformations and modular actuator mapping, followed by application of the chain rule, yields the Jacobian for the entire system as detailed in [27].

B. Robot material length limits

However, the kinematic analysis alone does not address the full behavior of a given robot. Due to the properties of the material used to construct the manipulator, there is a finite amount that the manipulator can be made to extend s_m, and similarly a finite amount the manipulator can be made to retract s_l. The kinematic model neglects the effects of the manipulator's physical elongation limits s_m and s_l. As a result, the kinematic model may try to drive the manipulator into an impossible configuration, where these length limits are exceeded.

A mathematical model for the limits can be derived by analyzing the manipulator in a bent configuration as shown in Figure 9. By definition of arc length, $\theta = s\kappa$, where $\kappa = \frac{1}{r}$. Similarly, $s_{out} = \theta r_{out}$, where s_{out}, illustrated in Figure 9, is defined to be to be the longest point of the manipulator and as such the point which first becomes subject to the s_m limit and $r_{out} = \frac{1}{\kappa} + \frac{d}{2}$. Substituting, the length limit can be expressed as $s_{out} = s\kappa\left(\frac{1}{\kappa} + \frac{d}{2}\right) = s\left(1 + \frac{\kappa d}{2}\right) \leq s_m$. Solving this expression for s provides an expression for the upper limit of s,

$$s \leq \frac{s_m}{\left(1 + \frac{\kappa d}{2}\right)}. \quad (2)$$

A lower limit must also be placed on s, because just as the manipulator is incapable of extending indefinitely, it is incapable of retracting indefinitely. The lower limit is similarly derived as

$$s \geq \frac{s_l}{\left(1 - \frac{\kappa d}{2}\right)}. \quad (3)$$

Figure 10 illustrates these two conditions on s.

Note that these limits are dependant upon the operational variable κ. As such, the material limits (s_m and s_l) of the manipulator also limit the degree of curvature (κ) the manipulator can achieve. Solving (2) for κ yields $\kappa \leq \left(\frac{s_m}{s} - 1\right)\left(\frac{2}{d}\right) = \kappa_m$. This is the κ limit due to s_m.

Similarly, solving (3) for κ yields $\kappa \leq \left(1 - \frac{s_l}{s}\right)\left(\frac{2}{d}\right) = \kappa_l$. This is the κ limit due to s_l. Whether κ_l or κ_m is smaller is dependent upon the manipulator's current s configuration because the smaller of the two is the actual physical limit. The κ_l term is smaller if s is closer to s_l than s_m, and the κ_m term is smaller if s is closer to s_m than s_l. Thus the limit on κ can be expressed as

$$\kappa \leq \min(\kappa_l, \kappa_m) \leq \left\{ \begin{array}{ll} \kappa_l, & s_l \leq s \leq \frac{s_l + s_m}{2} \\ \kappa_m, & \frac{s_l + s_m}{2} \leq s \leq s_m \end{array} \right\}, \quad (4)$$

Note that the physical elongation limits s_m and s_l are not ϕ dependent. Therefore, it follows that the s and κ

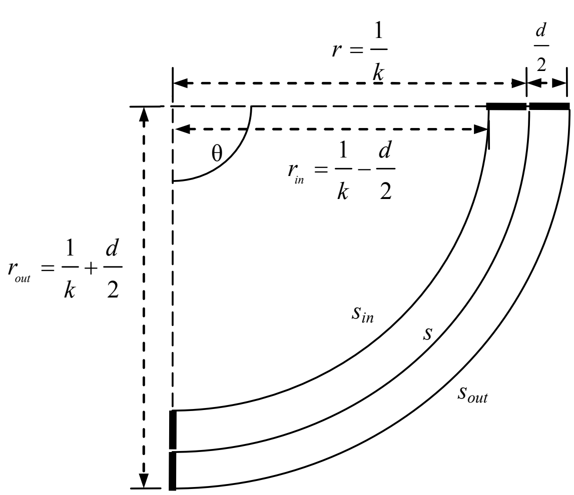


Figure 9. Illustration of a manipulator section in a bent configuration.

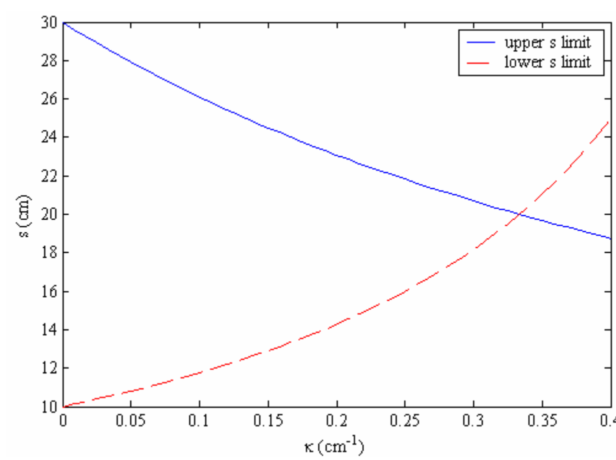


Figure 10. Plot of (2) and (3), which shows the upper and lower length limits on s as curvature κ is varied. This plot is based on elongation limits of s_m=30, s_l=10, and diameter of d=3. Note that manipulator configurations with curvatures greater than κ>0.333 are physically impossible and that maximum achievable curvature occurs at s = ½ (s_m + s_l) = 20.

limits are similarly ϕ independent. Unfortunately, the s and κ limits are co-dependent. However, these relationships can still be used to revise the kinematic model to avoid configurations that cause the material length limits s_m and s_l from being exceeded.

6. Results and Conclusions

This paper discusses ongoing research into the arms of the octopus, focusing on how models developed to understand and explain their operation can be used in the design and operation of octopus-like robot arms. By extracting general principles of motion from octopus arms, such as using longitudinal muscles to generate bending by pulling against variable stiffness, a model for a simple but effective robot arm was generated, and the appropriate kinematics derived. A novel manipulator design that uses this model has been implemented in hardware and appropriate kinematic models have been developed to control the hardware.

Additional work is being performed to derive the proper velocity kinematics that will allow the manipulator to be remotely operated with a joystick. Also, whole arm manipulation algorithms using the current kinematics models are being developed. Also, hardware work is being performed to design and construct practically useful octopus-like robotic manipulators, such as OctArm, for deployment in real life operations.

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