Some Issues in Creating 'Invertebrate' Robots

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Abstract

In this paper, we discuss some of the key issues involved in the design, analysis, and implementation of 'invertebrate-like' robots. Using as case examples several novel 'trunk and tentacle' robot arms recently constructed at Clemson University, we discuss the design of 'continuous backbone' and 'snakelike' robots, and their motion planning. The potential of these types of robots for enhanced manipulation and locomotion is discussed.

1. Introduction

Traditional robot manipulators are based strongly on the human (vertebrate) model, with a (relatively small number of) rigid links connected by joints. Thus, like the human model, bending down the length of the structure is restricted to a small number of (fixed) points. While this works well in numerous cases, there are many examples in nature where a different design philosophy proves to be more advantageous.

For example, in invertebrate structures such as those in 'tongues, trunks, and tentacles', highly dextrous manipulation can be produced via compact structures in which bending can occur down along the length of the structure [14, 24]. Consider the examples of octopus tentacles or elephant's trunks, which can perform 'whole arm' manipulations in cluttered environments beyond the capability of conventional robots.

Snakes are vertebrates, but their ability to bend at essentially arbitrary points along their body allows them to maneuver effectively in terrain that is inaccessible to wheeled, tracked, or even legged machines [7].

The above types of examples provide inspiration to engineers seeking to recreate the abilities of creatures in the biological world [6]. However, engineers do not have analogs of many of the amazing actuation and sensory systems present in the animals.

At Clemson University, we are conducting extensive research in the area of biologically inspired robotics, concentrating on the development of robot 'tongues, trunks, and tentacles'. We are working with both discrete (figure 1) and continuous (figure 2) backboned devices, each type of which presents interesting and unique challenges. In this paper, we summarize the results of our efforts so far, concentrating on design and motion planning issues.

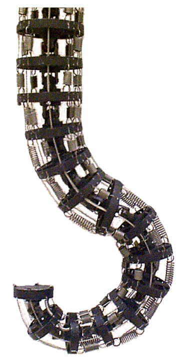

Figure 1: Discrete backboned elephant's trunk robot.

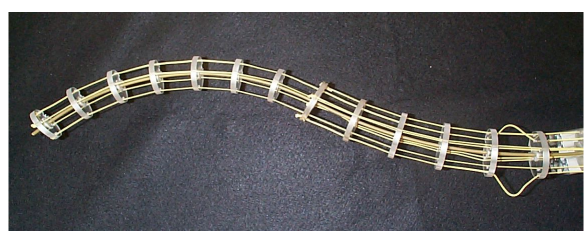

Figure 2: Continuous backbone tentacle robot.

2. Design Issues

Nature suggests two different strategies for constructing 'invertebrate' robot limbs; (1) an 'essentially invertebrate' (snake-like) approach, using a 'discrete backbone' comprised of (a large number of) small links; and (2) a 'fully invertebrate' continuous backbone. Each of these case presents unique issues.

In case (1) above, bending occurs at distinct and well-defined points of the mechanism, with the 'invertebrate' effect coming from the large number of joints and small intervening links. This can be considered a particular class of hyperredundant robot [2], or a natural extension of the traditional robot with the number of joints tending towards infinity and the link lengths towards zero. Physical examples of this type of robot include serpentine robots at NASA Jet Propulsion Laboratory [20], the EMMA manipulator [10] by GreyPilgrim, Inc., and the 'Elephant's Trunk' robot at Clemson [1, 26] (figure 1). Backboned robot 'snakes' are described in [4, 16, 19]. A series of novel 'snake' robots, which have inspired our own efforts, and indeed much of this field of research, are summarized in [12].

The 'discrete backbone' approach has the advantage of being (conceptually) a simple extension of traditional designs, and thus amenable to traditional kinematic analysis. However, as discussed in the following, the large number of joints and small links lead to difficulties in weight, actuation and complexity of analysis.

In case (2) (continuous backbone) above, bending can occur at any point along the structure (this is of course appealing from the perspective of 'whole arm manipulation). This type of robot is termed 'continuum' in [22]. Examples of manipulators of this general type are given in [5, 27]. The 'joint space' in thus infinite-dimensional. Practical considerations dictate that these devices must be actuated by a finite set of inputs. A key question therefore is how to constrain the backbone so that it can be effectively moved by a finite set of actuators.

The trunk robot in figure 1 has a 32 degree of freedom backbone, consisting of 16 two degree of freedom joints connected in series. The motion capabilities of the robot closely resemble that of a real elephant. For more details, see [26]. The tentacle robot in figure 2 features a continuous backbone, and bends in three dimensions. Both robots, along with similar variants, are under investigation in the robotics laboratories at Clemson University.

A key question is how best to actuate these types of devices. Two strategies present themselves: local and remote actuation. Local actuation, as featured in [4, 16, 19, 20], while conceptually simple, has several major disadvantages. Traditional electric motors are relatively bulky and heavy, and the prospect of having to package and move a large number of such actuators distributed through the robot is unattractive. The use of alternative types of actuators, such as new classes of artificial muscles [23] for local actuation (as is found in the biological equivalents) is an interesting possibility. However, at the present time, it seems, at least for macroscopic devices, that the strength of current artificial muscles is insufficient.

For the above reasons, in our robots we have chosen to follow the strategy of remote actuation for our devices. Tendons provide a simple way of transmitting power through the structure, and allow the devices to be fairly light, as the actuators themselves are remote. The trunk in figure 1 is actuated by 8 pairs of tendons, and the tentacle in figure 2 by 4 tendon pairs. Similar remote tendon drive approaches are used to actuate the EMMA robot [10] and the KSI tentacle robot [13].

An important factor in determining the capabilities of such remotely actuated devices is the physical routing of the tendons. Our group is conducting extensive analyses of the effects of tendon displacement (from the backbone), conduit selection, and termination points on robot workspace and strength. Initial results are reported in [15].

The key remaining design issue is how to endow the devices with structural stiffness. In the case of the tentacle robot in figure 2, the backbone itself (a rod of circular cross-section) provides the basic stiffness properties. Notice that robots of quite different characteristics can be obtained by changing backbone rods. The trunk robot in figure 1 is constrained by a series of springs running (segment to segment) down the exterior of the device. This provides the passive constraints that transform the actuation values (4 for the tentacle, 8 for the trunk) to the degrees of freedom (theoretically infinite for the tentacle, 32 for the trunk) of the device.

In each type of device, the resulting robot is relatively light, highly maneuverable, and very compliant, which together provide ideal testbeds for research in biologically inspired robot manipulation. However, in order to make use of the devices, the motions must be effectively planned and coordinated.

3. Motion Planning

In addition to the issues inherent in designing and constructing effective continuum robots, the issue of motion planning is a significant challenge. One immediate difficulty is the sheer complexity of the kinematics. Even for the 'discrete backbone' types of robots, where conventional kinematics can still sometimes be valid, the number and complexity of terms involved can be formidable.

The most commonly followed approach in the literature in this case has been to use concepts from differential geometry to analyze the kinematics of a continuous 'backbone curve', and then 'fit' the discrete robot backbone to that curve in some appropriate manner [2, 3, 17, 18]. However, a practical problem with this approach is that real robots have constraints that are not taken into account by traditional differential geometric methods [8]. Thus the real robots bend in ways not possible for the theoretical curves, and vice versa! In addition, the existing methods provide little intuition.

However, significant progress can be made by observing common features that are inherent in these types of robots, such as locally constant curvature. This feature, common to all the robots described in this paper, is a natural result of actuating a stiff backbone (with stiffness provided by springs in the trunk robot example, and by the inherent stiffness of the backbone rod for the tentacle) with finite pairs of tendons terminated at discrete points along the structure. Between the tendon termination points, the natural behavior of the device is to assume a configuration of constant curvature.

For an example with a planar continuous backbone robot, see figure 3. (Here the 'backbone' is a spring steel bar, and the actuation is by a single pair of tendons routed through discrete discs, and terminated at the 'end effector'). A curve of constant curvature is overlaid on the figure, and it can be seen that the device assumes an almost constant curvature configuration. Similar behavior can be seen in the figures of the trunk manipulator (note: 4 constant curvature sections in the plane in this case) in figures 1, 4, and 5.

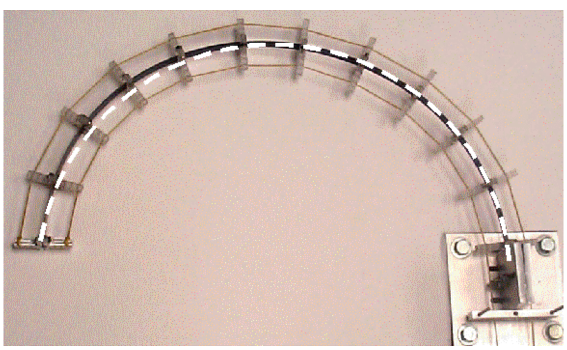

Figure 3: Continuous backbone planar robot.

In recent works, we have proposed several alternative methods for trunk and tentacle kinematics which exploit the constant curvature feature [8, 9, 11]. In [11], it is observed that a robot made up of constant curvature sections can be modeled as a series of prismatic/revolute joints (one pair per section) where the translation and rotation variables of each joint pair are coupled and determined by the curvature of the section. This fact is used to define the forward kinematics of the robot using the conventional Denavit-Hartenberg technique. This in turn yields a manipulator Jacobian (relating changes in *curvature* to task space velocities), the pseudoinverse of which can be used to plan *cur-*

Figure 4: Elephant's trunk robot - curved.

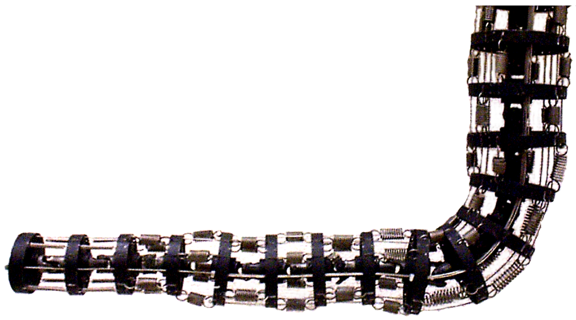

Figure 5: Elephant's trunk robot -outstretched.

vature space velocities using conventional redundancy resolution techniques. Details and examples are give in [11].

A key feature of the work in [11] is the replacement of the traditional joint angles in the kinematics by local curvatures. This allows us to reduce the problem of determining the shape of the robot (given task space requirements) from a large dimensional problem (32 axes for the trunk robot, and theoretically infinite for the tentacle) to a space of the dimension of the number of actuators (8 for the trunk, 4 for the tentacle). This is both computationally more tractable and significantly more intuitive.

A similar 'modal decomposition' approach has been proposed for abstract spatial 'fitting' curves in [3]. However, in [3] the modal functions were chosen to be the Fourier basis functions. In [8], we argue that other basis functions (such as the set of curvatures described above and in [11]) are more 'natural' and easy to use than the Fourier basis set (for example, a finite set always describes the robot configuration). In [9], an alternative basis set based on Wavelet decomposition is used to describe these continuum robots. In this case the 'joint angles' become a Wavelet basis set, the shape of which can intuitively be seen to define the shape of the overall robot. This approach is proving to be highly useful for motion planning for the devices.

However, effective performance of the devices is also dependent on the solution of other, lower level, problems. The overall kinematics for these types of robots involve issues not found in traditional robots. The kinematics must take into account the backbone stiffness profile, and external forces due to gravity or contact (note that a unique actuator position does not translate into a unique pose for the robot). In [8], a kinematic model taking into account the above issue is proposed. The model reveals some useful structure (including an appropriate mapping from changes in local curvatures to cable length changes, required for control). However, the resulting system of differential equations can be hard to solve. We are currently conducting active research in this area.

4. Discussion and Conclusions

The potential for the types of 'invertebrate' robots described in this paper is huge. The inherent maneuverability and compliance of the devices lend themselves to a number of arenas. For example, the ability of the structures to bend at essentially arbitrary points offers the opportunity for operation in cluttered and obstacle-filled environments, if sufficient actuation can be provided. Notice that a (biological) elephant's trunk can manuever very effectively in crowded spaces. This is also true for the class of robots described here.

The lack of rigid links, or 'bones' (at least of any significant size) is the key to the above maneuverability. It it also the key to the inherent compliance in the structures, which can bend around even quite complex shaped objects. This has obvious benefits for making 'soft' robots for hazardous environments or for interaction with humans, and also suggests strong potential for 'whole arm manipulation' (interaction with the world along a length of the structure, as opposed to simply the end effector), which is a key feature of the biological equivalents.

Motivated by our previous work in robot manipulation inspired by biology (specifically involving raccoons [25] and raptors [21]) we plan to investigate the potential of the trunk and tentacle manipulators for impulsive manipulation, where the dynamics of the interaction between the robot and the environment are actively exploited to achieve tasks. We believe that these 'trunk and tentacle' robots offer a novel and interesting vehicle with which to test new manipulation strategies. We are currently conducting whole arm manipulation experiments with the trunk manipulator, and in 2000 we plan to mount a tentacle arm (figure 6) to a mobile platform to conduct experiments in biologically inspired impulsive manipulation research. Results in this direction will be reported in future papers.

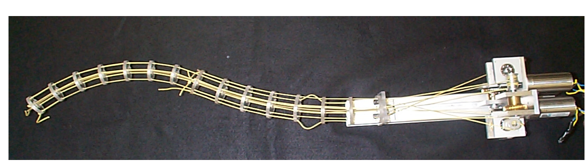

Figure 6: Continuous backbone spatial robot.

Longer term applications for the robot structures described in this paper include inspection and payload transport in complex environments, remote teleoperation, medical applications, and locomotion. The latter case seems particularly interesting in the longer term, if current constraints on weight, power, and sensing can be resolved.

Acknowledgments

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