EXTENSION VERSUS BENDING FOR CONTINUUM ROBOTS

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Abstract: In this paper, we analyze the capabilities of a novel class of continuous-backbone ("continuum") robots. These robots are inspired by biological "trunks, and tentacles". However, the capabilities of established continuum robot designs, which feature controlled bending but not extension, fall short of those of their biological counterparts. In this paper, we argue that the addition of controlled extension provides dual and complementary functionality, and correspondingly enhanced performance, in continuum robots. We present an interval-based analysis to show how the inclusion of controllable extension significantly enhances the workspace and capabilities of continuum robots.

1 INTRODUCTION

Recent interest in expanding the capabilities of robot manipulators has led to renewed interest in continuous backbone "continuum" manipulators (Robinson and Davies, 1999). The idea behind these robots is to replace the "vertebrate" (serial chain of rigid links) backbone of conventional manipulators with a smooth, continuous, "invertebrate" backbone. Continuum robots have the potential for revolutionizing robot operations, by enabling new applications (operation inside complex environments such as collapsed buildings, rubble piles, etc.), and via novel forms of manipulation (compliant and whole arm manipulation, adaptive environmental interaction).

The concept of continuum robots is not new (Hirose, 1993). A number of designs have been suggested, with a number of prototypes constructed (Robinson and Davies, 1999). Most of these are inspired by the biological examples of tongues (Takanobu, Tandai and Miura, 2004), trunks (Cieslak and Morecki, 1999), (Hannan and Walker, 2003), Tsukagoshi, Kitagawa and Segawa, 2001), (Wilson, Li, Chen and George, 1993), and tentacles (Aoki, Ochiai and Hirose, 2004), (Gravagne and Walker, 2000), (Ohno and Hirose, 2001), Pritts and Rahn, 2004), (Simaan, Taylor and Flint, 2004), (Suzumori, Iikura and Tanaka, 1991). Several designs have made their way to commercial products (Buckingham and Graham, 2003), (Immega and Antonelli, 1995).

In almost all of the above designs (with the notable exceptions (Immega and Antonelli, 1995) and (Pritts and Rahn, 2004)), movement of the "backbone" is created by bending of the trunk at discrete locations along its length. While this design allows for the inclusion of redundant degrees of freedom along the backbone, the degrees of freedom available locally are less than in the biological counterparts (Kier and Smith, 1985). In particular, the ability to extend the "backbone", present in many invertebrate limbs (Kier and Smith, 1985) is missing. This paper explores the functional gains obtained by including this "missing" degree of freedom in continuum robots.

In recent work (Jones, McMahan and Walker, 2004) we have developed a multi-section continuum robot, Air-Octor, whose design features both bending and extension (see figure 1). The design extends that of (Immega and Antonelli, 1995) in that the extension of each section can be independently controlled (as opposed to only the total length (Immega and Antonelli, 1995)). We are additionally conducting applied research (McMahan, Jones, Walker, Chitrakaran, Seshadri and Dawson, 2004)

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with the continuum robot hardware introduced in (Pritts and Rahn, 2004), which also feature controllable extension, as well as bending, in each section. Our operational experience with these robots (compared with our earlier series of continuum arms which lacked extension (Gravagne and Walker, 2000), (Hannan and Walker, 2003)) clearly indicates superior performance arising from the additional degrees of freedom, even for arms with comparable total degrees of freedom. This paper analyzes and quantifies this effect, in terms of the kinematic performance improvement.

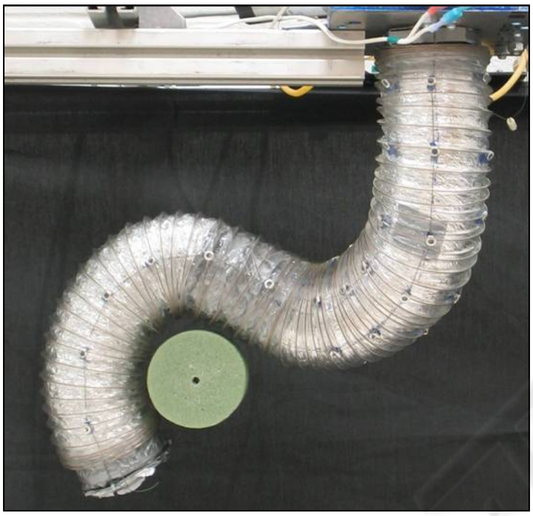

Figure 1: Continuum Robot "Air-Octor."

2 KINEMATICS

We wish to analyze and quantify how the inclusion of controllable extension in continuum robots increases the capability over previously developed designs with only controllable bending. In particular, from a task-based viewpoint, we are interested in quantifying any workspace enhancement obtained by adding extension. For this, we conduct a comparative interval-based analysis of the forward kinematics.

In our operational experience with Air-Octor (Kier and Smith, 1985) and the "Oct-Arm" series of continuum robots introduced in (Pritts and Rahn, 2004), we have found that the ability to extend the lengths of sections is very useful. For example we have found that active use of extension/contraction can greatly assist the stability of whole arm grasping, by effectively tightening and loosening the grip. However, the effects of extension, and their relationship to those bending, remain nonintuitive. A tool which could be used to analyze these effects would be valuable in practical motion planning. In the following we introduce such a tool.

We restrict our analysis to planar movements, for simplicity, and since this is sufficient to illustrate the key advantages of adding extension.

The tip location for a two-section continuum manipulator (for Air-Octor or Oct-Arm) when operated in the plane is given by (Blessing and Walker, 2004), (Jones and Walker, 2004):

$$x = (1/k_1)[\cos(k_1 l_1) - 1]$$
$$+(1/k_2)[\cos(k_1 l_1 + k_2(l - l_1)) - \cos(k_1 l_1)]$$
$$y = (1/k_1)\sin(k_1 l_1)$$
$$+(1/k_2)[\sin(k_1 l_1 + k_2(l - l_1)) - \sin(k_1 l_1)]$$

In the above, k_i represents the curvature of the ith section, and l_i stands for the section's length, both of which are controllable variables. From these equations, it is possible to evaluate the significance of including variable section lengths in addition to variable curvatures. The primary objective of the analysis is to assess the workspace enhancement of the continuum robot. In addition, the probability of reaching the locations within the workspace by means of different robot configurations will also be studied.

3 INTERVAL ANALYSIS

The method used for the analysis is based on multi-interval computations which provide accurate estimates for workspaces (i.e. 2D ranges) and have been extended to support probability descriptions in terms of probability density functions (PDFs). Multi-interval computations are an extension of interval analysis (Moore, 1979) that minimizes its overestimation problem. This problem appears when multiple instances of the inputs appear in the equation or algorithm under study (i.e. there are crossed data dependencies, as in the equations above). This method parallels that in (Walker and Carreras, 2003) where linear (straight line) links were considered. It also refines the initial results in (Blessing and Walker, 2004), where plain interval arithmetic was used for the analysis of a different continuum design, in which the bending location could be mechanically adjusted off-line, but not actively controlled.

Interval arithmetic allows fast and easy computations on ranges of values by means of computations on the intervals' endpoints (Moore, 1979). It is exact if there are no crossed data dependencies, but otherwise it produces oversized results. A classical example of this effect is known as the cancellation problem: given an interval $I = [a,b]$, the computation $I\text{-}I = [a\text{-}b,b\text{-}a] \neq [0,0]$. One alternative to reduce overestimation is to use multi-intervals: the original interval is divided into smaller adjacent disjoint subintervals, the computation is performed for each of them, and the individual results are merged into a single interval result. In the previous example, if I is represented by two subintervals, $[a,(a+b)/2]$ and $[(a+b)/2,b]$, the merging of the individual results of the computation I-I produces the interval $[(a\text{-}b)/2,(b\text{-}a)/2] \subset [a\text{-}b,b\text{-}a]$, thus reducing overestimation. Greater reductions are achieved if more subintervals are used. Therefore, multi-intervals are a simple yet powerful approach for function evaluation where increased precision (i.e. using more subintervals) is directly available at the cost of increased computation time.

The methodology to use multi-intervals has been automated in an in-house framework called Abaco, already used in (Walker and Carreras, 2003). Abaco is based on the GNU Multiple Precision Library GMP and includes all the tools used to carry out this study. Abaco has also been successfully used in other tasks related to reliability analysis and digital electronic design, and is constantly upgraded with new features and capabilities. Extensions to handle probabilities (each interval can have a probability, thus allowing the computation of output PDFs from input PDFs) are also supported. The significance analysis presented here has also motivated specific extensions to handle trigonometric functions and 2-dimensional outputs (i.e. locations in the plane), in the computation and graphics tools within the framework. In addition, the tuning of the tools for each particular analysis has been simplified to avoid test runs required in previous versions of the tools. Using Abaco, different multi-section robots can be quickly and extensively analyzed by simply specifying their kinematic equations.

The Abaco implementation is based on a discretization of the numerical space that simplifies the definition of two basic concepts: interval adjacency and number probability. Both are key issues when partitioning the input ranges into multi-intervals and when merging interval results extended with probabilities. Such discretization is described in terms of the precision (i.e. fractional bits) used to represent the endpoints of the input intervals. No precision is lost as the computations of the equations progresses, since precisions are modified according to the requirements of the operations involved. Trigonometric operations are an exception to this as they are not supported by the GMP library. In this case, they are computed using the standard math library and the results are represented with the same number of fractional bits as the input variables.

Automation and selectable precision are probably the greatest advantages of the multi-interval method implemented in Abaco over other classical methods. Standard sensitivity analysis suffers from the complexity of computing (by hand) the equations in partial derivatives (minimization/maximization problem). Simulations based on random sampling methods (Monte-Carlo and Latin Hypercube) do not provide accurate information about output ranges (i.e. to evaluate workspace enhancement) as they are intended to obtain statistical values of the outputs (mean, variance). Finally, it may seem that numeric simulations of the kinematic equations for a grid of input points could be used to obtain workspace estimates. However, for these estimates to be accurate, and especially if PDFs must also be obtained as in this analysis, the number of points in such grid must be very large. From the tests run, the computation times required by these standard numeric simulations are much longer than those required by the multi-interval method for a given accuracy in the results.

4 SIMULATION PARAMETERS

For the purpose of evaluating the potential advantages of variable lengths in addition to variable curvatures, a number of configurations for different multi-section robots and variability conditions have been studied. In particular, assuming that the total robot length remains constant (l = 29.8 cm), two types of robots have been analyzed considering the ratio between their nominal section lengths: robot R_1 with $l_1/l_2 = 1$ ($l_1 = l_2 = 14.9$ cm), and robot R_2 with $l_1/l_2 = 2$ ($l_1 = 19.87$ cm $= 2l_2$).

The angle in degrees of a section of length l and curvature k, $\theta = 180lk/\pi$, has been used as the variable parameter in the exploration of the configuration space. In particular, nine basic angles have been considered: 15, 45, 90, 135, 180, 225, 270, 315 and 360 degrees. For each robot type and basic angle θ, two basic curvatures can be obtained: $b_1 = \pi\theta/180l_1$ and $b_2 = \pi\theta/180l_2$. Expressing the section curvatures in terms of these basic curvatures, four types of configurations per robot type and basic angle have been analyzed: configuration C_1 ($k_1 = b_1$, $k_2 = b_2$), configuration C_2 ($k_1 = b_1$, $k_2 = b_2/2$), configuration C_3 ($k_1 = b_1$, $k_2 = -b_2$), and configuration C_4 ($k_1 = b_1$, $k_2 = -b_2/2$). Therefore, 36 configurations have been evaluated per robot type.

Two different strategies have been considered for the comparison of variable lengths and variable curvatures in each of the previous configurations, leading to two different and complementary analyses. The first analysis is based on variations in lengths and in curvatures of up to ±5% of their nominal values. The second analysis is based on variations around the nominal lengths and curvatures that change θ up to ±5 degrees. Each of the previous analyses is conducted by running three simulations where variations are described in terms of multi-intervals. In the first simulation, only curvatures are varied. In the second simulation, only lengths are varied. In the third simulation, the variations of curvatures and lengths from the two previous simulations are considered simultaneously. This has allowed verifying the impact of each type of variation in the robot workspace.

Considering that each of the 72 configurations is characterized through 6 simulations, a total of 432 simulations have been run to carry out this study. The Abaco tool set supports the full automation of the process, from input multi-interval representation to output plot generation, for all 432 simulations at once.

In the multi-interval computations, the precision of the input representation has been fixed to 16 fractional bits, because of the discretization required by Abaco. It is considered that $2^{16} = 65536$ different values between any two consecutive integers are more than enough for such discretization not to be relevant in the results, while still allowing for maximum performance in the computation of the GMP functions.

With respect to the number of intervals used for the multi-interval representation of the inputs, no optimal approach exists in terms of providing the minimum simulation length for some given output error. Therefore, a simple heuristic based on the size of the input ranges has been used. The results from this approach have been validated in all representative cases (i.e. when compared to the results from simulations using half or twice as many input intervals the differences are negligible).

The results from each simulation are represented as a reachability plot which is a 3D plot where the x-y plane describes the planar workspace of the robot for the given curvature and/or length variations in the given configuration. The z axis describes the probability of reaching each position in the workspace as result of the input variations being considered, thus providing a measure of redundancy. The workspace is also represented as a separate 2D plot. Only three fractional bits are used in the plot representation of the results to allow the visualization of the contour lines.

5 RESULTS

The results in the figures below show that varying lengths in addition to curvatures substantially enhances the robot workspace, with the two aspects clearly complementary to each other. In particular, the plots reveal that combining variable curvatures and lengths leads to larger workspaces. Due to the lack of space and the similarity of the conclusions, only a few of the analyzed configurations are presented here.

Figure 2 illustrates one possible physical configuration for the robot where the lengths l_1 and l_2 are equal and the angle formed by each section is 45˚. For this configuration, the first analysis method is presented, based upon variations in lengths and in curvatures of up to ±5% of their nominal values. Figure 3 illustrates the workspace achieved by the robot if the curvature of the sections is changed by altering the radius by ±5% while the length of the sections remains constant.

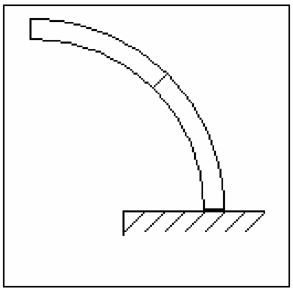

Figure 2: Physical configuration

In this configuration, only the 2D workspace plots are presented. Figure 4 illustrates the workspace when the curvature of the sections is unchanged while the length of the sections varies ±5% of the nominal length. In Figure 5, both the curvature and the length have varied up to ±5% of their nominal values.

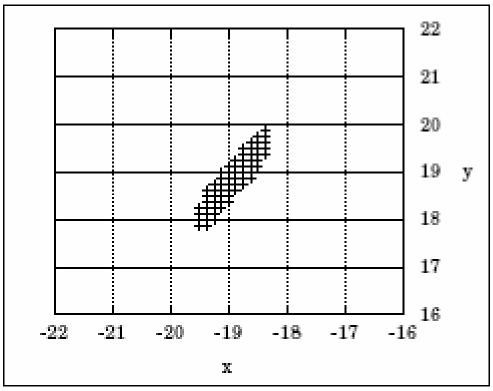

Figure 3: Curvature change only for example of Figure 2

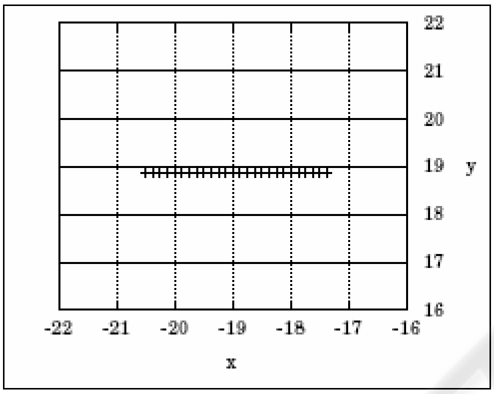

Figure 4: Length change only for example of Figure 2

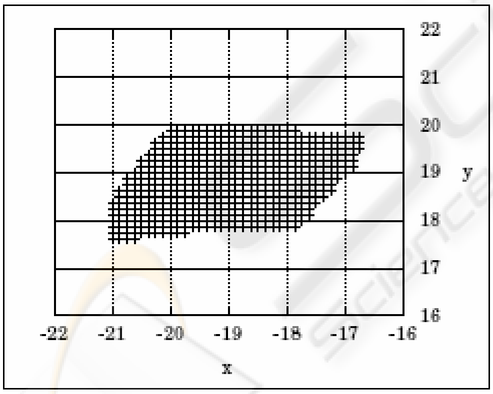

Figure 5: Length and Curvature change for example of Figure 2

As can be seen in Figures 3, 4, and 5, changing the curvature of the sections in concert with the lengths results in a significantly increased workspace. Indeed, the workspace achieved by the combined variations is a form of vector-product of the length and curvature workspaces.

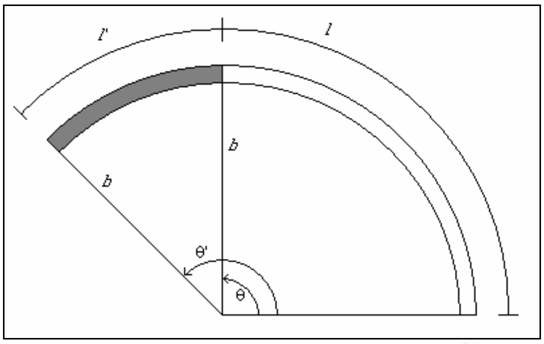

Figure 6: Changing length for a curved section

As the sections of the robot extend and retract, the angles formed by the sections (θ) also change, even though manipulation was performed on the length alone. This is an inadvertent effect that comes from altering the length of a curved section. In Figure 6, this concept is illustrated for a single curved section. As the length of the section increases from l to $l+l'$, the radius (which in turn defines the curvature 1/radius) remains the same while the angle θ increases to θ'.

In Figure 7, we consider a different configuration. Here, the angle formed by section 2 is the negative of the angle formed by section 1, essentially changing the direction of concavity for section 2. The lengths of the individual sections are again equal, but the angles formed are (90, -90) for sections 1 and 2 respectively. The second analysis method is presented for this configuration, based on variations around the nominal lengths and curvatures that change θ up to ±5 degrees.

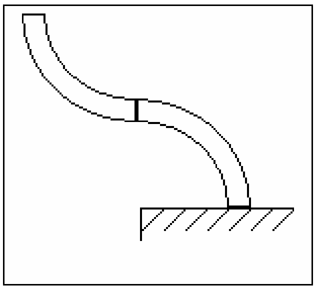

Figure 7: Physical configuration

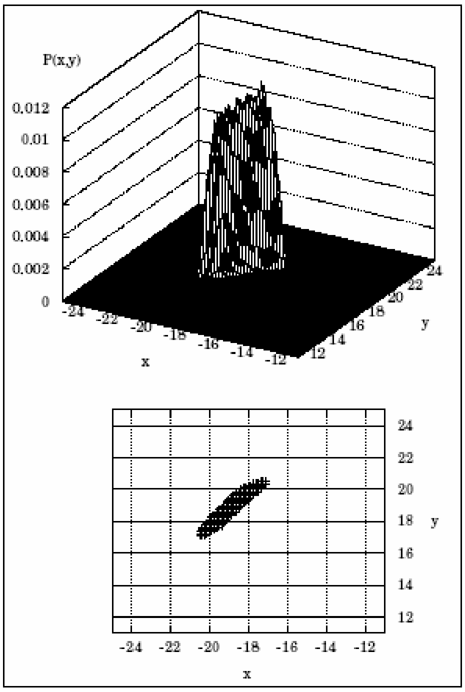

Figure 8: Curvature change only for example of Figure 7

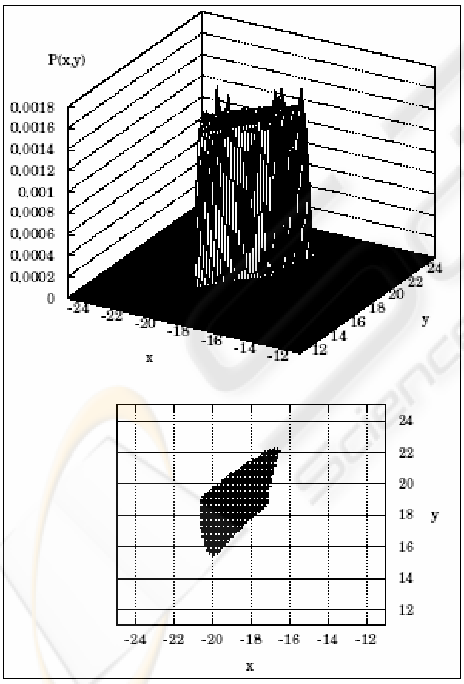

Figure 9: Length change only for example of Figure 7

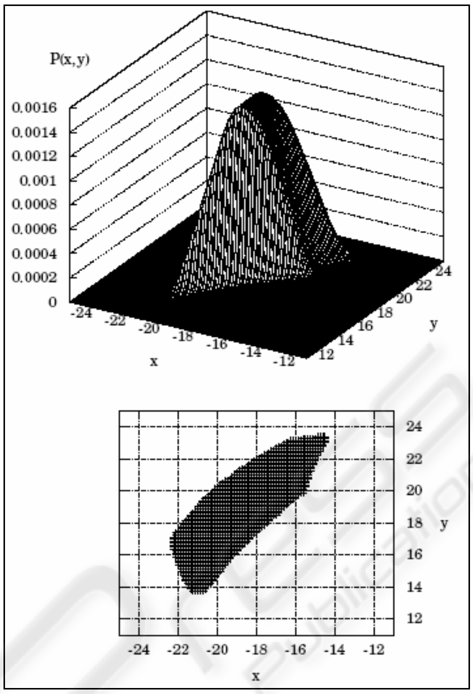

Figure 10: Length and Curvature change for example of Figure 7

In Figure 8, the curvatures of the sections have been changed ±5 degrees respectively. Figure 9 illustrates a change in link length that will change θ up to ±5 degrees, and Figure 10 is the workspace formed when the link length and the curvatures are changed in concert. Once again, the resultant workspace in Figure 10 appears as an intuitive combination of Figures 8 and 9.

In Figure 11, a third configuration is examined. Here, $l_1/l_2 = 2$ and the angles formed by the length and curvatures of the sections are (90˚, 180˚) respectively.

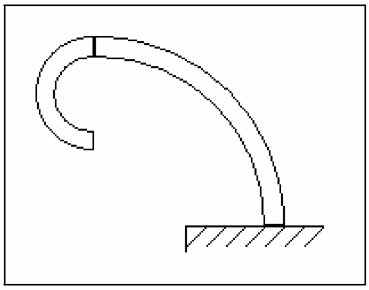

Figure 11: Physical configuration

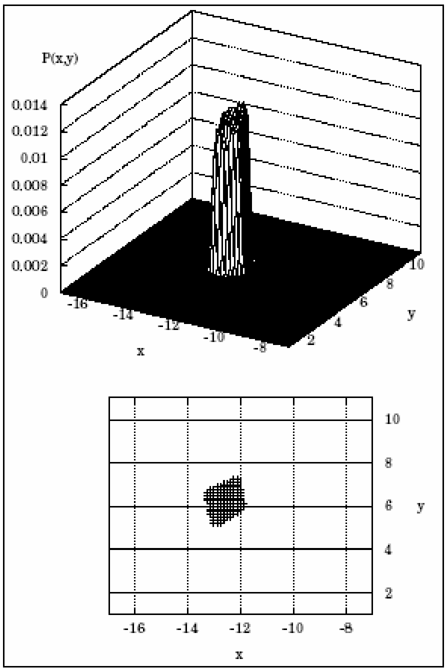

Figure 12: Curvature change only for example of Figure 11

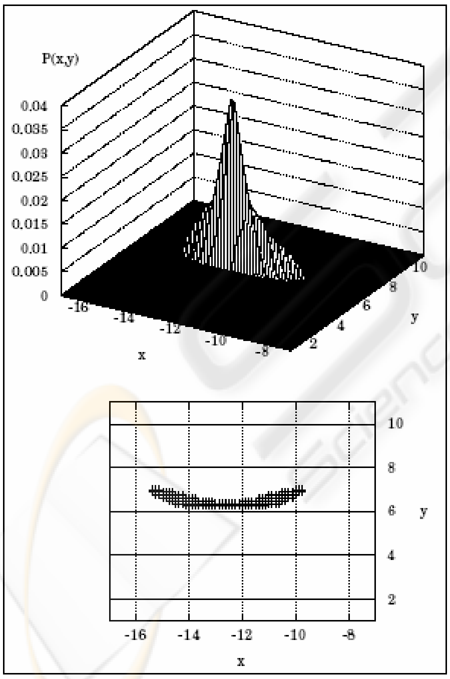

Figure 13: Length change only for example of Figure 11

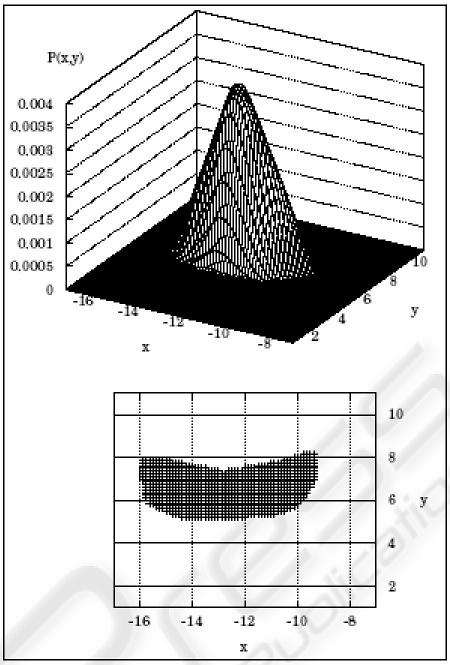

Figure 14: Length and Curvature change for example of Figure 11

Figure 12 illustrates both the workspace and the PDF generated when the length of the sections vary such that θ alters ±5 degrees.

When part of the workspace has a low PDF, as can be observed in Figures 13 and 14, it indicates that only a few combinations of the input variables would allow reaching that part of the workspace. This relationship could be important with trajectory planning, among other topics.

In the configurations examined, the workspace formed from the combined change in the curvatures and the lengths was significantly larger than the workspace achieved when only one attribute was altered. The fact that the resultant workspace appears as a combination of the two individual workspaces is also intuitive.

The above examples are typical of the results of the study, in terms of showing how both bending and extension significantly affect the workspace, and in complementary ways. The results also provide the workspace for a large number of more nonintuitive configurations. So the approach can also be seen as a useful tool for task and motion planning.

6 CONCLUSIONS

This paper clearly shows how extension is complementary to bending in continuum structures, in terms of workspace enhancement. This is a useful feature that has been taken advantage of by a variety of animals. The results motivate the inclusion of extension in future continuum robot designs. Our current work focuses on the use of the results in this paper for optimal design and operation of continuum robots by developing "synergies" from combinations of extension and bending in the Oct-Arm series of continuum robots.

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