Proceedings of the ASME 2023
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC-CIE2023
August 20-23, 2023, Boston, Massachusetts

DETC2023-116930

DESIGN SPACE ENUMERATIONS FOR PNEUMATICALLY ACTUATED SOFT CONTINUUM MANIPULATORS

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ABSTRACT

Pneumatically actuated soft continuum manipulators (SCMs) are constructed by combining several extending or contracting fiber reinforced elastomeric enclosure (FREE) actuators in series, parallel and a combination thereof. While it is well known that architectures with serial combinations of FREEs yield large workspace and dexterity, they suffer from design and control complexity, increased number of valves and inertia. Recent advances in exploring the FREE design space has demonstrated using parallel combinations of dissimilar FREEs (bending and rotating) to improve workspace and dexterity. This paper presents a comprehensive investigation of SCM design architectures by enumerating possibilities of serial and parallel combinations of similar and dissimilar FREEs. A novel dexterity metric is proposed to enable objective comparison of different SCM designs based on shape similarity and end-effector tangent. Given a fixed resource of control inputs (actuator and valve inputs), the paper systematically selects the best architecture of the SCM (serial, parallel, similar or dissimilar FREE) that maximizes dexterity and workspace. It is seen that optimal designs are heavily dependent on the context of the application, which may change how these manipulators are deployed. The paper presents two practical design applications that demonstrate the usefulness of the enumeration framework. While in general, serial design combinations using symmetric bending actuators result in larger workspace and dexterity, some architectures with asymmetric combinations of FREEs may see similar levels of dexterity and workspace.

1 Introduction

1.1 Motivation

Soft continuum manipulators (SCMs) [1] are robotic manipulators that use material elasticity to bend continuously along its axial length and produce motions by generating smooth curves similar to elephant trunks [2] and octopus tentacles [3]. They combine high dexterity and workspace with adaptability and elicit safe interactions with humans and the environment [3]. SCMs are gaining ground mostly in agricultural manipulation [4,5], assisting older adults with activities of daily living [6], manufacturing, search and rescue and many other applications. Deploying SCMs are getting easier thanks to a slew of recent research in soft manipulator control techniques. The limiting features for SCMs are thus their design, and specifically on increasing their dexterity and workspace without increasing design and control complexity and weight. Furthermore, a single SCM design may not be optimal for all applications alike, requiring customization. There is a need for a comprehensive design theory for SCMs by a thorough investigation of its design space.

1.2 Related Work

SCMs are traditionally actuated by cables driven by motors [7] or by soft muscle-like fluidic actuators [8] In both cases their design configurations (cable orientations, soft fluidic actuator architectures) are central to achieving spatial deformation and thus

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their workspace and dexterity. For example, novel cable routing configurations have been explored to attain complex shapes such as bending and spiral twist [9]. In the realm of pneumatically actuated SCMs, design explorations were primarily conducted by connecting several extending/contracting Fiber Reinforced Elastomeric Enclosures (FREEs) [10] in serial or parallel architectures [11]. An early study clearly demonstrated that while serial combinations of FREEs increases dexterity and workspace, parallel combinations were more compact, stiffer and less prone to inertial effects [12, 13]. More recently, the authors' previous work [14] investigated a parallel combinations of FREEs that included two rotational/twist actuators and an extending/bending actuator that showed promise for attaining spiral deformation behavior. This was the first instance of using asymmetric combination of FREEs (or actuators that do not purely extend/contract) in the construction of SCMs. In this paper, we expand the design space of pneumatically actuated SCMs by considering asymmetric combination of FREEs in both serial and parallel combinations, and compare them based on attainable workspace and dexterity.

1.3 Approach

In this paper, we present an enumeration-based design space investigation of SCMs that are composed of a serial or parallel combination of bending and/or rotating FREEs. Though workspace and dexterity are the major metrics that guide our design, we also pay attention to the design complexity and redundancy. The paper uses the popular Cosserat rod framework to computationally evaluate the deformation modes of the SCMs. Experimental data from single-section parallel combinations are used to fit the material parameters for the Kirchhoff model. Modeling serial combinations result from the mechanics of serial Kirchhoff rods. Furthermore, the paper builds on past research to propose novel workspace and dexterity metrics that can be derived from the Kirchhoff model. Extensive enumerations demonstrate the frontiers of dexterity and workspace achievable as a function of the number of control inputs (or actuators) that constitute the SCM. Furthermore, we investigate the effect of application specific deployment in choosing the optimal design configuration.

The paper is organized as follows. Section 2 introduces the background on FREEs, SCM construction and Kirchhoff rod modeling. Section 3 proposes novel dexterity and workspace metrics from the Kirchhoff rod simulations. Section 4 systematically enumerates SCM designs and compare their dexterity and workspace metrics. Section 5 showcases two examples to highlight how application dependent deployment can lead to different optimal designs. In section 6, we present conclusions and future work.

2 Background

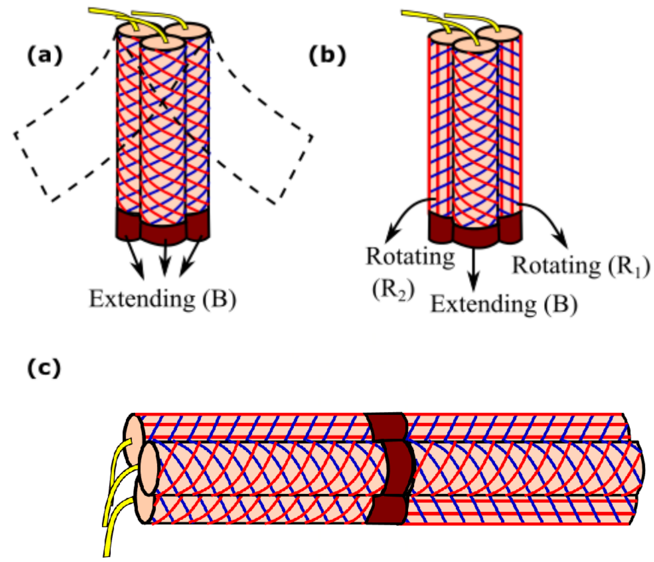


FIGURE 1. Contrasting the design architecture of conventional soft pneumatic continuum manipulators consisting of (a) symmetric building blocks (composed of three bending actuators), (b) combination of asymmetric building blocks (composed of one bending actuator, one clockwise rotating and one counter clockwise rotating actuator). (c) Serial manipulator composed of two segments of FREEs attached by a rigid connector. [14]

2.1 FREEs and their construction

FREEs are hollow cylindrical elastomeric membranes with two families of fibers wrapped on the surface at angles α and β with respect to its longitudinal axis [10, 15, 16]. FREEs are similar in construction to McKibben artificial muscles [17] but are capable of generating different deformation patterns that include extension, contraction, rotation, and screw motion depending on the wound fiber angles. The fabrication methodology of FREEs is detailed in the authors' previous publications [15]. The two most important FREEs used in this paper are the expanding FREE with equal and opposite fiber angles ($\pm 85^0$) and a rotating FREE with (70^0 and 0^0).

2.2 Parallel and Serial FREE Combinations

We consider the SCMs in this paper as a serial and parallel combination of several FREEs. Combinations of FREEs in parallel involves adhering each section of the same length along a common lengthwise seam (Fig. 1a and b). Depending on the combination of FREEs, parallel SCMs can be made to achieve varying characteristic deformation modes. For example, combining three bending segments along a common seam produces a FREE that can bend along equal tripartite axes and to any deformation angle when more than one section is pressurized (Fig. 1a). Another parallel manipulator may be a combination of two counter rotating sections with a single bending FREE attached (Fig. 1b) [14]. This SCM can twist along its length and at the same time bend to reach desired points within a workspace. We denote such a combination as asymmetric since all three FREEs are different. Each FREE in these configurations may be pressurized at a shared manifold at the manipulator base making the hardware relatively simple. The controls for single segment parallel FREEs are comparatively determinate as control inputs typically produce single unique deformation shapes. Combining FREEs in parallel configurations also increases stiffness and requires higher necessary control input pressures.

FREE designs can also be considered in serial combinations where each FREE is attached in succession one after the other. We define serial FREEs as an SMC constructed from single actuator segments attached lengthwise or combinations of parrallel FREEs attached lengthwise. The end tip of preceding FREE segments is capped off and rigidly attached to the control manifold at the base of the following FREE creating a lengthwise chain. Figure 1 section (c) depicts a serial manipulator consisting of two SCM segments. Different combinations may be used to create shapes that change rotation and bending direction at increments along length of the manipulator which is deformation that single segment parallel manipulators cannot achieve. The controls for serial manipulators are relatively stochastic as multiple control inputs may result in the same end effector position. Since extra hardware is necessary to pressurize successive segments, the hardware weight and complexity is higher in serial combined FREEs compared to single segment parallel designs. Compared to single segment manipulators, special considerations are required in the control and design of serial FREEs.

2.3 Cosserat Rods as a Modeling Tool for Continuum Manipulators

To understand the different design implications of combining FREEs in parallel and serial configurations, a Cosserat rod-based simulation platform is used. For a single FREE segment, a quasistatic forward model is used to converge on a simulated deformation based on precurved Kirchhoff's rod theory [11, 18]. A quasistatic precurved Kirchoff rod model is used to capture the backbone deformation profiles of a parallel combination of FREEs similar to the process shown in [11,14,18]. The following section details how model parameters were fit from experimental data. In this paper, we extend the Kirchhoff rod model to serial combination of FREEs, which entail imposing force and moment balance conditions on the intermediate connector between the two FREEs.

3 Methodology

3.1 Experimental Data to Train the Simulation

The FREEs that are designed and tested in simulation should mimic the physical FREEs used in application as closely as possible. To accomplish this, we first manufactured single segment FREE sections consisting of up to three actuators joined in parallel. Bending actuators have a diameter of a third of an inch and rotating actuators have a diameter of one quarter of an inch. Each FREE tested for the duration of the paper is a total of thirty six centimeters long. Serial manipulators studied consist of two eighteen centimeter segments. To gather material properties we actuated each FREE with a range of air pressures and measured the resulting shape with a Cartesian magnetometer. Using five points measured along the length of each FREE we reconstructed a spline to represent the final shape at pressure. 40 psi was chosen as the maximum air pressure that the FREEs can withstand without risk of damage to their material when held at that pressure for extended periods of time. The range of pressure from 0 to 40 psi was applied to each FREE discreetly at a resolution of 2 psi. With a three section FREE it is typically redundant to actuate more than two parallel sections at a time. For example, an SCM constituting a parallel combination of bending and clockwise and counterclockwise rotating SCMs (known henceforth as the BR^2 manipulator) may be actuated by the bending section and clockwise rotation section but would not want to also simultaneously be actuated by the counterclockwise rotation section because it would counteract the action of the first rotator. Within these limits we came up with a data set consisting of a maximum 400 splines per FREE design. Using these splines we ran a shape optimization code [14] that translated pressure inputs to variables used in the Cosserot rod model. Using the optimization on real spline data, we were able to produce material parameters for each FREE design as well as a library to translate between physical and simulated FREEs. With single section manipulators studied, we began the study of FREEs attached in serial configurations.

Four serial two section FREE designs were manufactured consisting of six SCM's each. The designs were chosen based on an effort to choose a wide variety of symmetrical and asymmetrical FREE designs. Similar to the single segment study, we then pressurized the FREE combinations to a 40 psi range of pressure at 2 psi resolution. The pressurized physical sections were measured using 10 equally distributed points along their length to recreate the full spline shape. The resulting experimental shapes were overlaid with the shapes obtained from the serial Kirchhoff rod model as shown in Fig. 2. The leftmost image is of one of the physical prototypes alone with each subsequent image depicting an overlay of the same control inputs applied to physical and simulated models. With the simulation platform verified, we now proceed to evaluate workspace and dexterity for SCMs with different design architectures.

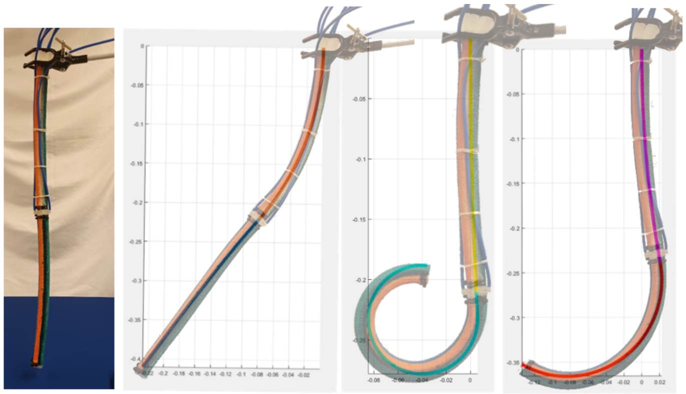


FIGURE 2. Overlay between simulation and physical deformation shapes using the same control inputs

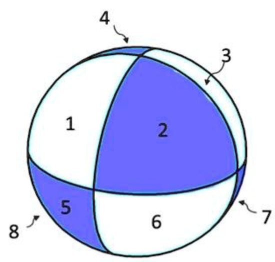


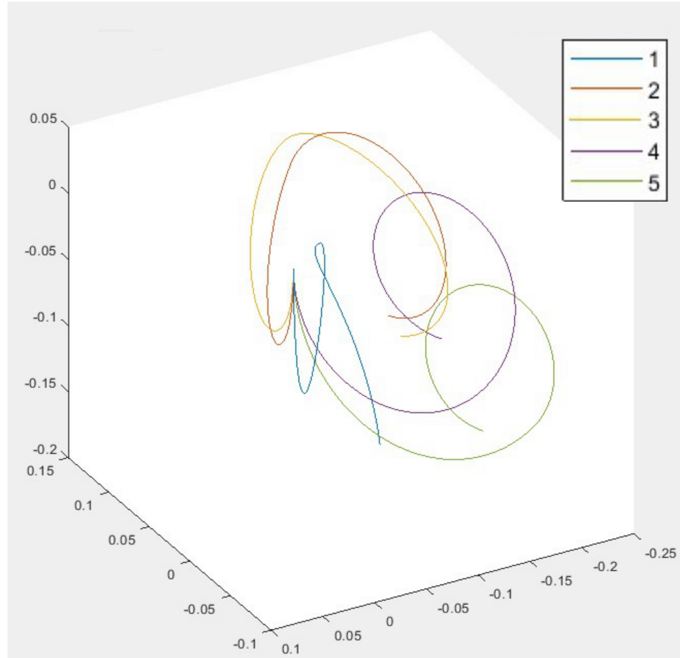
FIGURE 3. Colored sphere depicting eight equal octants that delineate end effector tangent vector orientation by number

3.2 Workspace

One of the metrics to characterize an SCM behavior is the volume of the workspace its end effector inhabits over a range of control inputs. Each FREE is given a set of uniformly random generated pressure inputs for each actuator and simulated for 10,000 pressure combinations. Once solved for, the Cartesian coordinates and tangent vector of each splines terminal point is recorded. The number of pressure combinations simulated was chosen based off of a plateau of the workspace volume with increasing number of pressure combinations over 10,000. The volume of the point cloud is then found using a Delaunay triangulation algorithm which was chosen as it can account for possible hollow volumes within a workspace point cloud.

3.3 Dexterity

The method for finding the dexterity metric is reliant on a process of organizing and categorizing the workspace point cloud. In this paragraph the steps to achieve dexterity are laid out and exemplified in Figure 4. The first step is to divide the simulated workspace point cloud into 1 centimeter cubic sections. In the workspace each point is categorized into which 1 centimeter cube it falls in to. Since the cubes are generated for the bounds of the



Lines Compared	Average Distance Between Lines	End Tangent Vector Octant
Lines 1 & 2	13.4 cm	5, 7
Lines 1 & 3	12.3 cm	5, 7
Lines 1 & 4	11.0 cm	5, 5
Lines 1 & 5	13.3 cm	5, 8
Lines 2 & 3	3.9 cm	7, 7
Lines 2 & 4	9.8 cm	7, 5
Lines 2 & 5	11.3 cm	7, 8
Lines 3 & 4	10.2 cm	7, 5
Lines 3 & 5	13.0 cm	7, 8
Lines 4 & 5	6.0 cm	5, 8

FIGURE 4. Dexterity comparison table between five deformation shapes resulting in a dexterity metric of four distinct shapes for the region

workspace, all cubes will have at least one data point inside of them. The second step is an analysis of the entire spline shape of each FREE that is found in the sorted cubes. Figure 4 depicts the spline shape of five simulated configurations of the same SCM whose endpoints all reside within the same cube. Once the splines are found, the third step uses a comparison matrix, comparing each spline to another one by one. Figure 4 depicts the matrix as a table. The average scalar distance each spline is away from each other is then found by comparing the distances from each spline point in the two shapes. Step four decides if this average distance is below a third of the length of the entire manipulator, the two shapes are collapsed into one and treated as the same line in all further comparisons. For example, in Figure 4 the average distance between the lines 2 and 3 being 3.9 cm is below a threshold of 8.0 cm so the total number of lines in the cubes goes from five to four as lines two and three are counted as the same. In the fifth step the tangent vector at the endpoint of each of the shapes is assigned an octant one through eight using spherical coordinates. Each couple of splines that were collapsed in step four are brought back to two separate shapes if their tangent vectors fall in different octants. Finally, step seven counts the total number of shapes in the cube and adds this number to a total of all cubes in the workspace. The summation of all distinct spaces in every cube is divided by the number cubes in the workspace to find our "dexterity" metric.

This process following the example in Figure 4 shows that there are originally five lines in the cube. Once compared with distance there are only counted to be three as pairs two-three and four-five are considered single shapes. Lastly, the tangent vectors of lines four and five are in different octants meaning that the shapes are counted again as two. The total number of lines in this cube is ultimately four. The dexterity metric for this cubic centimeter of the workspace is four. When we talk about designs more generally however, the dexterity metric is taken as an average over all cubic centimeter sections in the workspace.

4 Results

4.1 A scheme for enumerating SCM designs

Manipulators are built using a set of rules that guide their design. The two basic deformation modes that are explored in this paper are bending and rotating. A bending actuator is a single section that when pressurized will deform from a straight shape to a curved shape along the axis in the center of the FREE. For brevity, we notate bending actuators as 'B' and rotating actuators as 'R'. A dash in between letters notates a junction in serial sections. For example, a BR2-B3 is a 2 section serial manipulator with one bending with two opposing rotation actuators in the proximal section and three bending actuators separated by 120 degrees (360/3) in the distal section. The first step is to decide which designs are worth exploring by setting a limit to the amount of actuators (and thus control inputs) in the SCM. We chose the maximum possible actuators studied to be six due to the expense and controlling complexity of air pressure regulators. The number of serial sections is also capped at three since designs that utilize four or more sections result in the proximal section being weighed down by the latter weight of the arm. Testing has shown that no more than three actuators per section accomplishes desired manipulability while remaining flexible enough to deform. Using over three parallel actuators causes the section to have decreased movement due to increased stiffness. Practically, proximal sections of a serial manipulator should have either more or equal numbers of actuators as following distal sections. This rule arises from the fact that distal sections must be supplied with air from hoses that are attached along the length of proximal ones. Not only do the hoses add rigidity to proximal sections but also increase weight such that heavy distal sections with high actuator counts limit the movement of sections before

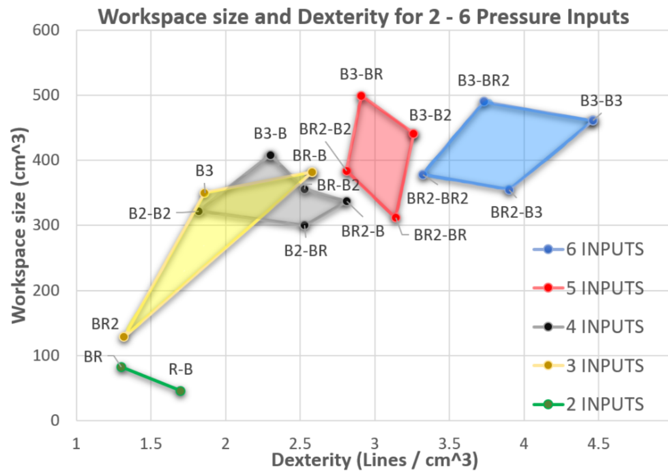


FIGURE 5. Dexterity and workspace figure depicting all FREE designs categorized into colored regions based on control input number

them. Avoiding redundancy is another tenant of the design of serial manipulators. Redundancy occurs for example in designs that have more than two rotating actuators as there are only two modes of rotation, clockwise and counterclockwise.

The results are catalogued in the following tables ordered by number of increasing actuators or control inputs. Manipulator designs are most closely compared using the same number of control inputs used as they will have an equivalent number of deformation modes. Figure 5 shows all of the designs tested in a plot with axes of workspace and dexterity. The colored regions of the plot represent different numbers of control inputs with each point at the demarcation of the region boundary labeled as a specific SCM design. The trend of the regions from lowest control input to greatest follow a logarithmic rise. This approximately correlates to the fact that increasing control inputs of soft arms gives diminishing returns. This trend is important when considering choice deployment of a certain SCM design as more control inputs is comorbid with increased cost and complexity.

4.2 General Tabulated Results

The use of a single control input results in either one bending or rotating actuator. This manipulator will have a two dimensional workspace that results in a trivial dexterity metric.

Table 1 shows the results of the two control-input SCM designs. The designs are represented in Figure 5 by the green area on the plot. The single section B2 design was avoided as it would have resulted in a two dimensional workspace from each actuator separated by 180 degrees. As stated in the previous section, the dexterity metric used in this paper relies on a 3 dimensional workspace. The two section R-B may have interesting design applications as it can mimic a rotating base for the arm when one may not be possible using conventional means. For the ap-

TABLE 1. Dexterity and Workspace (cm^3) volume of FREE designs using two control inputs

Type	Dexterity	Workspace
BR	1.30	83
R-B	1.70	46

plications studied in this paper however, attaching the soft arm to a rotating base using a rigid link is preferable. Overall the BR design is the highest rated in the table. A commonly studied soft arm (source) is the BR2 though with only two-thirds of the needed control inputs this design achieves over eighty percent of the performance.

TABLE 2. Dexterity and Workspace (cm^3) volume of FREE designs using three control inputs

Type	Dexterity	Workspace
BR-B	2.58	382
B3	1.86	350
BR2	1.32	129

Table 2 shows the results of the three soft arm designs that use three control inputs. The designs are represented in Figure 5 by the yellow area on the plot. Notably, the single section BR2 performs significantly worse in both metrics than the other two 3 port designs. The BR2 has the approximately same dexterity as the 2 port BR. This result is explained simply as the BR2 workspace is close to the same as the BR workspace mirrored across the X-Y axis to account for the opposite rotating actuator. In applications that involve a rotational base, a BR is likely suitable over a BR2. The single section B3 and two section BR-B perform comparatively closer to designs with 4 control inputs. The BR-B is the standout of the 3 port group as the lightweight bending distal segment and simple BR proximal section combine to give standout performance. In every general case studied but one, it is advisable to choose a 3 port BR-B over a 4 port design.

Table 3 shows the results of the five SCM designs that use four control inputs. The designs are represented in Figure 5 by the grey area on the plot. The BR-B design discussed in the previous section performs better than the similar BR-B2 design. This difference is likely due to the doubled weight of the distal segment of the latter design. With a rotating actuator in the proximal section the second bending mode is also rendered redundant as much of the same points can be reached by flipping

TABLE 3. Dexterity and Workspace (cm^3) volume of FREE designs using four control inputs

Type	Dexterity	Workspace
B3-B	2.30	408
BR-B2	2.53	356
BR2-B	2.81	337
B2-BR	2.53	300
B2-B2	1.82	322

manipulator using the rotating actuator. Simplification is a tenant of selecting appropriate FREE designs when approaching any application. In the four control port group the best performance comes from the BR2-B. Having decreased workspace as compared to the BR-B due to the added weight of a second rotator, the extra rotation adds significant dexterity.

TABLE 4. Dexterity and Workspace (cm^3) volume of FREE designs using five control inputs

Type	Dexterity	Workspace
B3-BR	2.91	499
B3-B2	3.26	441
BR2-B2	2.81	384
BR2-BR	3.14	312

Table 4 shows the results of the four soft arm designs that use five control inputs. The designs are represented in Figure 5 by the red area on the plot. Unlike the insignificant separation between the 3 and 4 port groups, the 5 port group perform better on average in both workspace and dexterity. For applications that require high workspace from a single section FREE the B3 manipulator is typically chosen. Despite having no rotation modes, the offset bending actuators of a B3 can achieve high workspace volume. Once combined with a lightweight rotator in the distal section, the FREE design combination achieves maximum workspace capability. The B3-BR design is the highest achieving workspace off all the FREE design combinations studied. Because of the high reaching and heavier B3 in the proximal section and lightweight rotational BR in the distal section, this design is recommended for general applications that seek to maximize workspace volume. With a trade-off of approximately 10% less workspace volume is the B3-B2. This specific design test includes bending actuators in the B2 section that are offset from the axis on the B3 section. One shortcoming of the B3-B2 design is high redundancies that do not sum into the dexterity metric. Despite the offset attachment, many agitations that are achieved in this design fall within the same 1cm cube as each other with the tangent vector in the same octant.

TABLE 5. Dexterity and Workspace (cm^3) volume of FREE designs using six control inputs

Type	Dexterity	Workspace
B3-B3	4.46	461
B3-BR2	3.73	490
BR2-B3	3.90	355
BR2-BR2	3.32	378

Table 5 shows the results of the four soft arm designs that use six control inputs. The designs are represented in Figure 5 by the blue area on the plot. The four FREE designs that include six control inputs are separated by a wide margin compared to all other designs. Indeed if weight and complexity is not a dominant factor in looking for a serial soft robot manipulator design to be used in a general case, six input designs are recommended. Despite the five control input B3-BR having the greatest workspace volume due to its relative low weight and flexibility, all four designs have comparably high workspace volume with greater dexterity. In a general case, the pattern of symmetrical B3 manipulator segments performing well as a balance of workspace and dexterity emerges again in this control input group. The B3-B3 manipulator has the highest equally weighted average dexterity and workspace volume values over any design studied. Both segments are symmetric and therefore end effector's rotation would not be able to be directly controlled by the user. The control complexity for the six control input designs are comparatively stochastic. If the rotation of the end effector is desired, the B3-BR2 is recommended as a balance of symmetric and asymmetric manipulators that will enable the user to develop a more straightforward control scheme. The proximal B3 segment provides greater workspace volume as compared to proximal BR2 designs and the distal BR2 enables rotational control.

4.3 Discussion

4.3.1 Symmetric vs Asymmetric: An interesting area of study made possible by serialized SCMs is the combination of symmetric and asymmetric segments in a single manipulator. Symmetric SCMs consist of only bending segments such as the B3 manipulator studied. Asymmetric actuators have at least one bending segment but must also have between one and two rotating FREEs. Symmetric SCM designs are typically made for higher workspace and lower dexterity applications as compared to asymmetric SCMs with the same number of control inputs. Purely symmetric actuators produce a workspace of points where each point is achieved by exactly one control input. Since each end effector point is achieved by a single unique shape, the dexterity metric consists only of points near each other whose end effector tangent vectors align with different octants. Since every control input is used for bending deformation, the workspace point cloud is also typically larger in volume as compared to asymmetric workspaces. Asymmetric SCMs may have greater dexterity since points in a workspace may be achieved by multiple control inputs reaching the same position in space. The mechanism that achieves this is the use of either clockwise or counterclockwise rotating manipulators. For example, a BR2 workspace may contain a point in space located near the axis of the FREE that is achieved through low bending pressure and high rotation pressure. The end effector tangent vector in this case will vary depending on the rotation direction being applied and may not fall into the same octant if rotated in the opposite direction. Two points in the same position but with different orientations will produce a higher dexterity value for the point in the workspace. It should also be noted that FREE designs that contain both types of manipulator in series have dexterity benefits over uniform designs. The B3-BR for example achieved the highest overall dexterity metric for its proximal symmetric actuator that expanded the SCMs workspace and distal lightweight asymmetric segment providing rotation and stochastic deformation possibilities. This trend towards variety is most pronounced over higher control inputs as knputs of three or lower are primarily a study for serial vs parallel design. In summary, symmetric manipulators typically produce a workspace consisting of points achieved by a one to one function of control input to shape. Asymmetric manipulators are unique in that the workspace may contain some points where the use of opposite rotating manipulators provided the same end position with different vector orientation leading to higher dexterity. Creating a serial FREE with a combination of both symmetric and asymmetric segments yields the greatest performance increases. These increases are most evident for application studies and high control input availability (< 3).

4.3.2 Serial vs parallel: Serial manipulators in two segments as studied in this paper require extra considerations when made. Physically they are more complex as air lines for distal segments typically run along each preceding proximal segment. Comparatively, parallel manipulators are more simple to construct as all air hoses may be directed to a single manifold at the base of the FREE. Since extra effort is required to create serial FREEs, dexterity and workspace benefits of FREEs with more than one segment can be used to justify their consideration. An example showing advantages of serialized designs over parallel equivalents are seen in the above study of FREE combination designs with three control inputs. Studied are the two most common parallel manipulators: B3 and BR2 and a simple two segment serial manipulator: BR-B. Despite both designs consisting of the same length and control inputs, the BR-B out performs both of the parallel variants in workspace volume and dexterity. The increase in dexterity is attributed to by the increase in deformation modes that can be achieved with serial configurations. Symmetric parallel manipulators such as the B3 only have a single control input for any given point in their workspace. Asymmetric parallel manipulators may have additional control input possibilities to achieve a given workspace position in space, but for the case of the BR2, the maximum possible number of inputs is two. To reach some desired points with a BR2 the control input may use either the clockwise or counterclockwise rotators. However, with a serial configuration, achieving a certain end effector point is a function of controlling both segments, increasing the number of possible input combinations. Since some points in space reached by a serial manipulator consist of an increased variety of shapes, the dexterity metric for those points is greater.

It is shown by these examples that serial design architecture is superior to equivalent parallel combinations of FREEs. Figure 5 has a yellow comparison region of two parallel three input FREEs and one serial. The serial actuator due to its increased shape possibilities and decreased weight achieves both greater workspace volume and dexterity. The trend continues across other control inputs as well.

5 Examples

While we compared absolute workspace and dexterity for architectures of several FREE combinations, the results may not truly represent optimal design choices for some practical applications. For example soft manipulators in agricultural berry picking [4] are deployed in a hybrid configuration, where part of the workspace and dexterity of the overall robot stems from conventional rigid links and joints. In this section, we will investigate two such applications which may result in interesting design alternatives.

5.1 VALENS

The VALENS configuration [19] stores a soft manipulator within it to be extruded outwards at a desired margin. The control of the length of the serial arm designs being studied changes their performance when measured with dexterity and workspace volume. Typically in applications, the VALENS device is attached to the end of a six degree of freedom robotic arm. The

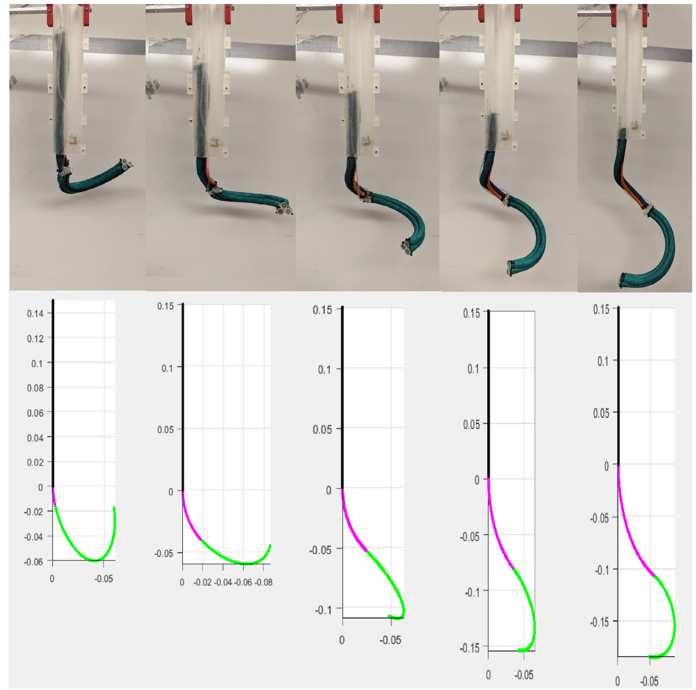


FIGURE 6. Five VALENS Extrusions of a BR2-B3 under the same pressure inputs used in simulation and the physical manipulator

workspace volume and dexterity in this case would be dictated by the properties of the rigid manipulator, making a comparison between soft manipulators meaningless. In order to circumvent the study of rigid manipulators used in tandem with the SCMs, we are assuming that the VALENS device is stationary, pointing downwards as depicted in Fig. 6. Each design has been simulated using a uniform distribution of 1000 different control input pressures each applied at five equal extrusion lengths. Figure 6 shows each extrusion length on a physical BR2-B3 and the simulated equivalent, both formed using the same pressure control inputs and extrusion lengths. The characteristic shapes in the physical model and simulation are similar with differences occurring possibly due to slightly inaccurate weight and flexibility calculations.

The total 5000 point cloud generated in simulation for each design is run through the Kirchhoff framework used in the general case studies to determine dexterity and workspace volume. The results of these simulations are catalogued in table 6. The table lists each design in order of resultant dexterity as workspace can be changed in application through rigid manipulation. As a departure from the generalized case where the best manipulators had proximal symmetric segments, the VALENS study suggests the dominance of proximal asymmetric designs. The top model recommended for the application and chosen to be depicted in figure 6 is the BR2-B3. The proximal BR2 is assumed to not rotate or bend in sections that are within the VALENS and can be seen following this assumption on the physical model.

TABLE 6. All FREE designs on the VALENS system studied each for 5000 points at five extrusion subdivisions

Type	Dexterity	Workspace
BR2-B3	3.88	297
BR2-BR2	3.32	332
B3-BR2	3.23	416
B3-B3	3.13	376
BR2-BR	3.10	310
BR2-B2	2.77	334
B3-B2	2.45	318
B3-BR	2.41	329
BR2-B	2.79	338
BR-B2	2.50	345
B2-BR	2.12	291
B2-B2	1.48	274
B3-B	1.44	246
BR2	1.37	119
BR-B	1.35	213
B3	1.10	265
BR	1.32	63
R-B	1.05	57

5.2 FarmBot

FarmBot [20] is an agriculture CNC farming project whose product being studied is a Cartesian coordinate robot farming machine. Traditionally, the FarmBot Genesis being used for our experimentation does not come equipped with an end effector more than one degree of freedom. The capabilities of the FarmBot can be enhanced with the attachment of a highly dexterous SCM. The gantry enables the FREE to translate in all directions making this experiment unique to the other stationary base cases studied. Similar to the VALENS setup, the SCM will also be attached at its base to a platform that rotates on the vertical axis of the gantry. In order to determine which FREE design and combination is best suited to this application, the simulation data must first be manipulated. Since a rotating platform is now attached to the SCM: the point cloud data generated in the general application cases are rotated about the Z axis onto the X-Y plane. From here our workspace metric becomes meaningless as the points are now planar with no volume. Because the FarmBot's gantry allows for translation in three dimensional space, the only metric being considered is dexterity. The FREE design and combination with greatest dexterity is projected to provide the most use with the FarmBot application.

FIGURE 7. BR2-BR2 attached to the FarmBot showing a possible deformation shape to get around the back and under a leaf of a basil plant

Table 7 shows the planar dexterity results all FREE designs studied when attached to a rotating base as found on the FarmBot system.

The dexterity metric is averaged by 1 centimeter square areas on the YZ plane that the workspace inhabits likewise to the 1cm cube volumes of the primary results section.The most notable finding in the table and corresponding figure 7 overall is that once the FREE workspace is rotated about the vertical axis to the YZ plane, proximal rotating segments dominate in high dexterity measurements. An explanation for this phenomena is that any pure bending proximal segment is made redundant by the rotating base. The three port single section B3 in the table has a dexterity of 1.19. This is a result of the B3 having nearly the same characteristics as a single bending section when measured in planar space. Single bending actuators will always result in a dexterity metric of 1 as there is only a single control input to achieve a desired actuation shape.

TABLE 7. All FREE designs studied on the FarmBot gantry using a planar form of the dexterity metric as it is assumed the farmbot setup includes a rotating base

Type	Dexterity	Type	Dexterity
BR2-BR2	12.48	BR2-B3	11.72
B3-BR2	10.03	B3-B3	9.47
BR2-BR	12.24	BR2-B2	10.44
B3-BR	9.19	B3-B2	8.72
BR-B2	10.90	BR2-B	10.35
B3-B	6.65	B2-BR	4.58
B2-B2	3.14		
BR-B	6.79	BR2	4.21
B3	1.09		
BR	3.78	R-B	1.27

6 Conclusion and Future Work

The paper presents a design space enumerations of pneumatically actuated soft continuum manipulators for their workspace and dexterity. Fiber reinforced elastomeric enclosures (FREEs) are used as the building blocks to construct the SCMs as they enable versatile deformations such as contraction and rotations. Combining different FREEs in series and/or parallel can result in a number of interesting architectures with different behaviors. Specifically, the paper compares asymmetric combination of FREEs (i.e. two rotating FREEs in parallel with a bending FREE) with the more conventional symmetric combination (three bending FREEs in parallel). While in general, symmetric combinations yielded large workspace due to persistent bending, combining rotational FREEs could give larger dexterity. The effect was consistent in serial architectures as well, although as the number of control inputs increase the difference between symmetric and asymmetric architectures diminish. The paper also emphasizes the importance of how the optimal design changes with the conditions of deployment as dictated by the application. Furthermore, the paper presents a computational framework built on quasistatic Kirchhoff rods to evaluate dexterity and workspace of any combinations of FREEs (serial and/or parallel). The methodology presented in the paper is deemed useful for selecting the right SCM for any application.

In future work we would like to explore considerations such as dynamics, hysterisis and controls in the design selection methodology. Furthermore, load dependence is another factor that need to be studied. Certain SCM architectures may naturally bear more loads and yield precise motion than others. We also aim to present the resulting enumeration and workspace and dexterity evaluation method within a user-interactive framework.

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