

Design of Soft Continuum Manipulators Using Parallel Asymmetric Combination of Fiber Reinforced Elastomers

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Abstract—Soft continuum manipulators have large workspace, dexterity and adaptability, but at the cost of complex design construction highlighted by concatenating several individually controlled serial segments. In this paper, we propose a new design architecture for a soft continuum manipulator composed of a parallel combination of pneumatic actuators. The BR^2 manipulator, featured in this paper is asymmetric as it combines one soft bending (B) actuator and two soft rotating (R^2) actuators, as opposed to state of the art symmetric architectures that adopt bending segments. Spatial deformation modes are achieved by combining curvature and torsion of the individual actuators. This paper formulates a forward analysis method based on Cosserat rod mechanics to predict the spatial deformation of the manipulator under effect of external loads with an accuracy less than 9 % of the manipulator length. The model takes into account ‘the coupling effect’ inherent to the asymmetric combination, where pressurizing the rotating actuator attenuates the bending curvature and vice versa. Consequently, the paper studies the optimal design of the manipulator constituents that minimize the coupling, and thus maximize the workspace and dexterity. A detailed performance study of the BR^2 manipulator on a swiveling base demonstrates a spatial workspace quantified by an axisymmetric area, and sufficient dexterity such that at least 87% of the workspace can be approached with two or more orientations. These are validated through obstacle avoidance, and a pick and place task. The manipulator is also capable of whole arm manipulation by spiraling along cylindrical objects of varying diameters. These performance attributes surpass any other single segment module, and is a potential building block for constructing customized continuum manipulators.

Index Terms—Biologically-Inspired Robots, Flexible Arms, Parallel Robots, Smart Actuators

I. INTRODUCTION

SOFT robots are gaining significant attention from the robotics community due to their adaptability, safety, lightweight design and cost effective manufacturing [1]–[4]. They are primarily used in manipulation, locomotion, and wearable devices [1]. In manipulation, soft continuum arms are used to explore uneven terrains, handle objects of different sizes and interact safely with the environment [4]. They are shown to be feasible in assisting with activities of daily living, especially where the robot needs to interact with aged or disabled humans [5]–[7]. These soft continuum arms are generally long, slender, and compliant. Their body structure is made of a combination of muscles and soft appendages similar to octopus tentacles or elephant trunks [8]. They

deform spatially due to inherent actuation of these muscles combined with passive elastic deformation due to external loads, thus adapting to the surroundings and reducing the need for complex controls [7].

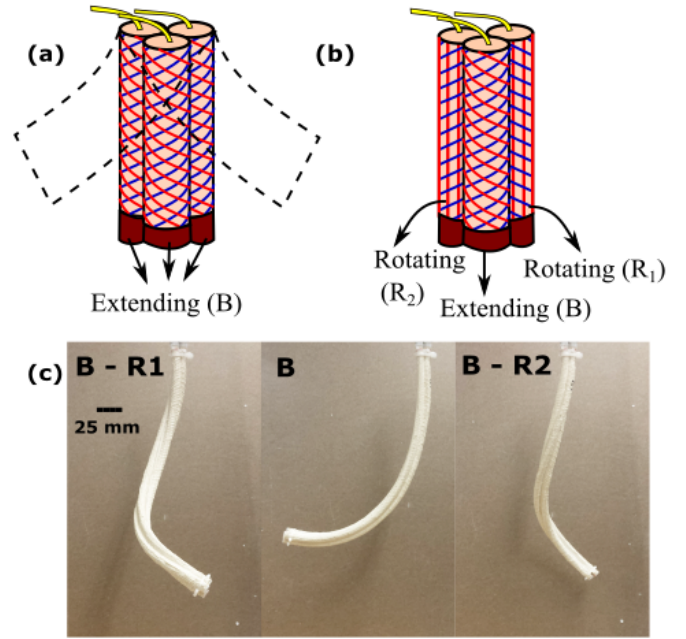


Fig. 1. Contrasting the design architecture of conventional soft pneumatic continuum manipulators consisting of (a) symmetric building blocks (composed of three bending actuators), (b) combination of asymmetric building blocks (composed of one bending actuator, one clockwise rotating and one counter clockwise rotating actuator). (c) Deformation modes of BR^2 manipulator proposed in this work (Bending with counter clockwise rotation, bending alone and Bending with clockwise rotation)

Soft continuum arms are actuated either (a) pneumatically, or (b) by motor-driven tendons, or a combination of the two. Pneumatically actuated continuum arms are designed using several bending segments serially concatenated to yield a spatial workspace [9]–[11]. Each bending segment consists of several soft pneumatic actuators that extend upon pressurization, and are connected along a common seam as shown in Figure 1a. The extension is due to the orientation of reinforced fibers on an elastomer cylinder (also known as Fiber Reinforced Elastomeric Enclosures or FREEs [12]). Pressurization of a single FREE leads to bending as its uniform extension is restricted at the seam. This combination of extending building blocks is considered symmetric because each FREE actuator

has similar behavior, and their parallel architecture results in spatial bending in different directions (shown as dotted lines in Figure 1a). Typical examples that use this architecture include the Tri-chambered actuator [13], [14], and the stiff flop manipulator [15], [16].

To obtain a large spatial workspace, dexterity, and to enable whole arm manipulation, state of the art soft continuum arms consist of several such symmetric sections that are serially combined. Serial concatenation leads to a complex design architecture, where hoses running through the body of the manipulator supply pressurized air to the distal ends. This results in bulky designs, with inertial effects that attenuate the workspace [17]–[19] and complicate the controls.

In contrast, we propose a design architecture involving an asymmetric combination of soft pneumatic FREE actuators that can potentially yield spatial deformation. Figure 1b illustrates an architecture where an extending FREE is combined with two FREEs that axially rotate upon actuation. The combination of a bending mode (B) and two axially rotating modes (R^2) gives rise to a spiral deformation profile as shown in Figure 1c. This is achieved without the necessity of serially concatenating segments. Therefore the BR^2 manipulator is extremely useful in tasks such as whole arm manipulation where the entire length of the arm spirally wraps around objects. In contrast, the conventional OctArm manipulator is able to spiral [9] with four serially concatenated segments that are individually actuated.

In this paper, we investigate the BR^2 architecture for its common attributes such as workspace and dexterity using an experimental characterization scheme and mechanics based modeling. We demonstrate that this architecture yields large spatial workspace and dexterity, while simultaneously maintaining compactness.

A. Challenges and Related Work

Asymmetric architecture of the BR^2 manipulator is challenging to model and design because of the coupling between the bending and the rotating FREE constituents. The rotating FREE and bending FREE limit each other deformation. In this scenario, the performance of the arm: workspace, dexterity and ability to manipulate using the entire arm, greatly depends on an optimal design that reduces the coupling between these FREE constituents. Thus, capturing the coupling effect is an important aspect for an effective model. The second challenge is the dependence of the manipulators deformation on external loads. While this issue exists in conventional design architectures [19], the BR^2 design additionally experiences variations in elastic properties such as flexural and torsional rigidity that are a result of change in the actuation pressures. Manufacturing variations, which are typical in soft robotics fabrication, further contribute to these nonidealities.

There are several modeling formulations used to predict the deformation of soft continuum arms ranging from the simplistic constant curvature models [20]–[25], to geometrically exact Cosserat rod models [17]–[19]. The latter takes into account the elastic properties of the arm, and predicts deformation under external loads, thus making it ideal for design [26].

The real challenge in using the Cosserat rod formulation in the context of the BR^2 design is to incorporate the coupling between asymmetric constituents and accurately estimating the varying elastic properties, which are often neglected in most models.

B. Approach

Our approach in this paper is an experimental characterization scheme, followed by an inverse analysis to predict the actuation coupling and material elasticity variations. These quantities are then fed into a precurvature-based Cosserat rod model for forward analysis. The BR^2 design is experimentally characterized for its end effector position and its orientation for various combinations of applied pressure to the extending and the rotating FREE actuators. An inverse Cosserat rod formulation maps the precurvature, torsion and the flexural rigidity of the continuum arm as a function of pressures in the bending and the rotating FREEs. These three quantities are maximally invariant to the external applied load and boundary conditions. Thus, the quasistatic deformation profile of the arm can then be predicted for any loading condition and input actuation pressure.

An initial investigation into the aforementioned characterization scheme for a combination of a single bending B and rotating R manipulator was presented in our previous work [27]. In Section III of this paper, we briefly review this characterization scheme, which is now generalized to predict the forward analysis of the BR^2 manipulator. The focus of this paper is different from [27], in that it uses the analysis framework for the optimal design of the BR^2 manipulator, and to study its workspace and dexterity metrics. The resulting implications of this paper are significant, as it demonstrates the advantage of BR^2 architecture over existing symmetric architectures through an objective comparison of the workspace and dexterity.

In Section IV, we study the coupling behavior between the rotating and bending FREEs, and determine optimal diameter ratios between the two constituents to minimize coupling effect on each other and maximize the workspace. Furthermore, we study and validate the forward analysis model of the optimum BR^2 architecture under the action of different end loads. In Section V, we study the workspace and dexterity of the BR^2 manipulator stationed on a swivel base. We demonstrate that such a configuration is able to attain a spatial axisymmetric workspace, and is able to approach almost 87% of its workspace in more than one orientation without redundancy. The workspace and dexterity is demonstrated through standard manipulation tasks such as obstacle avoidance, pick and place, and whole arm gripping. In Section VI, we summarize the major contributions of the paper.

II. WORKING PRINCIPLE OF ASYMMETRIC MANIPULATORS

In this paper, we conceptualize a soft continuum manipulator as a parallel combination of soft pneumatic building blocks known as FREEs. 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 [12], [28], [29] as shown in Fig. 2. FREEs are similar in construction to McKibben artificial muscles [30] but are capable of generating different deformation patterns that include extension, contraction, rotation, and screw motion. The deformation patterns are determined by fiber angles. The fabrication methodology of FREEs is detailed in the authors' previous publications [28], [31].

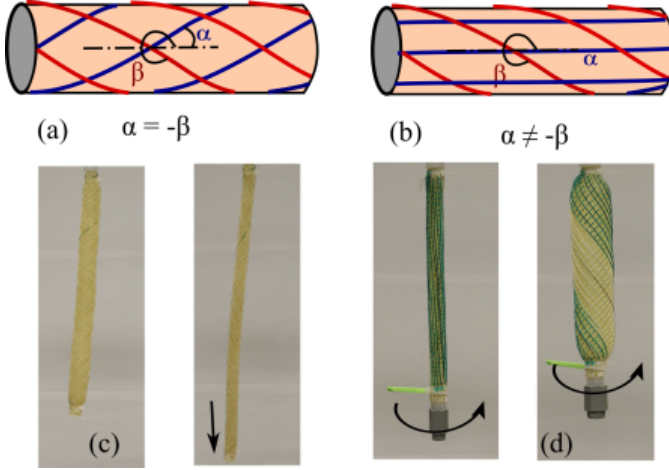


Fig. 2. Fiber Reinforced Elastomeric Enclosures (FREEs) consist of two families of fibers. (a) Extending FREEs have equal and opposite fibers, and (b) rotating FREEs consist of a straight and helical fibers. Their corresponding deformations are shown in (c) and (d) respectively.

The BR^2 manipulator consists of three FREEs, one extending FREE denoted by B , and two rotating FREEs denoted by R (one rotating clockwise and the other counterclockwise). The three FREEs are joined in parallel and share a seam along its length. The manipulator is mounted on a motor controlled swivel base, and is hanged vertically downwards under gravity as shown in Fig. 3(a). The extension in the B FREE is constrained by the seam leading to unidirectional bending deformation, which in an ideal scenario corresponds to a constant curvature deformation. The combination of the bending and the rotating FREE changes the direction of the curvature spatially as shown in Fig. 3(a), enabling the end of the arm to reach any point in the workspace at an angled pose. The simultaneous actuation of the swiveling base and the FREEs enable the accessibility of any region in the workspace through multiple orientations.

We have chosen the fiber angles for the B and the R FREEs based on their ability to maximally bend and twist. Using the simplified kinematic equations presented in [12], we observe in Fig. 3(b) that maximum possible bending occurs when the the fibers are purely circumferential. However, we choose a fiber angle of $\alpha = -\beta = 85^\circ$ as perfectly circumferential annular rings are difficult to manufacture. Similarly, the maximum possible torsion (axial rotation per unit FREE length) is observed close to $\alpha = 60^\circ$ and $\beta = 0^\circ$ from Fig. 3(c), and is therefore adopted in our design.

III. MODELING OF THE BR^2 CONTINUUM MANIPULATOR

In this section, we propose a Cosserat rod model to predict the deformation of the continuum arm composed of asymmetric

building blocks. The Cosserat rod model is ideal for continuum manipulators because they are long, slender and deform as a continuum [32] [8] [33] [34]. However, there are challenges in applying the Cosserat model for asymmetric building block architecture, which are elucidated in this section.

A. Precurved Cosserat rod model

In Cosserat rod model, we describe the manipulator by a curve in space $\mathbf{r}(s) \in \mathbb{R}^3$ with the material orientation given by $\mathbf{R}(s) \in SO(3)$ where s is the reference variable given by $s \in [0, L]$. Deformation of the curve is described by the kinematic variables $\mathbf{u}(s)$ and $\mathbf{v}(s)$, where $\mathbf{v}(s)$ represents the linear rate of deformation while $\mathbf{u}(s)$ represents the angular rate of change of the spatial curve describing the manipulator. In our manipulator, due to its construction, axial extension and shear are assumed to be negligible. Therefore, we write $\mathbf{v}(s) = [0 \ 0 \ 1]^T$. Using the equilibrium equations and constitutive laws with the stated assumptions on $\mathbf{v}$, we can obtain the full set of differential equations describing the manipulator deformation given by:

$$\dot{\mathbf{r}} = \mathbf{R}\mathbf{v} \quad (1)$$

$$\dot{\mathbf{R}} = \mathbf{R}\hat{\mathbf{u}} \quad (2)$$

$$\dot{\mathbf{u}} = -\mathbf{C}^{-1}(\hat{\mathbf{u}}\mathbf{C}(\mathbf{u} - \mathbf{u}_0) + \hat{\mathbf{v}}\mathbf{R}^T(\mathbf{f}_b(\mathbf{L} - \mathbf{s})\mathbf{g} + \mathbf{f}_e)) \quad (3)$$

where $\mathbf{C}$ is the elasticity matrix for bending and torsion given by:

$$\mathbf{C} = \begin{pmatrix} EI & 0 & 0 \\ 0 & EI & 0 \\ 0 & 0 & GJ \end{pmatrix} \quad (4)$$

here, $\mathbf{f}_b$ is weight per unit length, $\mathbf{f}_e$ is the end load. $\mathbf{e}$ is direction of gravity and $\mathbf{g}$ is acceleration due to gravity. $\hat{\mathbf{u}}$ and $\hat{\mathbf{v}}$ are the skew symmetric matrices of $\mathbf{u}$ and $\mathbf{v}$ respectively. The other set of parameters needed are the material and geometry parameters that go in the stiffness matrix, $\mathbf{C}$, namely the flexural rigidity, EI and torsional rigidity, GJ . Here, E is Youngs modulus, G is shear modulus, I is second area moment, and J is the polar area moment of the cross section. Both rigidities EI and GJ which appear as products in the model equations are treated as a single unknown variable. The actuation in the model is considered as a constant precurvature κ_0 and torsion τ_0 that constitute the vector $\mathbf{u}_0$, and are functions of applied pressure in the rotating and bending FREEs.

B. Coupling effect due to combining asymmetric actuators

To apply the Cosserat rod model, we need to estimate the actuation κ_0 , τ_0 and stiffness EI , GJ as a function of pressure. However, because of the nature of the design, pressurizing either rotating FREE or extending FREE effects the other FREEs deformation. This implies that κ_0 is a function of the pressure not in the bending FREE alone, but also the pressure in the rotating FREE. Similar coupling also exists for the rotation deformation, where torsion τ_0 is attenuated by the pressure in the bending FREE in addition to that of pressure in rotating FREE. Similarly, the flexural and torsional rigidity vary as a function of the applied bending and rotation pressure.

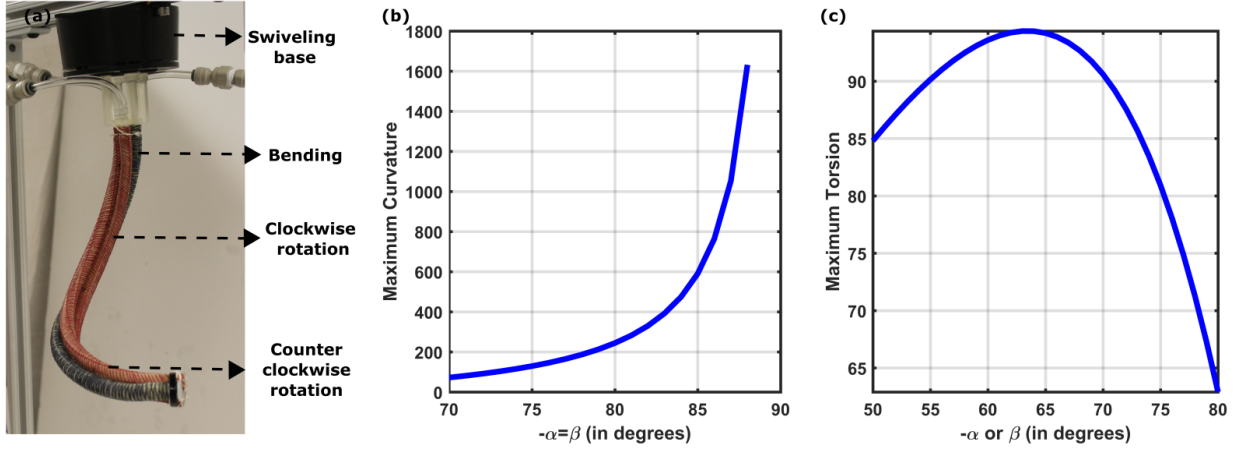


Fig. 3. BR^2 and the selection of fiber angles. (a) The different constituents of the BR^2 manipulator. (b) Curvature as a function of fiber angle for bending (B) and (c) Torsion as a function of fiber angle for the rotating (R)

The overall coupling is difficult to evaluate using a mechanics based model because of its dependence on minute variations in the manufacturing process, and the strength of the interface between the FREEs.

C. Inverse formulation

In this paper, we present an experimental method followed by an inverse model to estimate the four parameters (κ_0 , τ_0 , EI , GJ) [27] as a function of actuation pressures in the FREEs. The procedure involves collecting the shape of the manipulator at different pressure combinations of the bending (B) and rotating (R) FREEs. This is followed by an optimization-based inverse routine to estimate the four parameters by factoring known manipulator length, weight and end effector load (if any) in the Cosserat rod equations.

For any given pressure P_{BR} (subscript denotes the pressures of bending and rotating actuators respectively), the optimization-based inverse problem can be formulated as [27]

$$\min \left[\left(\frac{\kappa_0}{\kappa_p} - 1 \right)^2 + \left(\frac{\tau_0}{\tau_p} - 1 \right)^2 + \left(\frac{EI}{EI_p} - 1 \right)^2 + \left(\frac{GJ}{GJ_p} - 1 \right)^2 \right] \quad (5)$$

where κ_0 , τ_0 , EI and GJ are the optimization variables. κ_p is curvature at P_{B0} under no load condition, τ_p is curvature at P_{0R} , EI_p is the flexural rigidity at P_{B0} and GJ_p is the torsional rigidity at P_{B0} . Furthermore, we impose the following nonlinear constraints on matching the deformed shape between the experiment and the model.

$$\| \mathbf{r}_{analysis}(end) - \mathbf{r}_{exp}(end) \| < \epsilon_1 \quad (6)$$

$$\| \mathbf{r}_{analysis}(s) - \mathbf{r}_{exp}(s) \| < \epsilon_2 \quad (7)$$

Equation 6 represents a constraint that the Euclidean distance between the experimental and analytical end position is within a threshold value, ϵ_1 . Equation 7 is the constraint that the Euclidean distance between the experimental and analytical positions throughout the curve are less than a threshold value ϵ_2 , which is equal to the maximum cross sectional dimension of the manipulator. Global optimizer in MATLAB is used to solve with fmincon optimization routine that uses SQP

method. The method of continuation [35] is used to solve the set of differential equations.

Once the parameters are estimated at discrete combinations of P_B and P_R , they can be interpolated and the forward Cosserat model can be solved to obtain the deformed profile under any external loading condition.

IV. OPTIMAL DESIGN CONSIDERATIONS

It is evident that the manipulator's performance metrics such as workspace and dexterity will be maximum if no coupling based attenuation occurs. While the mechanics of combination cannot prevent coupling based attenuation, it can be minimized by tuning the geometry parameters that govern the relative FREE stiffness. In particular, we explore the dependence of the coupling on the ratios of the B and R diameters. Finally, we map the actuation and stiffness parameters for the optimized BR^2 design, and validate a forward analysis model that predicts the manipulators deformed shape under the action of external loads.

A. Optimal diameter ratios

To study the effects of the relative FREE diameters on the manipulator workspace, we simplify the manipulator design to a BR architecture. This is similar to the BR^2 architecture with only one R FREE and one B FREE [27]. Three BR manipulators with R to B diameter ratios of 1, 2/3 and 1/3 are fabricated using the method described in [28] and we denote these prototypes as $P1$, $P2$, and $P3$ respectively. The length of the three fabricated prototypes are 310 mm. The bending actuator inner diameter is fixed to 9.52 mm in all three prototypes. Thus, Prototype 1 ($P1$), Prototype 2 ($P2$) and Prototype 3 ($P3$) have rotating actuators with diameters 9.52, 6.35 and 3.18 mm respectively. In order to compare these manipulators on a common ground, we normalize the extremities of the workspace for each prototype. We note the pressures in the bending FREE (P_{iBmax} , where $i = 1..3$ denotes the prototype number) that deforms it to one full circle on a plane, and the rotating FREE (P_{iRmax}) that leads to a 360° axial rotation. For a given prototype, this

will be the maximum actuation pressure for the B and the R FREE respectively. Then, we apply pressures within this range for each prototype and digitize the deformed shape using a microscribe. The pressure ranges and the step size of pressures used to obtain the experimental shape are in Table I.

TABLE I
OPERATING PRESSURE RANGES FOR THE THREE PROTOTYPES. (UNITS OF PRESSURE IN PSI)

Prototype	$R_B:R_R$	P_B	ΔP_B	P_R	ΔP_R
P1	1:1	36	9	16	4
P2	2:3	36	9	36	9
P3	1:3	28	7	60	15

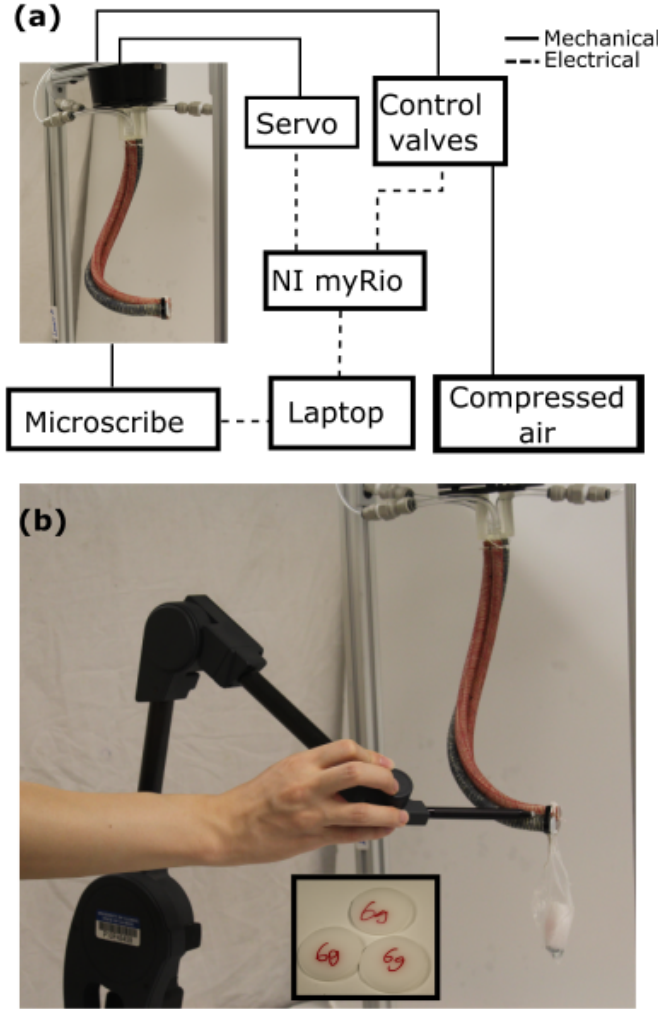


Fig. 4. (a) Block diagram of the setup used to control the actuation pressures, base rotation angle and obtain the deformed shape using Microscribe digitizer . b) Microscribe used to obtain the deformation of the BR^2 manipulator when actuated to 23 psi and 15 psi in bending and rotating actuators respectively with and end weight of 21 gms (including the weight of end caps). In inset weights used shown.

The schematic of the experimental setup is shown in Fig 4 (a). The shape of the manipulator is obtained using a 3D digitizer (Microscribe). The input pressures in the manipulator and the angle of the swiveling base are set using National

Instruments myRIO. The pressure is controlled using pressure regulator (SMC ITV0050-2UN).

Once the experimental shape is determined the parameters are estimated using the inverse framework (Eq. 5, Eq. 6, Eq. 7) described in modeling section. The inverse framework estimates the actuation parameters, which are the uniform pre-curvature (κ_0) and torsion (τ_0) in the B and the R FREEs respectively from the deformed shape of the manipulator under the effect of gravity. Figure.5 shows the variation of κ_0 and τ_0 as a function of actuation pressures in the B and the R FREEs. In Fig. 5(a), we see a strong coupling effect where the curvature for a given bending pressure ($P1_B$) decreases with increasing pressures in the rotating FREE ($P1_R$). Similarly, in Fig. 5b, we observe a decrease in torsion with increase in bending pressure $P1_B$. Furthermore, the maximum pressures for the bending FREE $P1_{Bmax}$ is more than the rotating FREEs $P1_{Rmax}$, indicating greater attenuation in bending than in rotation for prototype P1.

The attenuation in curvature κ_0 is seen to decrease for P2 and P3, where the diameter of the rotation FREE is progressively smaller than the bending FREE. This makes the rotating FREE less stiff than the bending FREE. From Fig. 5(c) and (d) we observe that the maximum pressures for both the B and the R FREEs are in the same range for prototype P2 (R over B ratio of 2/3). This scenario is preferred as it simplifies controls, by permitting similar valve pressure presets for both actuators. On the other hand, Prototype P3 (R over B ratio of 1/3) experiences reduced attenuation for bending while the actuation pressure for rotation is significantly higher. Both prototypes P2 and P3 experience reasonable attenuation in torsion.

The attenuation in κ_0 and τ_0 manifest as a reduction in workspace. From Fig 6(a) and 6(b) it is observed that the spatial points spanned by P2 and P3 reach a larger workspace area than P1, indicating that the bending attenuation maximally influences the workspace. From the analysis of attenuation, pressure ranges and workspace considerations, we choose P2 to have the optimal diameter ratio. Adding an additional R FREE that rotates in the counterclockwise direction does not change the results, as in this work we limit only one R to be actuated in combination to B to reach any spatial point. The optimal BR^2 manipulator is fabricated with rotating actuators having inner diameter of 6.35 mm and extending actuator with inner diameter of 9.525 mm. As mentioned in Section II, the fiber angles used for the bending actuator are $\alpha = 85$ degrees and $\beta = -85$ degrees. For the rotating actuator the fiber angle is $\alpha = 0$ degrees and $\beta = -60$ degrees. Each of the actuator in BR^2 achieve one full circle when B actuator is actuated and 360° rotation when R actuator is actuated individually at 28 psi. If the FREE actuators were made with stiffer elastomers, the pressure ranges to obtain the same deformation could be higher.

The inverse formulation is used to estimate the actuation pre-curvature and torsion parameters of the BR^2 manipulator. The procedure is similar to the process for BR prototype and the results are shown in Fig. 7(a)-(b). Here, it is assumed that only one of the R FREEs in the BR^2 will be actuated at a time. The results from the inverse model also capture the variation

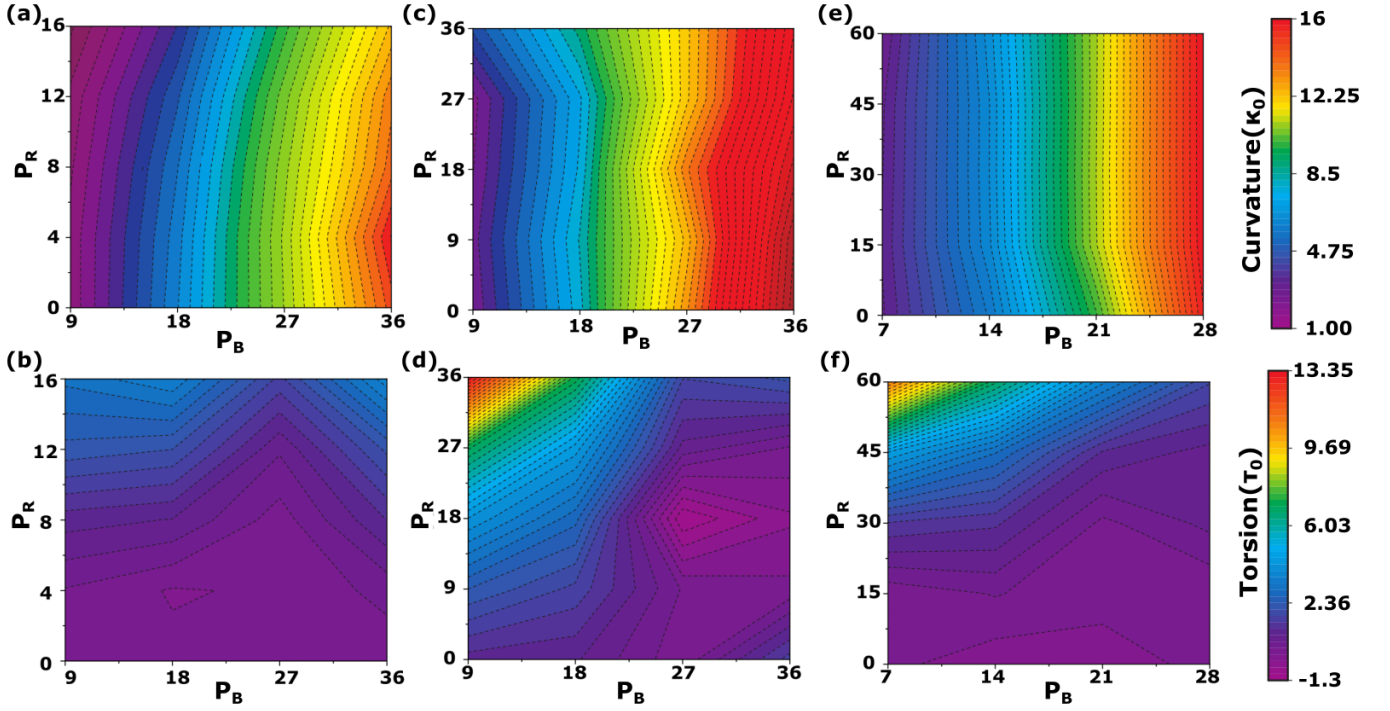


Fig. 5. Estimated actuation parameters (Curvature, κ and Torsion, τ) of three prototypes with rotating to bending diameter ratios of $P1 = 1$ (a),(b), $P2 = 2/3$ (c),(d) and $P3 = 1/3$ (e),(f)

of the flexural rigidity EI as a function of the pressures in the B and the R FREE with only one R FREE actuated as shown in Fig. 7(c). However, when both the R FREEs are actuated simultaneously, there is an increase in flexural rigidity and thus the stiffness as observed in Fig. 7(d). In this scenario, the clockwise and counterclockwise rotations negate each other leading to bending deformation alone. The flexural rigidity denoted by EI is three times more in Fig. 7(d) than in Fig. 7(c).

B. Analysis of the BR^2 manipulator

After mapping the design and actuation parameters for BR^2 in Fig. 7, forward analysis can be used to obtain the deformed profile of the manipulator under action of external forces using the steps elucidated in Fig. 9. The external forces can be either in the form of a uniform distributed load or as a load at the end point due to an end effector or an object to be manipulated. The forward model can be used to simulate the deformed profile of the continuum arm during the manipulation operation such as path tracing, pick and place and whole arm grasping.

C. Validation

To validate the model, we define an error metric that captures the difference between the end effector position estimated from the modeling framework and the experimental measurement, normalized by the total distance moved by the end effector.

$$\text{error}_{metric} = \frac{|r(l)_{exp} - r(l)|}{r(l)} \quad (8)$$

where $r(l)$ is the end effector position determined by solving Eq. 1. The experimental end effector position $r(l)_{exp}$ is measured from the Microscribe digitizer for 165 different combinations of the actuation pressures. Fig 10(a) shows the histogram of the error metric. The minimum error is 2.2 mm and maximum error is 54.6 mm. The mean error is 25.4 mm which is 8.19% of the manipulators length.

The BR^2 continuum manipulator's deformation is strongly dependent on the external loads imposed on it. The analysis methodology proposed identified the actuation and the stiffness parameters that could be fed into the Cosserat rod model to simulate the manipulator's deformation under any load distribution. The validity of the proposed model can be ascertained by comparing the manipulator's end position to the experimental values under different external loads.

The BR^2 is actuated to bending and rotating pressures of 23 psi and 15 psi respectively. The end effector is loaded with weights as shown in Fig4(b) and the end positions are collected and compared to the forward model with different loads. Fig 10(b) shows that the errors are less than 25 mm for the loads applied, which is similar to the error range evaluated under no external loads. Furthermore, the errors in clockwise rotation was found to be relatively more than the errors obtained in counterclockwise rotation, which indicate asymmetries in the manufacturing of the two rotating FREEs.

V. MANIPULATOR PERFORMANCE STUDY

The single section BR^2 manipulator presented in this paper can perform spatial deformations due to its unique design. Previous explored pneumatic soft manipulators [10] [36] used serial arrangement in order to achieve similar spatial motion

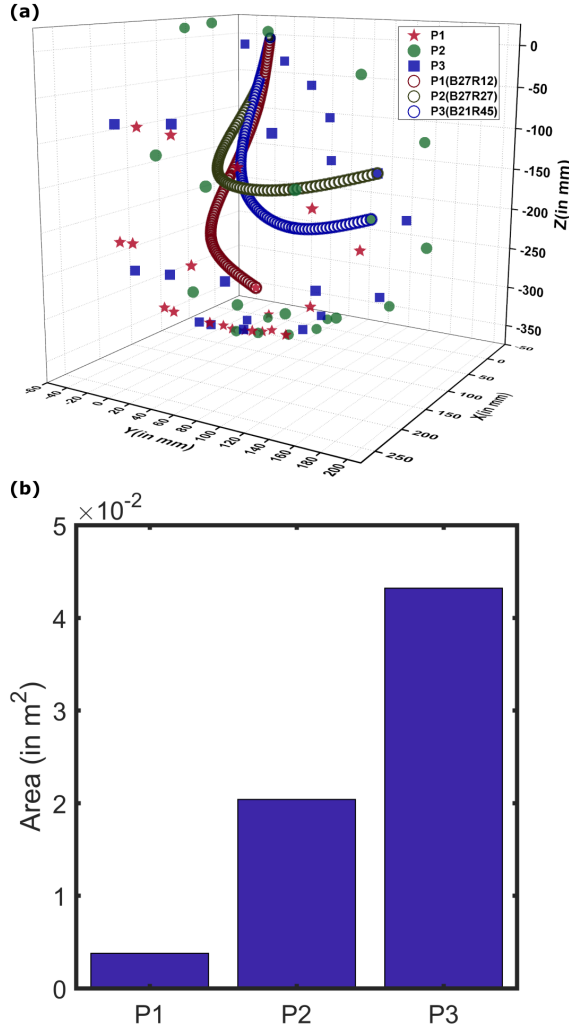


Fig. 6. Effect of the diameter ratios on the workspace (a) Workspace of three prototypes (with rotating to bending diameter ratios of $P1 = 1, P2 = 2/3, P3 = 1/3$) of the BR^2 manipulator. (b) Area metric of three prototypes from the experimental data. The manipulators are actuated to their normalized pressure ranges in Table I

patterns. In this section we present a detailed study of the BR^2 performance such as workspace and dexterity. We then demonstrate the capability of BR^2 manipulator in some general case studies such as obstacle avoidance, pick and place and whole arm manipulation tasks. Throughout this study except for the whole arm manipulation, the manipulator is mounted on a motorized swiveling stage.

A. Workspace Analysis

We refer to workspace as the collection of the end effector positions and orientations attained by the manipulator within the pressure ranges applied to the FREE actuators. The workspace is obtained by conducting a forward analysis for several pressure values of one R and the B FREE within the maximum permitted values. The weight of the arm is accounted as a uniformly distributed load along its length. An

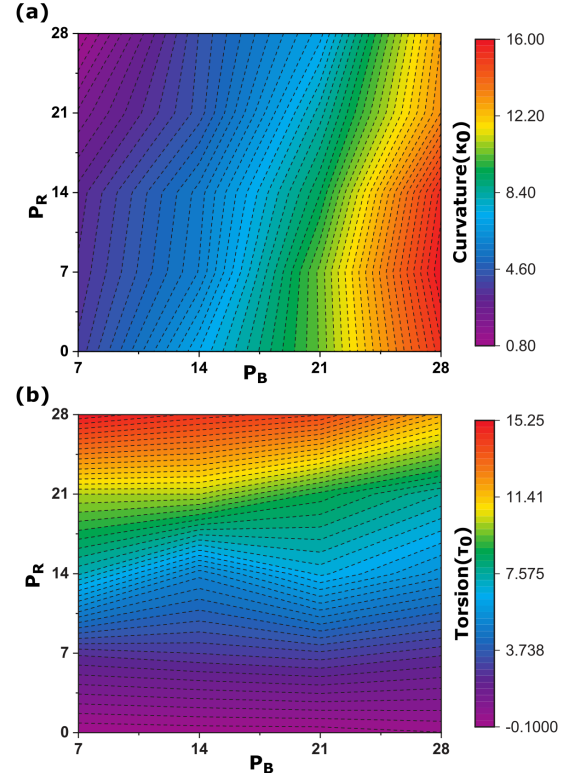


Fig. 7. Estimating the (a) Curvature, κ and (b) Torsion, τ as a function of pressures in R and B FREEs in the BR^2 manipulator.

end effector load of 3 *gms* is included to account for the end cap weights.

The resulting workspace observed is shown in the highlighted regions of Fig. 11(a). The workspace is mirrored about the $Y - Z$ axes, by actuating the other R FREE. Assuming that the BR^2 is oriented with bending curvature on the $Y - Z$ plane, any other spatial end effector position obtained by actuating the B and R FREEs can be re-positioned into this plane by rotating the manipulator about the Z axis (using the swiveling base). Therefore the resulting workspace can be envisioned as an area that can be rotated axisymmetrically about the Z axis. This axisymmetric workspace area can serve as a quantitative description of the workspace, whose value was estimated to be 0.0243 m^2 . In contrast, a single-section symmetric manipulator with three bending segments as shown in Fig. 1a will be able to bend along an axisymmetric curve alone as shown in Fig. 11(b). An area can be achieved by a single section symmetric manipulator only by concatenating at least one more such segment in series.

The workspace of the manipulator changes with the external load acting on it. With greater end effector loads, larger actuation pressures are required to attain the desired curvatures. The forward analysis can be used to obtain the end effector position for the operating pressure ranges under varying end load applied to the manipulator. The reduction in the workspace area is clearly observed with applied load as shown in Fig. 11(d) (where almost a 100% reduction in workspace area is observed for 50 *gms* of applied load).

Furthermore, we also study the variation of the manipu-

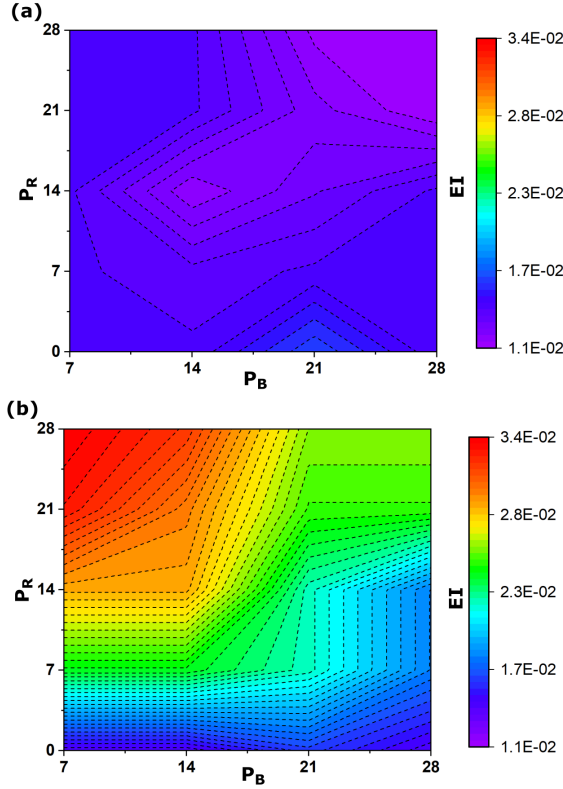


Fig. 8. Estimating the flexural rigidity, EI in the BR^2 manipulator as a function of pressures in R and B (a) when one bending and rotating actuator actuated. (b) when one bending and both rotating actuator actuated simultaneously to same pressures

lator workspace as a function of its length. While a larger manipulator length ideally gives a larger workspace, it also increases the flexibility of the manipulator making it prone to bending due to gravity. Larger actuation pressures are required to overcome the gravity effects. For a set actuation pressure range, there should be an optimal length of the manipulator where the workspace is maximum. Using the forward analysis, the workspace can be obtained for different manipulator lengths for a given operating pressure range. Figure 11(c) shows that the workspace is maximum at an optimal length of 350 mm , which is close to the length of the fabricated prototype (310 mm).

B. Dexterity analysis

Dexterity is the capability of the manipulator end effector to reach a particular position in its workspace via multiple possible configurations or orientations [37] [38]. Dexterity is defined quantitatively using a service sphere, which is a unit sphere centered around the point under consideration. The manipulator tip at the sphere center may orient itself along a set of directions that correspond to certain regions on the service sphere. A collection of all such regions, known as the service region is indicative of the dexterity. The dexterity $D(P)$ at the spatial position is defined as:

$$D(P) = \frac{A_{SR}(P)}{A_S} \quad (9)$$

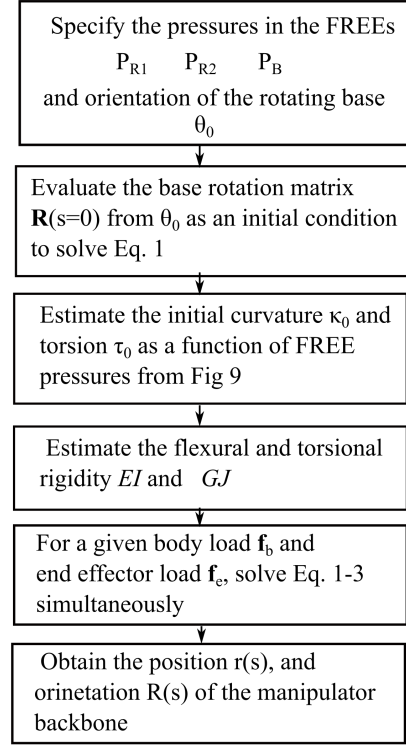


Fig. 9. Flowchart for the forward analysis of the BR^2 manipulator.

where, $A_{SR}(P)$ is area of the service region and A_S is surface area of the unit sphere. To evaluate A_{SR} computationally, we discretize the service sphere into $M \times N$ patches of equal area [38]. We then evaluate $A_{SR}(P)$ by determining the number of patches ($N_o(P)$) that can be oriented by the manipulator tip at a position P . Therefore, the dexterity at a point P in the workspace equals $N_o(P)/(M \times N)$.

In order to obtain the total dexterity, the axisymmetric workspace area is evaluated using the Monte Carlo method [38] by randomly sampling the input pressures. For each pressure combinations, the forward kinetic model is used to obtain the end effector positions, which are then rotated to the YZ plane. The axisymmetric workspace area is discretized with N_p rectangular meshes of length δy and δz . Then, the total dexterity can be written as

$$D_t = \frac{\sum_{i=1}^{N_p} N_o^i}{N_p M N} \quad (10)$$

1) *Dexterity for BR^2 manipulator:* The dexterity simulations are carried out in MATLAB 2017b on a WINDOWS 10 64 bit platform with Intel Xeon 3.40 GHz CPU and 8.0 GB RAM. The pressure range for each of the actuator in FREE is between 7 to 28 psi for the bending FREE and 0 to 28 psi for the rotating FREE. When one rotating FREE is pressurized, the pressure in another rotating FREE is set to zero. 10^7 samples are randomly collected from the pressure ranges. Then the forward model is used to calculate the position and orientation of the end in each sample configuration.

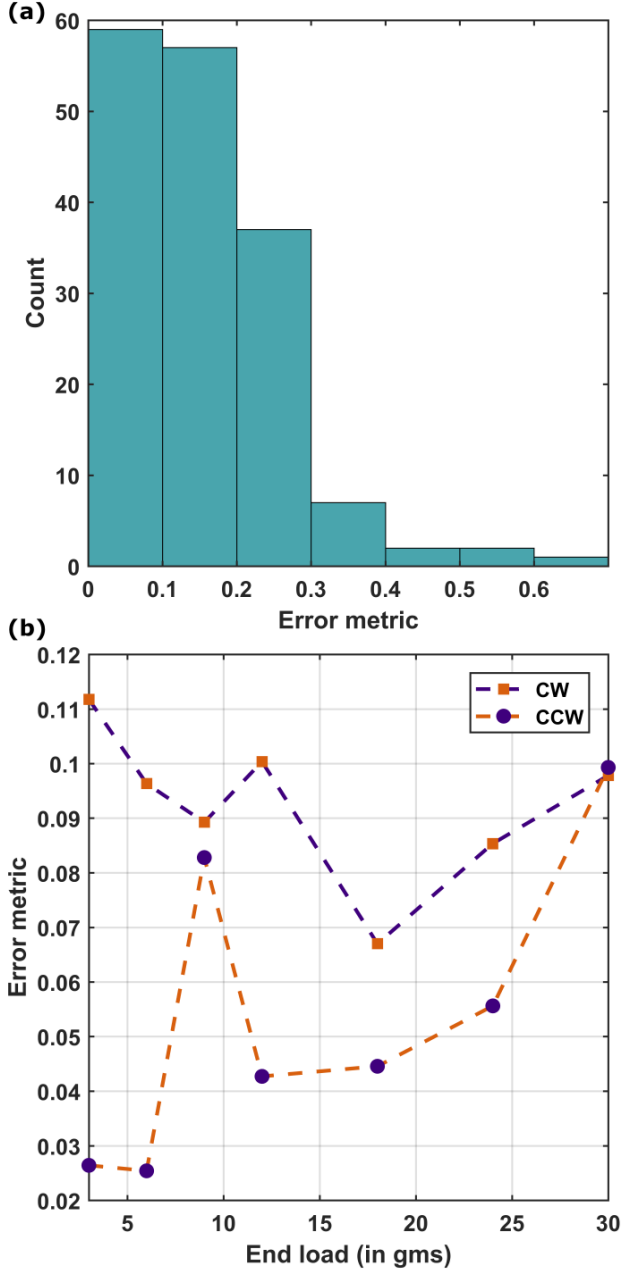


Fig. 10. Validation of the forward analysis model. Error metric (a) between the analytical and experimental end points and (b) with varying loads when either clockwise rotation or counter clockwise rotations are actuated to 15 psi. The bending actuation is 23 psi for both the cases.

As explained earlier, the tip position is moved to the Y-Z plane by actuating the rotating base to obtain the axisymmetric work area. The position and orientation of each sample is tagged with four patch numbers Y, Z, M and N . Those having the exact same four tags are merged to one pair of position and orientation. Then for a given position, the number of different orientations are evaluated to calculate the total dexterity.

The discretization parameters are set to $\delta y = 5 \text{ mm}$, $\delta z = 5 \text{ mm}$, $M = 60$ and $N = 30$. All the approachable positions are plotted in a scatter diagram (Fig. 12) to show the workspace and a color bar is also shown to indicate the dexterity distribution

across the workspace.

We highlight two points in the workspace in Fig. 12, one of which exhibits the maximum dexterity with $D(P_1) = 0.0194$, and another random point with dexterity $D(P_2) = 0.0144$. The corresponding service regions in their respective service spheres is shown in Fig. 13. The overall axisymmetric workspace area for the manipulator is 0.0243 m^2 and the total dexterity is 0.0061.

In contrast, a single section manipulator with three symmetric bending segments such as the one shown in Fig. 1(a), will be able to reach a point in the workspace in only a single orientation. Thus $N_o^i = 1$ in Eq. 10, giving a total dexterity of 0.00055 ($M = 60$ and $N = 30$), which is at least ten times lower than the dexterity of the BR^2 manipulator. In addition at least one serial segment needs to be concatenated to the symmetrical architecture shown in Fig. 1(a) for higher dexterity.

C. Demonstrating the capabilities of the manipulator

1) *Obstacle avoidance:* In this study, we demonstrate the ability of the manipulator to reach a desired location by avoiding obstacles. This is directly indicative of the dexterity of the manipulator.

The manipulator end effector is required to reach a ball of radius 35 mm placed at the location, which corresponds to a dexterity of 0.0144 as shown in Fig. 14a. While this position can be directly reached by actuating the bending FREE alone (the first row in Table II), a cylinder is placed to obstruct this deformation mode. However, we demonstrate that the manipulator tip is able to touch the ball when a rotating FREE is actuated together with the bending FREE. The pressures required to reach the ball from the left or the right are shown in the second row entries of Table II. In contrast, the symmetric design shown in Fig. 1(a) would not be able to avoid the obstacle unless a second serial segment was concatenated to it.

TABLE II
ACTUATION PRESSURES FOR THE BR^2 MANIPULATOR IN ORDER TO REACH THE LOCATION OF BALL. (ALL PRESSURES IN PSI)

S.No	P_B	P_{RC}	P_{RCC}
1	7.6	0	0
2	14.4	18.1	0
3	15.2	0	-19.09

2) *Whole arm gripping:* The BR^2 manipulator is capable of using its entire length to spirally wrap and grip long and slender objects. In our previous work [31] we have demonstrated a single spiral FREE to grip cylindrical objects of different radii. The BR^2 manipulator is also capable of spiral motion, because of its ability to generate simultaneous curvature and torsion. Furthermore, the pitch of the spiral can be varied depending on the relative pressures in the rotating and bending FREEs. For successful gripping, the spiral must generate at least one complete turn along a cylindrical object to ensure force (or form) closure [31].

In this study, we actuate the BR^2 to larger pressure range to ensure a complete spiral turn, and demonstrate its capability

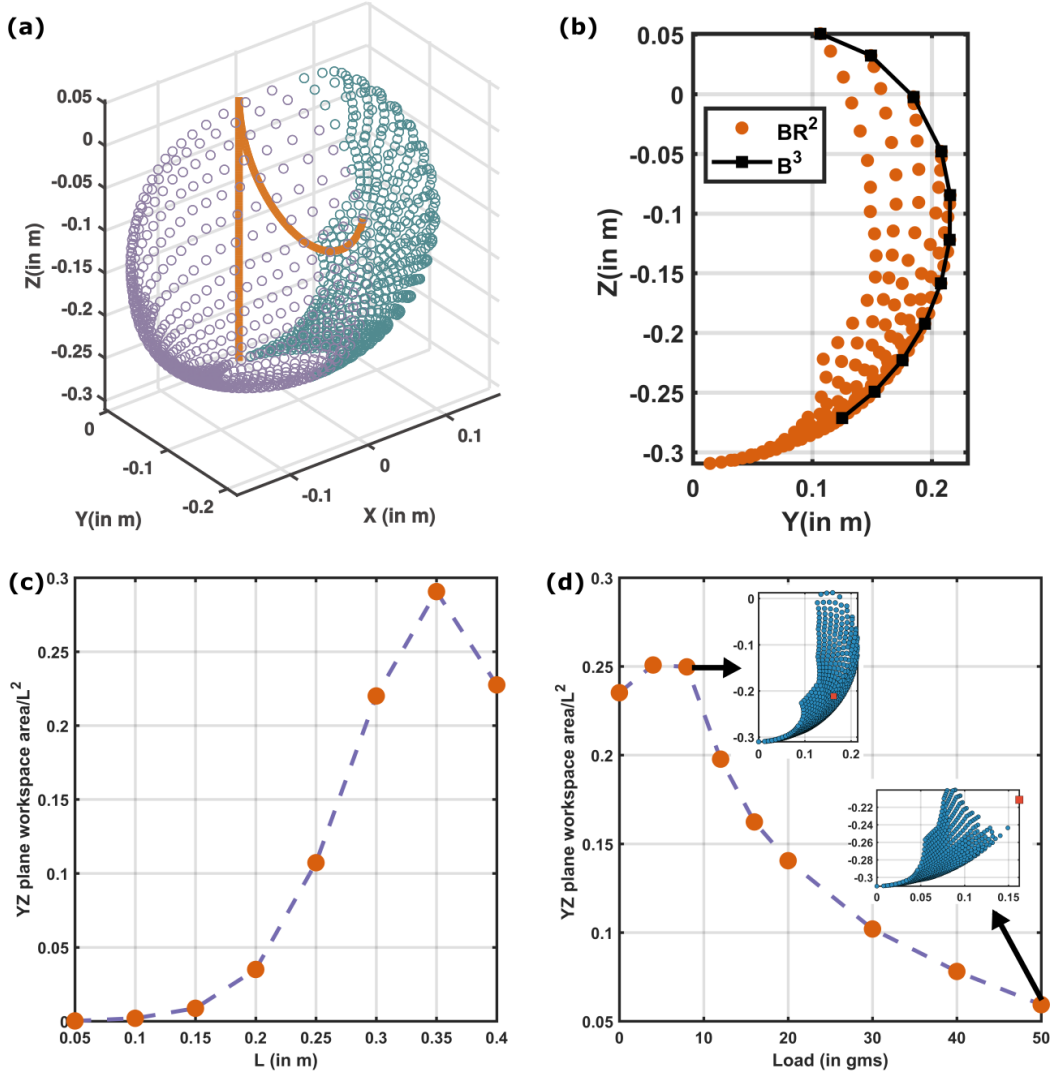


Fig. 11. Analysis on the BR^2 manipulator (a) Workspace of BR^2 with its rotation base fixed. (b) Axisymmetric workspace of the BR^2 manipulator and the symmetric B^3 manipulator. Variation in the workspace with increasing (c) length and (d) end load. The axisymmetric workspace of the BR^2 manipulator with an end load of 8 gms and 50 gms is also shown in inset.

to grip cylindrical objects. In Fig. 14(d) we demonstrate cylindrical objects of varying diameter ranges from 30 mm to 60 mm being gripped with the entire length of the manipulator. The diameters of the cylindrical objects and corresponding actuation pressures are given in Table III. In contrast, the symmetric design shown in Fig. 1(a) cannot spiral, unless more than two sections are concatenated in series.

TABLE III
DIAMETER OF CYLINDRICAL OBJECTS(Φ) AND CORRESPONDING ACTUATION PRESSURES USED TO GRIP THE CYLINDRICAL OBJECTS. (ALL PRESSURES IN PSI)

S.No	Φ (in mm)	P_B	P_{RCC}
1	30 mm	30	34
2	40 mm	24	30
3	50 mm	30	28
4	60 mm	37	18

3) *Pick and place operations*: Here, we demonstrate a pick and place operation, and study the effects of the external load

in planning the manipulator path.

For gripping an object, a vacuum suction cup weighing 3 gm is fixed to the end of the manipulator. The manipulator is required to move from its home position $P_0 = [0 \text{ mm}, 0 \text{ mm}, -310 \text{ mm}]$, to position $P_1 = [0 \text{ mm}, 120 \text{ mm}, -255 \text{ mm}]$, where it picks up the object and to position $P_2 = [56.3 \text{ mm}, 152.3 \text{ mm}, -211.5 \text{ mm}]$, where the object is dropped off, and then back to P_0 . These paths are shown in Fig 14(e).

To trace this path without picking and dropping the object, i.e. under the no load condition, the pressures applied to the bending and rotating FREE are shown in the first two rows of Table IV. However, if a ping pong ball of weight 2.7 gm were to be picked and dropped, then the path $P_1 - P_2$ operates in an attenuated workspace shown in the top inset of Fig. 11d. A larger pressure shown in Table IV is required to successfully place the object in its target position.

When the task is repeated using a golf ball (46 gms) instead of a ping pong ball, the manipulator is unable to reach the position P_2 . This can be seen from the attenuated

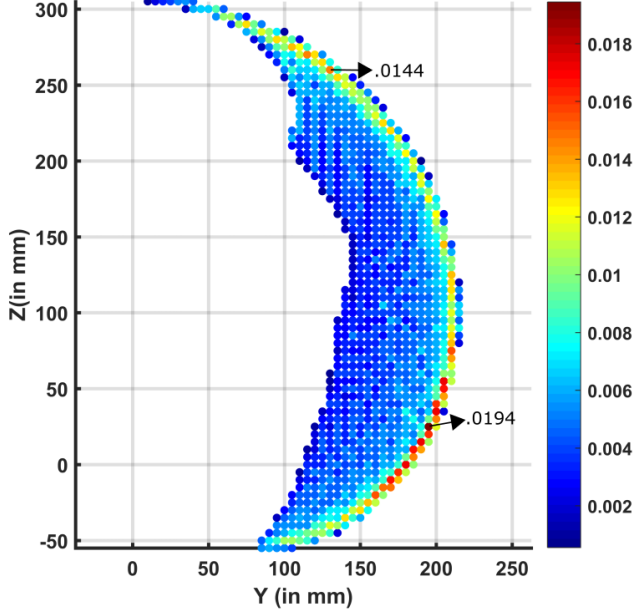


Fig. 12. Dexterity of the BR^2 manipulator (a) Dexterity distribution in its axisymmetric workspace (color indicates dexterity at each position patch). Gravity is acting in positive Z direction. The actuators base is at origin.

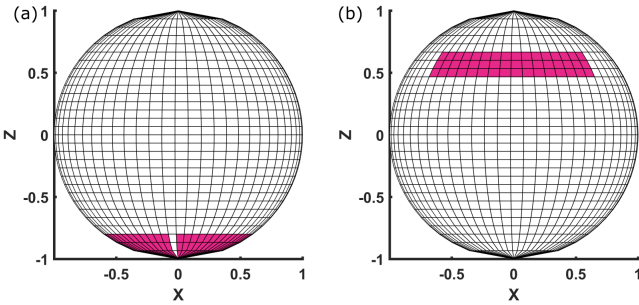


Fig. 13. Dexterity of BR^2 manipulator. XZ view of the service regions of BR^2 at position (a) with maximum total dexterity (.0194) and (d) with total dexterity of .0144 which are marked in Fig12 .

axisymmetric workspace with 50 gms load as shown in Fig 11(d) (bottom inset). This demonstrates the effect of end load on the manipulators reachable workspace.

Though an open loop control policy has been used for this study, it demonstrates the importance of factoring the external load in formulating the control policies for manipulation applications.

Further, there could be multiple actuation strategies in planning a similar path. This can be seen in Fig. 14(f) where the manipulator is picking a golf ball and is placing it in the bin located towards its left side using only bending actuation and rotating base. A similar task of placing the ball in a bin to its right can be performed by actuating (Fig. 14(g)) bending and rotating FREEs.

TABLE IV
PRESSURES USED IN THE BR^2 MANIPULATOR TO REACH DIFFERENT POSITIONS WITH DIFFERENT END LOADS. (ALL PRESSURES IN PSI)

Path	Load(gms)	P_B	P_{RCC}	$\theta_{base}(deg)$	Success
$P_0 - P_1$	0	8.2	0	0	Y
$P_1 - P_2$	0	16	15	49	Y
$P_1 - P_2$	2.7	21	18	25	Y
$P_1 - P_2$	46	19	1	30	N

VI. CONCLUSION

A. Contributions

Design is crucial for soft robots, because unlike rigid robots, their performance metrics such as workspace, dexterity and structural complexity are not just dependent on kinematics, but also on the external and internal loads, and the resulting non-linear elastic deformation. In this paper, we propose a unique soft pneumatic manipulator that can attain large workspace and dexterity, while maintaining a completely parallel and compact architecture. The BR^2 manipulator is constructed using three soft pneumatic building blocks known as Fiber Reinforced Elastomeric Enclosures (FREEs), which individually yield three different motion profiles, namely uniform curvature or bending, and axial rotation in the clockwise and counterclockwise directions respectively. When the actuation in these building blocks are combined, the manipulator deforms spatially.

The design and analysis of BR^2 manipulator is challenging because of the coupling effect, where actuating one FREE attenuates the deformation of the other FREE. The significant contributions of this design presented in this paper are

- A unique design for spatial manipulators that constitute a combination of asymmetric pneumatic building blocks: one bending B and two rotating actuators R^2 .
- A novel forward analysis technique based on Cosserat rod formulation, and an inverse formulation based on selected experimental data to estimate the pressure varying actuation (curvature and torsion) and elastic parameters (flexural and torsional rigidity). Forward analysis is validated for any external loading profile.
- Optimal relative diameters ratio of the bending and rotating actuators to maximize the workspace.
- A detailed study of the dexterity and the workspace, and their demonstration in routine manipulation tasks such as pick and place, obstacle avoidance, and whole arm grasping.

B. Implications of the BR^2 design architecture

The BR^2 design architecture proposed in this paper may have far reaching implications in applications where continuum manipulators have found use. A single module of the architecture yields a three dimensional axisymmetric workspace, and larger dexterity than any other parallel architectures to best of our knowledge. Consequently, this architecture requires fewer valves, sensors and simple control policies for deployment, which further decreases the overall cost of energy consumption.

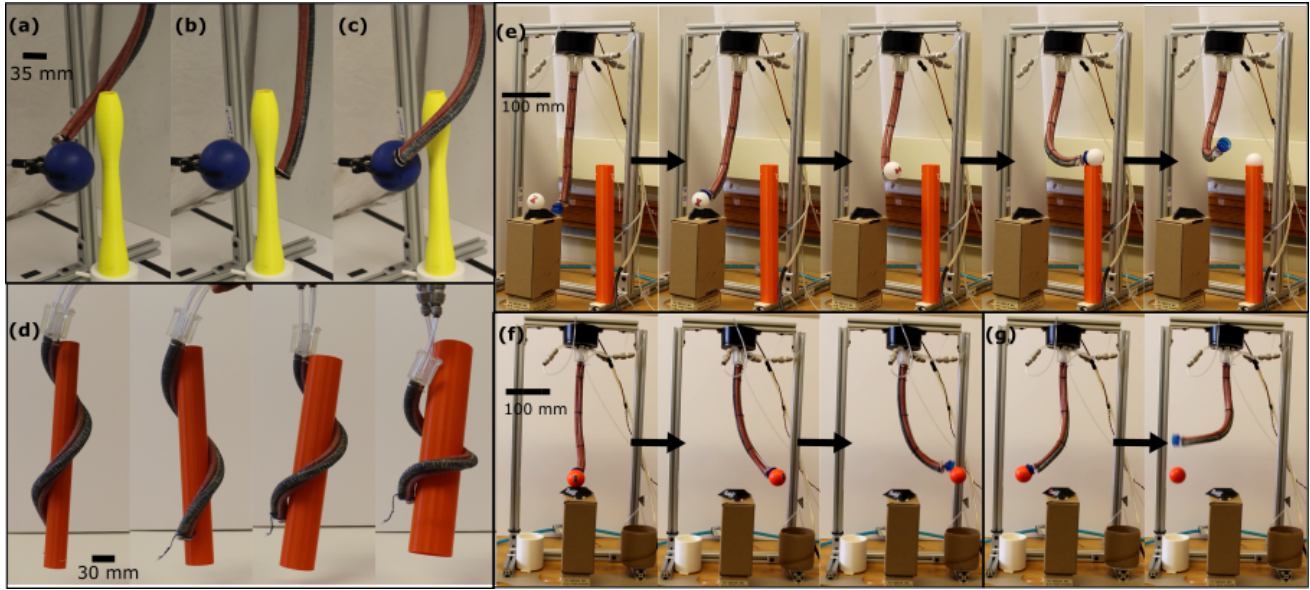


Fig. 14. BR^2 capabilities. Obstacle avoidance (a) The manipulator able to reach the ball using bending and counter clockwise rotating actuator, (b) using only the bending actuator (unable to reach the desired position due to presence of an obstacle) and (c) able to reach the ball using bending and clockwise rotating actuator. (d) Whole arm gripping by the BR^2 manipulator gripping the cylinders of diameters 30mm, 40mm, 50mm and 60mm respectively. Pick and place operation (e) Ping pong ball picked using vacuum suction and placed at a new location (f) Golf ball picked and dropped in a bin using only bending and rotating base (g) Golf ball picked and dropped in a bin using bending and rotating actuators

C. Implications of the analysis methodology

The paper formulates an inverse formulation using Cosserat rod mechanics from the experimental data to estimate actuation and elasticity parameters, which can then be used for forward analysis. This results in a more accurate analysis as the changes and the coupling in the actuation and elasticity parameters can be captured as a function of the applied pressure. The major significance of the analysis methodology is its ability to model manipulator deformations under any external load distribution. A similar approach can be used on any other soft parallel manipulator designs.

D. Implication on controls

Controlling the BR^2 manipulator requires determining the actuation pressure inputs to the bending and the rotating FREEs for the end effector to reach a particular destination or to trace a required path. We observe through the pick and place study that different actuation strategies were required to traverse a particular path depending on the end load on the manipulator. Any control algorithm must therefore factor in the end load. Though analytical equations for the inverse kinematics cannot be obtained, the fast and accurate forward analysis method may be used to train a model-free control framework using a neural network approach for [39] different end loads applied.

E. Future work

While we presented a single section of the optimized BR^2 design architecture, its workspace and dexterity can be further increased by concatenating one or more BR^2 modules in series. The optimized architecture for the series module will be studied in future work. Furthermore, the experimental

characterization of the manipulator deformation was accomplished manually in this paper using a microscribe. In future work, this will be accelerated by integrating a curvature and torsion sensor [40] that evaluates the deformed profile of the manipulator backbone in an automated fashion. We also propose to use the BR^2 continuum arm as a manipulator for autonomous agricultural applications because of its dexterity and energy efficiency.

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