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3D Kinematics and Quasi-Statics of a Growing Robot Eversion

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Abstract—Growing robots and their eversion principle have wide applications ranging from surgery to industrial inspection and archaeology. The eversion process involves deploying an inflatable device with a material located at the tip of the robot, which, when under pressure, elongates the robot’s body. However, the simulation of this complex kinematic phenomenon is a significant challenge. Our approach proposes to use a combination of kinematics and quasi-static modeling to parameterize the starting conditions of the eversion process. This facilitates the understanding of the behavior of this complex kinematic phenomenon and help identify factors that have a significant impact on the eversion process and its response to external factors. The kinematic model uses the Cosserat rod models for local coordinates, while the quasi-static model is based on finite element analysis. The two models are combined to capture the behavior of the robot tip during eversion. This approach has been implemented and tested using the SOFA framework and has been evaluated on the deployment of a vine robot on a narrow passage. The results of our approach are encouraging to better understand the behaviour of soft growing robot during eversion.

I. INTRODUCTION

In the last couple of years, the field of research in robotics has significantly evolved, going from well-known rigid structures toward articulated [1], flexible [2] and now soft structures [3]. Soft robotics revisits the concepts of traditional rigid robotics with the objective of expanding its capabilities for various purposes such as exploring environments, enhancing agricultural practices, and advancing medical treatments [4], [5], [6].

Inspired by the process of plant expansion, growing robots reinvent locomotion in robotics by creating a continuous forward motion, growing from the tip, called eversion. Growing robots can navigate in constrained and unconstrained environments, while conforming their shape to the environment without direct friction [7], [8], [9]. Eversion is achieved through an inverted membrane that is pressurized at its tip, which lengthens the apparent distal part of the robot. While the concept seems simple, the underlying mechanical behavior is challenging to model [10]. Previous work has proposed geometric and physical simulations to model the behavior of the growing robot and its interaction with the environment [11], [12], [13]. These simulations are based on models involving a series of rigid bodies, connected or not by joints or springs, and implementing the elongation

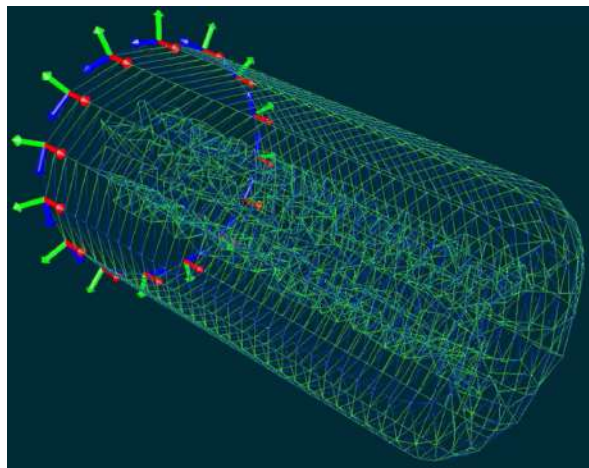


Fig. 1. Modeling of the eversion of a growing robot by combining the Cosserat rod model with FEM simulation using the SOFA framework [15].

phenomenon by the incremental addition of small segments of fixed length. In a recent study [14], the SOFA software was used to model a steerable growing robot, with the robot body represented by a 2D planar thin-walled conical mesh. The model takes into account parameters to simulate the incompressible eversion behavior that is specific to the robot application. However, previous simulations of growing robots have not fully considered the eversion phenomenon, a critical aspect of their behavior. To gain a better understanding, it is necessary to account for various properties, including the packing and storing method of the robot material inside itself, the impact of internal pressure on the membrane during deployment, the potential self-collision of the inner membrane, and finally the deformation of the outer membrane in response to encountered obstacles. A geometric description of the translation of the inner membrane towards the eversion zone is required to reproduce the 3D kinematics of the growing robot. Additionally, other membrane parameters such as deformation, pressure exertion, and potential self-collision leading to internal friction must be considered to fully describe the motion. By modeling and integrating these factors into the kinematics, critical parameters for successful navigation in complex environments can be identified, and the robot’s adaptability can be assessed in different environments. This knowledge can also contribute to the optimization and design of soft robots for practical applications.

This paper proposes a new approach to soft robot modeling by combining the Cosserat and FEM models and is depicted

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in Fig. 1. The use of local coordinates allows a direct description of the eversion kinematics, while global coordinates allow a detailed understanding of the force balance between membrane stresses and wall pressure. Thanks to this approach, it is possible to provide a first parameterization and a first geometrical representation of the initial physics involved in the eversion process of growing robots. Although the presented work does not introduce an experimental validation, the proposed approach represents a crucial first step in the understanding of the complex mechanics of growing robots and their potential applications in various fields of robotics. The proposed model is described in detail in section II and III, and the numerical results are reported in section IV.

II. METHODOLOGY

Our approach combines a Cosserat-type model with a 3D finite element analysis. The Cosserat model is based on reduced bending and torsion coordinates, which allows a more efficient and accurate description of the complex deformations involved in the eversion process. Specifically, the growing robot membrane, possessing a tubular shape, is represented as a bundle of distributed Cosserat *fibers*, which captures the local curvature observed in the eversion zone. However, this model alone cannot fully capture the self-collision and pressure effects that occur during the eversion process. To address this limitation, a second local analysis at the tip of the robot is applied, based on 3D finite elements. This allows to consider external collisions, as well as to accurately capture self-collision and pressure effects. Finally, a coupling between the two models is defined to apply appropriate boundary conditions to the FEM model and simplify its computation.

A. Discrete Cosserat Modeling with local coordinates

Cosserat models are often used to accurately model the deformation of thin structures during large transformations. These models assume no cross-sectional deformations, with each section of the continuum represented by a rigid body. In the paper [16], a piecewise constant deformation (PCS) formulation of the Cosserat model is proposed to model soft and thin robots. The PCS formulation is based on the use of reduced coordinates in the deformation space, which makes it easy to define the types of deformations that is allowed. For example, if no elongation is defined in the coordinate space, the model is perfectly inextensible. Furthermore, the deformation space is a vector space, which can be easily interpolated to reduce the coordinate space [17].

Although these models can reproduce the behavior of a large class of continuum robots, it is more difficult to fit them directly to growing robots. Some assumptions, such as no cross-sectional deformation, are not applicable to buckling zones. In addition, these models cannot represent the complexity of the eversion phenomenon, which is due to surface deformation.

However, if we consider the behavior of a growing robot with straight eversion and no interaction with its environment

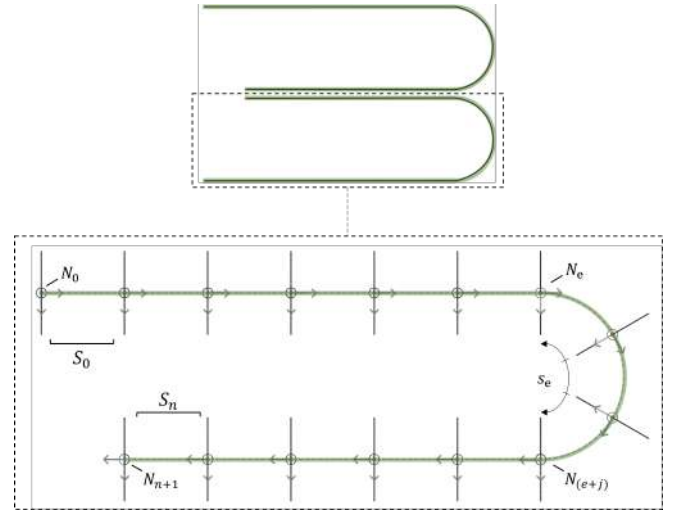


Fig. 2. The representation of the growing robot under the Cosserat model is based on its 1D structure. The robot consists of several sections, labeled S_n , which are connected by nodes labeled N_n . The base of the robot is represented by the section S_0 and the node N_0 . The eversion of the robot is represented by the section S_e , the beginning of the eversion being represented by the node N_e , and the end of the eversion by the node N_{e+j} .

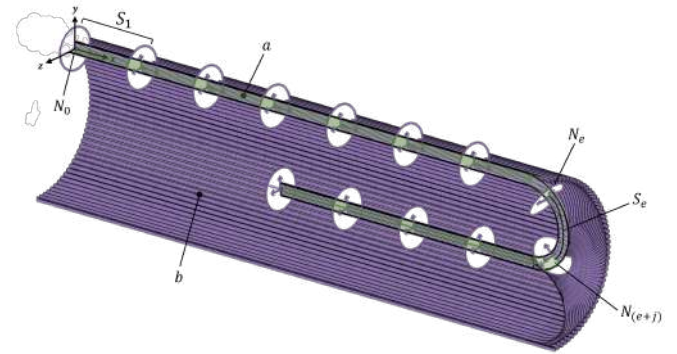


Fig. 3. Representation of the hybrid model of the growing robot, which includes the fibers (a) that give it its shape and the entire membrane (b). These fibers begin at node N_0 associated with section S_1 and are described by node N_e at N_{e+j} associated with section S_e during eversion.

(see Fig. 2), we can assume that the section representing a segmented element of the beam is undeformable. It is therefore possible to divide the robot body into several constant sections from S_0 to S_n , connected by nodes from N_0 to N_{n+1} . The resulting configuration is reduced coordinates of the nodes according to their torsional or bending deformation state.

B. 3D Finite Element Method with global coordinates

The finite element method (FEM) is a numerical technique used to solve partial derivative problems. In the context of deformation modeling, FEM allows capturing the 3D geometry of the structure through a mesh. Moreover, the weak formulation facilitates the expression of boundary conditions, such as pressure or contact conditions. In practice, FEM balances the forces at the nodes of the mesh in global coordinates, which simplifies the management of contact

forces, for example. The FEM calculation can be used to model soft robots, both directly and inversely [15].

C. Combination

Recent research [18] has demonstrated the possibility of combining the Cosserat and FEM models to better capture the behavior of flexible robots. Specifically, the FEM model is used to represent the global 3D geometry of the robot structure, while the Cosserat model is used to describe the behavior of flexible elements in local coordinates. This combination allows a more accurate simulation of the robot behavior, especially when considering complex deformations and interactions with the environment.

This study proposes a new hybrid modeling framework for the growing robot by combining the Cosserat model and the FEM model, building on the previous ability to combine these two models for accurate modeling of soft robots.

III. IMPLEMENTATION

Our methodology is based on a dual modeling system that combines two models for the eversion process of the growing robot (see Fig. 3). The first model represents the membrane using a system of curves (called "fibers") regularly positioned along the tube formed by the membrane. The motion of the fibers is parameterized using local coordinates, as in the discrete Cosserat model described above. This model is used to support a kinematic model of the eversion process.

The second model focuses on the balance of forces in the eversion zone, using a finite element method to model the membrane in global coordinates.

A. Eversion kinematics based on the strain based reduced coordinates

To model the kinematics of the growing robot eversion, we represent the shape of its membrane tube as a series of parallel fibers of size L . Each fiber is sampled in sections $S_i, i \in [0, n]$, with local coordinates \mathbf{q}_i that provide their curvature. We adopt the use of angular velocity parameters (bending and twisting angles per unit length) as in [16] to simplify the calculation. The different sections are connected by N_i nodes along the beam.

At the base of each fiber, there is a reference frame F defined on the node N_0 , which is mechanically fixed in space. Each reference frame is rotated so that the x-axis is oriented in the direction of the tube, with the y-axis and z-axis normal and tangent to the membrane surface, respectively.

To describe the eversion phenomenon, a first node N_e is placed at the curvilinear abscissa representing the beginning of the eversion zone and a second node $N_{(e+j)}$ at the end. Although multiple s_e sections can be added to each fiber in the eversion zone, we found that one section per fiber was sufficient for our implementation ($s_e = 1$).

To capture the eversion process, we use the local coordinates corresponding to the bending along the Z axis for each fiber.

$$\mathbf{q}_e^z = -(s_e/l_e) * \pi \quad (1)$$

The length of the eversion along the fiber is the distance between N_e and $N_{(e+j)}$ along the curvilinear abscissa, and determines the shape of the U-turn made by the fiber in the eversion region. Depending on the value of l_e , the U-turn can be either sharp (for a small l_e) or smooth (for a large l_e). To model a non-homogeneous eversion geometry at the end, each fiber can have its own parameters for N_e and $N_{(e+j)}$. If more than one section is used between N_e and $N_{(e+j)}$, the curvature need not be constant. In this case, it is sufficient to ensure that the curvature created by the succession of bent sections creates a U-turn:

$$\sum_{i=0}^j \mathbf{q}_{e+i}^z * l_{e+i} = -\pi \quad (2)$$

Here l_{e+i} is the length of the section $e+i$

To recreate the revolution geometry of the growing robot, we project the desired number of fibers n times into the reference frame. The same transformations as in Cosserat's theory [16] are applied along each fiber to obtain the global position \mathbf{p} of the fibers from the local coordinate space \mathbf{q} . In practice, in the global space, the points are uniformly spaced $\mathbf{p}_k = (x_k, y_k, z_k)$ along each fiber. Thus, due to the rotational motion, all fibers create a mesh of points that represents the surface of the membrane.

To create growing motion (see Fig. 4), we shift the curvilinear abscissas of N_e and $N_{(e+j)}$ (increase to move forward and decrease to move backward) and update the discretization of each fiber accordingly. Since the \mathbf{p} points of the membrane are distributed along each fiber according to their curvilinear abscissa, moving the U-shaped bending region forward or backward along this abscissa for each fiber results in eversion motion of the membrane. In practice, the use of three sections S_i for each fiber is sufficient to model the kinematics, with S_1 representing the section before eversion, S_2 representing the eversion region, and S_3 representing the section after eversion. However, to model the curvatures before, during and after the eversion zone, the fiber modeling approach must be enriched.

B. FEM model of the pressurized membrane at eversion

From a mechanical point of view, the quasi-static equilibrium at the eversion level comes from 4 types of forces (for a 3D position of the nodes \mathbf{x}):

- Internal forces, noted $\mathbf{F}(\mathbf{x})$, which depend on the material used for the membrane,
- Pressure forces, noted $\mathbf{P}(\mathbf{x})$ inside the structure that leads to the deployment of new material at the eversion point,
- The self-collision forces of the membrane on itself and the associated friction, noted $\mathbf{H}'\lambda$,
- The boundary conditions $\mathbf{B}(\mathbf{x})$ are also very important. In some vine robot designs [7], a motor is placed at the base of the robot to counteract the eversion pressure and precisely control the eversion point.

To determine the internal forces of the membrane, we use a FEM model based on triangular elements. In our

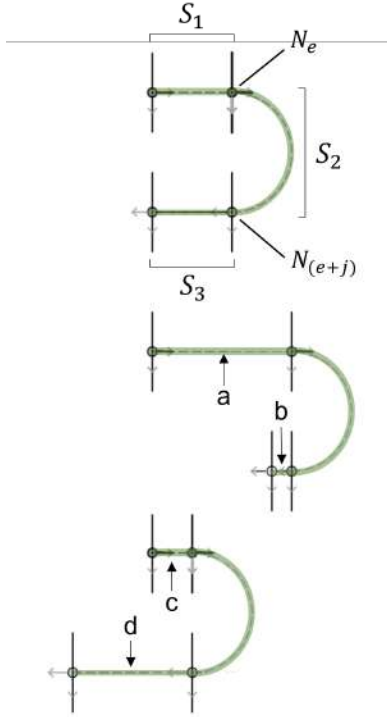


Fig. 4. The fiber of the growing robot is divided into three sections: S_1 (pre-eversion), S_2 (eversion), and S_3 (post-eversion). To move the robot forward, we increase the curvilinear abscissa between N_e and $N_{(e+j)}$. As a consequence, the section S_1 stretches (a), and the section S_3 shrinks (b). On the other hand, to make the robot move backwards, we decrease the curvilinear abscissa, which causes the section S_1 to shrink (c) and the section S_3 to stretch (d).

approach, we assume a linear elastic constitutive law, and the elements are designed to support large displacements while maintaining small deformations. We consider only in-plane forces for the membrane model, and each element can rotate freely relative to its neighbor along their shared segment, allowing for the natural flexibility of thin materials. However, this approach creates a dependence on the mesh. For future work, a more continuous approach to FEM analysis of the membrane could be considered. To distribute the pressure forces, we use the surface area of each triangle. We compute the self-collisions using the Lagrange multiplier constraints [15]. Finally, the boundary conditions are defined by the coupling model (described below).

All these forces are computed in the 3D space of the FEM mesh nodes by solving the non-linear quasi-static equilibrium, i.e, finding \mathbf{x} so that:

$$\mathbf{F}(\mathbf{x}) + \mathbf{P}(\mathbf{x}) + \mathbf{H}^T \lambda + \mathbf{B}(\mathbf{x}) = 0 \quad (3)$$

C. Coupling model

The coupling approach exploits the strengths of both models to provide a complete description of the robot's behavior. Although the curved fiber model captures the 3D kinematics of the eversion motion, it lacks physical realism. Conversely, the FEM model of the pressurized membrane is complex and computationally demanding, and does not account for self-

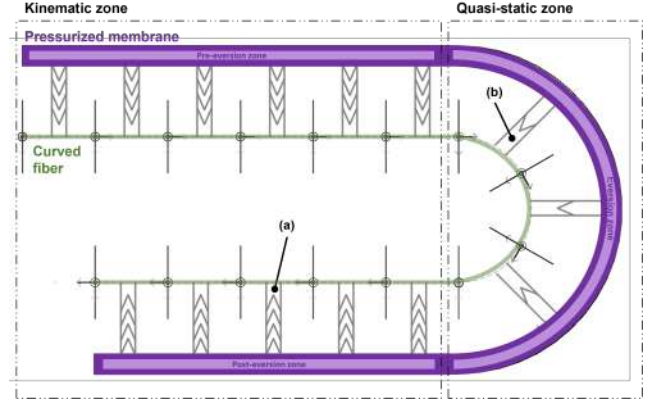


Fig. 5. The coupling model is represented by the curved fiber model associated with the pressurized membrane. The coupling is done by means of rigid springs (a) in the kinematic zone and relaxed springs (b) in the quasi-static zone.

collisions within the robot, which are difficult to simulate and irrelevant to the eversion process. However, the FEM analysis at the end of the robot is useful for studying the effect of membrane properties on eversion. By combining the two models, we can obtain a more accurate and computationally efficient simulation of the robot behavior.

A coupling model is therefore proposed (see Fig. 5) for which the position of the membrane points is given by the kinematic model in the pre- and post-eversion zones (called kinematic zone), and by the FEM model in the eversion zone (called quasi-static zone). The kinematic model allows starting the FEM meshes in eversion position and to define realistic boundary conditions for the quasi-static analysis.

Both models use the same level of discretization, so each point k on the membrane has a position given by the kinematic model, denoted as \mathbf{p}_k , as well as a position from the static model, denoted as \mathbf{x}_k .

Some springs are defined between the two positions

$$\mathbf{B}(\mathbf{x}) = \sum_k \mathbf{k}_k (\mathbf{p}_k - \mathbf{x}_k) \quad (4)$$

In the kinematic zone, a high stiffness value is assigned to \mathbf{k}_k to ensure that the position of \mathbf{x}_k closely follows the position given by the kinematic model. In contrast, in the quasi-static zone, the value of \mathbf{k}_k is set to zero, allowing the membrane to follow the equilibrium of forces due to the membrane elasticity, pressure, and self-collision.

IV. RESULTS

In the previous sections, we presented a new method that integrates the Cosserat model and the FEM model to describe the eversion and the shape of growing robots. In this section, we present the simulation results obtained with our method, focusing on robots with various geometric properties and in different constrained environments.

A. Shape of eversion

We evaluated the capability of our initial attempts at geometric eversion simulation by testing them on three

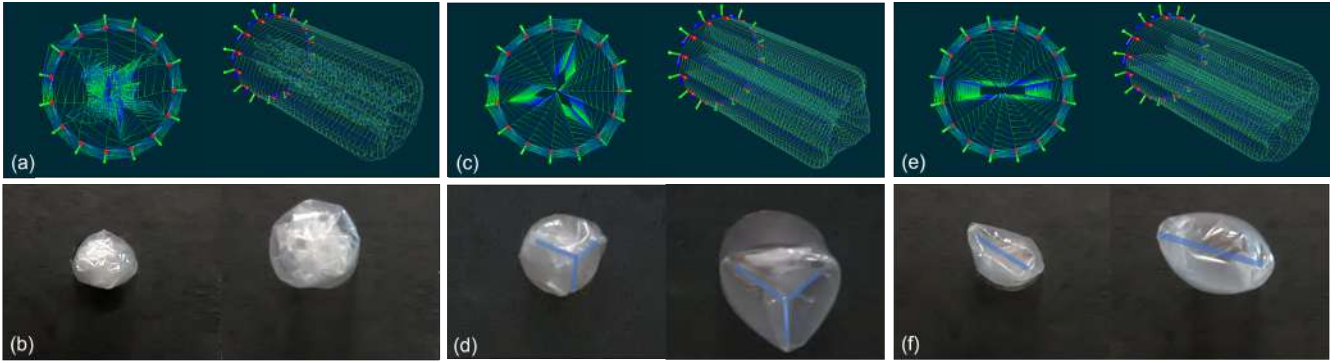


Fig. 6. Comparison between the simulated (a) (c) (e) and real geometries (b) (d) (f) of the growing robot in the free and imposed cases. The simulated free geometry is represented by a randomly shaped membrane (a), while the simulated imposed geometry is represented by a triangular (c) and linear shape (e). The simulations capture the complex shapes of the free and imposed geometries by initializing the fiber length along the curvilinear abscissa.

commonly observed eversion shapes in real life, which are determined by the way the growing robot body expands on itself: random (see Fig. 6.b), triangular (see Fig. 6.d), and linear (see Fig. 6.f). These shapes can be categorized as either a free geometric shape, in which all fibers initially bend uniformly and produce a consistent revolution, or an imposed geometric shape, in which the fibers are initially bent to match a desired shape and produce a modified revolution.

We defined a motion for the local coordinates over three sections (pre-eversion, eversion, post-eversion) in these three examples, accepting slight variations in the curvilinear abscissa. To create a simulation close to reality, we assigned the membrane elasticity parameters similar to those of the low-density polyethylene (LDPE) material, applied a small pressure, and activated the self-collision of the membrane on itself.

Our first analysis focused on a free geometry, here associated with a random shape (see Fig. 6.a), allowing the membrane to bend freely during the eversion process without any constraints on its shape. The results showed that the material had a tendency to form folds in a seemingly random fashion, resulting in a unique and interesting pattern. This behavior is not surprising, as the fibers that make up the membrane are free to bend in any direction. The results are consistent with real-world observations and can provide important information about the behavior of the material when not under specific stress, highlighting the natural tendency of the material to take on unique shapes and structures.

The second part of our analysis involved implementing a geometric shape imposed on the membrane during the eversion process, representing triangular (see Fig. 6.c) and linear (see Fig. 6.e) shapes. We found that the eversion process complies with the previously established preforming conditions by imposing specific values of the curvilinear abscissa during the revolution. During the simulation, the eversion process maintains the imposed shape and the self-collisions of the membrane on itself remain present, although varying with the shape and the applied pressure. This results in different maximum induced pressures for each shape.

B. Constrained environment

In this section, we propose a model to study the eversion behavior of a growing robot in a narrow space, which has been explored in previous studies [7]. The robot's pressurized membrane, which constantly inflates from the inside out, allows it to stretch and adapt to its environment (at least when the pressuring media is air). When the robot encounters a narrow space, the pressurized membrane on its front edge deforms and slides along the edges of the space, reducing the robot's diameter to pass through. Once the robot has passed through the gap, the pressurized membrane returns to its original shape and diameter.

To investigate how the robot behaves in a restricted space, we conducted tests by introducing two narrow slots that constrain the robot's expansion. In these experiments, we used the same simulated robot parameters as in our previous tests, which included dividing the fibers into three sections (pre-eversion, eversion, post-eversion) and using an LDPE membrane.

Our model provides insight into how the growing robot behaves during eversion and responds to environmental stresses. Our analysis indicates that the robot's pressurized membrane, with relaxed springs, is sensitive to external forces and can adapt to the constraints it faces. When the pressurized membrane encounters an obstacle such as a narrow gap, the eversion tip responds to the balance of forces, causing the membrane to deform, which reduces the diameter of the robot according to the size of the gap, allowing it to pass. Once the eversion tip passes through the gap, the pressurized membrane returns to its original diameter and the robot maintains the membrane deformation in the previously constrained region (see Fig. 7).

V. CONCLUSION AND FUTURE WORK

In conclusion, this study presented a new approach that combines the Cosserat model and the FEM model to simulate the eversion behavior of a growing robot. Our simulations demonstrated the effectiveness of this approach in capturing the complex eversion of the robot in various shapes and under different environmental conditions. However, it is

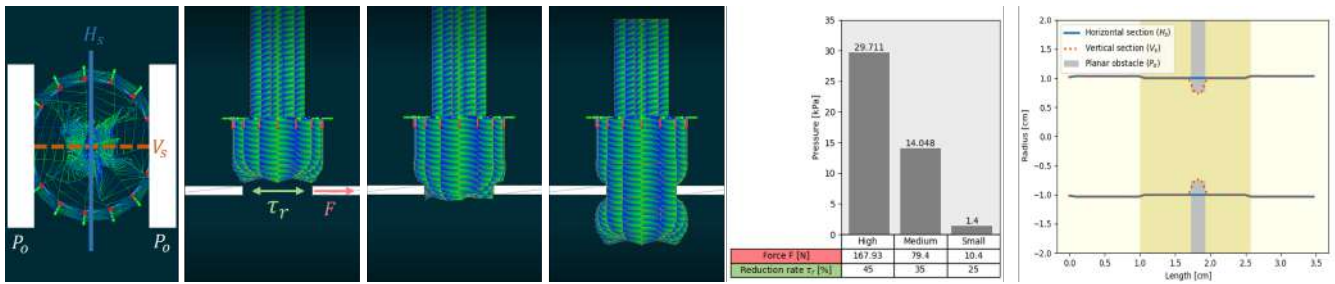


Fig. 7. Simulation results of the eversion constrained by external obstacles. As the robot passes through the narrowing, the membrane exerts a pressure on the planes, which is proportional to the contact force F applied and depends on the type of constriction (high, medium, or small). The vertical section V_s of the membrane undergoes deformation, causing a reduction in diameter equal to that of the constriction, while the horizontal section H_s , which does not encounter any constriction, remains unchanged.

important to note that these results represent only a first step towards understanding and modeling the eversion behavior of growing robots.

Future work will involve improving the accuracy of our model by incorporating more complex physical effects and optimizing its computational speed by reducing the membrane model in the reduced space. In addition, we plan to validate our model against physical experiments to confirm its applicability to real-world scenarios.

The successful validation of our model would have important implications for the development of growing robots. By providing a more accurate representation of the eversion process, our method could contribute to a better understanding of how growing robots navigate dynamic environments.

In summary, our results highlight the potential of the Cosserat-FEM model to advance the study and design of growing robots. By accurately simulating the eversion behavior of these robots, we can gain a better understanding of their capabilities and limitations, and ultimately develop more effective and efficient designs for a wide range of applications.

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