Static modeling of multisection soft continuum manipulator for Stiff-Flop project

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Abstract. This paper describes the design and implementation of a static model used for position estimation of a flexible modular medical manipulator equipped with optic-fiber based sensors. Flexible manipulators are emerging technology in medical applications especially in minimally invasive surgery as it allows to perform the operation with tight space constraints without damaging other organs. Such option is often impossible with use of rigid surgical instrument. However one of the technical challenges in implementation of the flexible manipulator is to be able to determine the position of the manipulator during operation. A theoretical model of use of different information derived from opti-fiber based sensors to allow measurement of the position and deformation of the manipulator has been proposed. In comparison to typical constant curvature bending approach, proposed model allow to estimate deformation caused by external force applied to the structure. Simulation test has been carried out to present the advantages and possibilities of use of that model in data fusion algorithms to obtain precise positioning of the manipulator during the operation.

Keywords: Stiff-Flop, surgical manipulator, constant-curvature, continuum manipulator, static modeling, minimal invasive surgery

1 Introduction

In modern medicine, minimal invasive surgery (MIS) is a surgical operation that is performed by the surgeon through small incisions. It is an established alternative to conventional open surgery [1]. Advantages are such as reduced post-operative pain, blood loss, tissue trauma and recovery time. Additional benefit is less chance of post-operative infection [2]. However, there are also several problems associated with this surgical technique. The surgeon has limited feedback – including visual and haptic. There is also a reduced number of degrees of freedom during the operation available to the surgeon. Use of current available technology result in relatively high chance of instruments damaging other tissues during transit of the MIS instruments. Current research conducted in project like Stiff Flop (EU FP7 founded project) is focused on introducing new flexible robotic manipulators into the MIS. This kind of structures

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are able to bend in a snake-like way and thanks to that the number of degrees of freedom is increased during MIS [7]. In results majority of the mentioned problems can be reduced or eliminated and surgeon is capable to reach targets which are inaccessible with conventional rigid surgical instrument. Despite the soft manipulator construction issues the challenge lies also within the accuracy that is required to perform the surgical operation. However there is no one good solution to estimate the localization of the manipulator. To provide accurate and reliable positioning and control of the flexible structure multiple position estimation sources are required [6]. For that purpose several sensors were designed and developed [4]. This paper proposes a model that enable to estimate the shape and sizes of a flexible robotic manipulator module developed within Stiff-Flop project. The design of the STIFF-FLOP soft robot module is presented in **Fig. 1** Whole robot is constructed from three similar modules. The end module is equipped with a tool for surgical operations. Each module is built with a braided silicone rubber tube, and current prototype has 2.5cm in diameter. Inside the tube, there are three chambers [7]. The air or fluid pressure within each of these three chambers determine the bending, elongation and direction in 3D space. This design is inspired from a three-chamber micro actuator first proposed by Suzumori [8]. Different modeling methods have been proposed for continuum robots. A recent review of these methods can be found at [9]. Most of typically applied approaches are based on constant curvature assumption or are using numerical methods that has no direct physical relevance. This has not been thoroughly verified in experiments [10]. Additionally the Stiff-Flop robot is developed in order to interact with the patient. This implies the requirement to model not only robot movement and shape but also the deformation caused by external forces. These effects make its modeling more challenging. The proposed approach takes into account the pressure applied by the control system and forces measured by distributed tactile force sensors. It will be used for data fusion the provide accurate and reliable position (shape and size) of the manipulator for control system and as a main source of feedback information for surgeon.

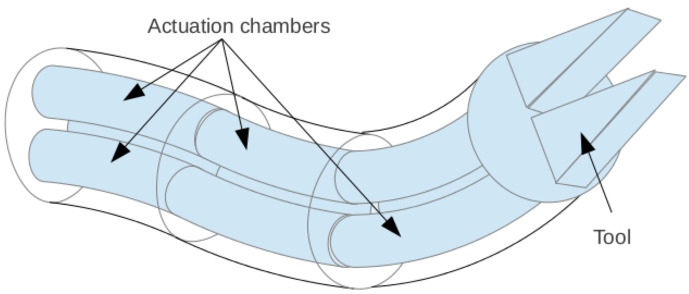

Fig. 1 Visualization of the Stiff-Flop manipulator

2 Construction of the manipulator

The manipulator consists of three identical modules. Each module is made of silicon material with three pressure actuation chambers. To prevent deformation of the chambers, braiding is applied around the whole module. The module cross section is presented on **Fig. 2**. Real prototype of two segment manipulator is presented on **Fig. 3**

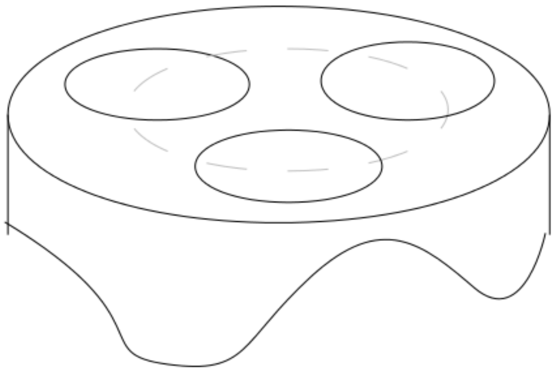

Fig. 2 Cross section of the Stiff-Flop module

Fig. 3 Photograph of a two segment arm manufactured by partner from the Stiff-Flop project

3 Modeling the arm

In order to determine the shape of the manipulator, a proper model has to be designed and implemented. It has to be precise and its implementation cannot be computationally complex, because the results are to be used in real-time controlling of the arm.

Therefore, techniques based on numerical simulation like Finite Element Method (FEM) are not directly applicable, because of their computation overhead. In order to achieve above mentioned goals, a tradeoff between simplifying the model and it's precision has to be considered. On one side the precision requirement demands taking any factors that have significant influence on the manipulator shape into account. On the other side, modeling too many physical effects increases the amount of required calculations. Since the Stiff-Flop arm is designed to operate in tight spaces, there is high probability of contact with other bodies. This fact makes calculating the influence of external forces acting on the arm a must. This significant factor is not considered by the popular Constant Curvature model of continuous robots [9], what renders it unusable in this case. For the model described in this paper, following assumptions had been made: the pressures in each chamber and the values of external forces acting on the module are measured at any point of the module; the segment is made of homogenous material of known stiffness, with three pressure chambers hollowed out; the dimensions of cross-section of the pressure chambers are constant (provided by the braiding); the pressure in chambers is constant at any point. The other influence of the braiding and optical fibers running through the module has been neglected. Nevertheless the influence of the omitted factors on the model is still subject of the research. Since the arm consists of three separately actuated segments (modules), equations for a single segment are presented.

4 Single segment model

The segment is controlled by pumping the work fluid in and out of the chambers. This causes the pressure to change its value accordingly. The pressure in each chamber is constant at any point of its volume. A cross section of the module showing the pressure changes is presented on drawing 2. Treating it as internal stress, the force acting at any cross section of the chamber can be described with the formula 1:

$$p=\frac{F}{A} \tag{1}$$

Forces in each cross section are parallel with its Z-axis (perpendicular to the cross section). Therefore, the Z-axis moment is zero. The resulting moment causes pure bending of the module. Because the chamber diameter and pressure is constant throughout the module length, the resulting moment is also constant. Using the force values and cross section geometry, the resulting bending moments can calculated:

$$M_{kp}=\overrightarrow{C_{k1}}\times\overrightarrow{F_{k1}}+\overrightarrow{C_{k2}}\times\overrightarrow{F_{k2}}+\overrightarrow{C_{k3}}\times\overrightarrow{F_{k3}} \tag{2}$$

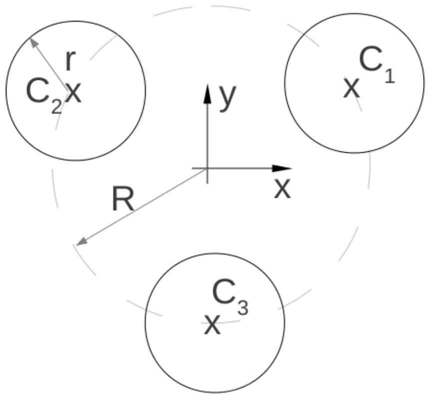

Fig. 4 Cross section of the module at point k, perpendicular to the chamber axis

The Euler-Bernoulli formula relates the bending moment with resulting curvature as follows [12]:

$$\kappa = \frac{1}{\rho} = \frac{M}{EI} \tag{3}$$

where E is the Young's modulus constant of the silicone, and I is the second moment of inertia of the module at cross section k. Assuming no presence of external forces, the bending moment has the same value at every cross section. Therefore, we calculate the total curvature:

$$\forall_k \kappa_k = \kappa_0, \qquad \kappa_0 = \frac{M_0}{EI} \tag{4}$$

In this situation, the module shape can be described as a fragment of circle with radius rho. This is presented on **Fig. 5**

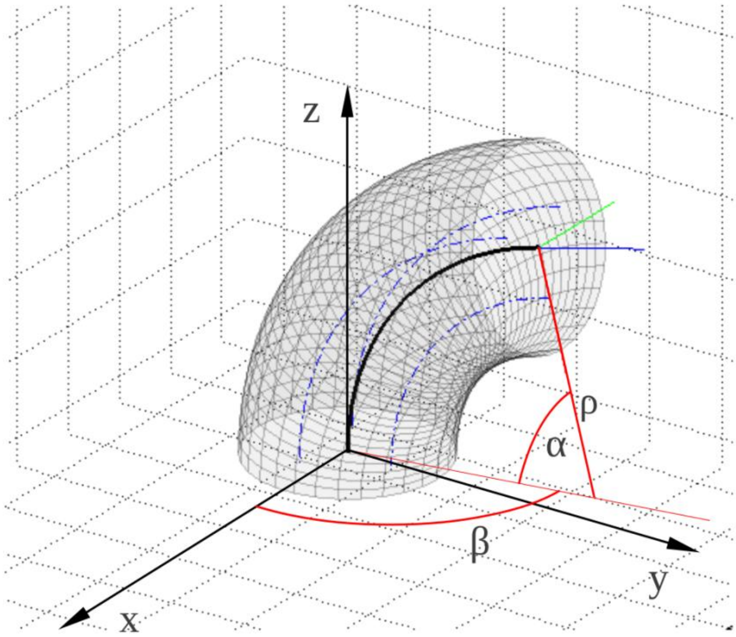

Fig. 5 Module bending with no external forces applied

This is the Constant Curvature case. The position and shape of the module can be described with only three parameters: the bending angle alpha, direction beta and curvature rho. Forces resulting from pressures also influence the module's length. Elongation at any point along the module's axis can described using the Hooke's Law [12]:

$$\Delta dl = \frac{F_p}{A E} dl \tag{5}$$

where F_p is the overall force resulting from chamber pressures, at single cross section. It is calculated by adding forces resulting from each chamber pressure. A is the area of the silicone part of the cross section (cross section area minus the area of three chambers). **Fig. 6** presents a fragment of the module elongated by the chamber pressures.

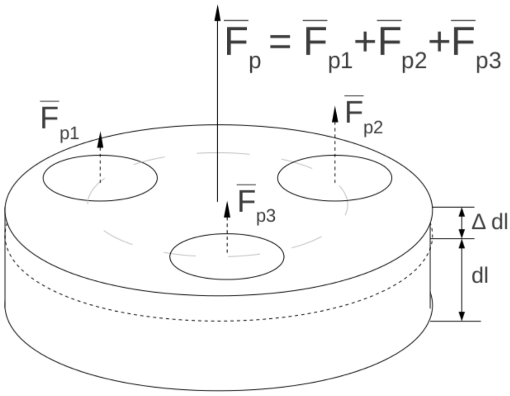

Fig. 6 Elongation of the module at point l

The overall change of length of the module can be calculated by integrating the previous formula from 0 to l_O:

$$\Delta l = \int_0^{l_0} \Delta dl = \int_0^{l_0} \frac{F_p}{AE} dl \tag{6}$$

The value of the bending angle (alpha – see **Fig. 7**) can be evaluated by integrating the curvature from 0 to l+ Δ l w:

$$\alpha = \int_0^{l_0+\Delta l} d\alpha = \int_0^{l_0+\Delta l} \frac{1}{\rho} dl \tag{7}$$

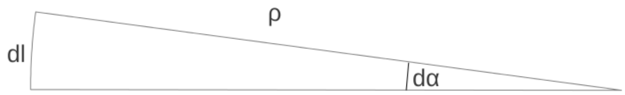

Fig. 7 Bend of the module at point l

In the case of external forces having any non-zero values constant curvature model does not apply, because of variable bending moment.

5 Modeling the module with external forces applied

When taking the influence of external forces acting on the module into account, their values need to be included in previous equations. That determines the value of the bending moment to be variable throughout modules length. It can be generally expressed with the following equation:

$$M_k = M_{kp} + M_{k\,ext} \tag{8}$$

The external forces influence has to also be represented in bending, torsion and elongation calculation.

At the current state of the Stiff-Flop project, the force sensor is located on the tip of each module. Therefore, the equations for one force acting on the tip are presented next.

The measurement of tip force is expressed in terms of the tip frame. External force causes additional moment to appear in all module's cross sections. Its value in the tip frame can be calculated with the following formula:

$$\overrightarrow{M_{kext}} = \overrightarrow{F_{ext}} \times \vec{r_k} \tag{9}$$

where F_{ext} is the vector of the external force applied to the tip and r_k is the vector from center point of the k-th cross section to the tip center. Both vectors are expressed in coordinates of the tip frame. This situation is presented on **Fig. 8** and **Fig. 9**.

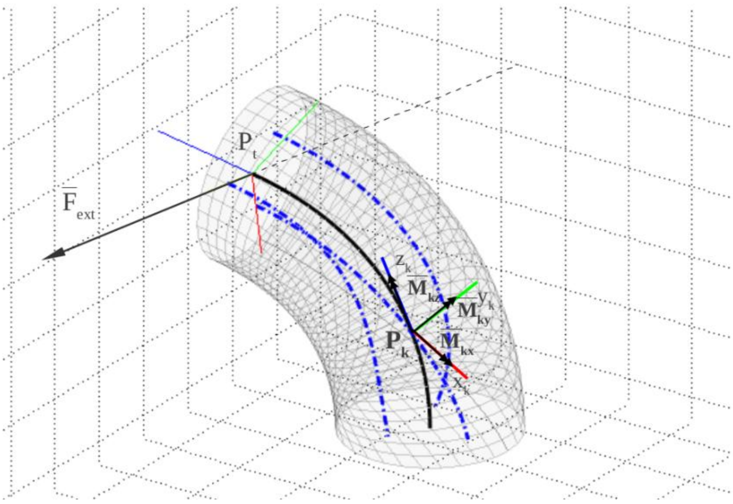

Fig. 8 Moments in cross section k

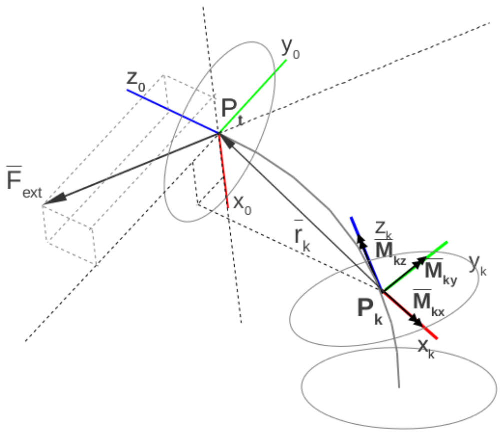

Fig. 9 Coordinate frames and vectors

As one can observe, the force and moment at cross section k depend on its position. Knowing the relative orientation of tip frame in the frame of cross section k and combining it with the force and moment resulting from pressures, one can calculate F_k and M_k – the overall force and moment acting on that cross section. Those values can be then used to determine the elongation and curvature of the module at point P_k (equations 10, 11)

$$\Delta dl_k = \frac{F_k}{A E} dl \tag{10}$$

where

$$F_k = F_p + F_{k\,ext,z}$$

and

$$\kappa_k = \frac{1}{\rho} = \frac{M_k}{EI} \tag{11}$$

where

$$M_k = M_{kp} + \overrightarrow{F_{ext}} \times \vec{r_k}$$

Twist can be calculated with [12]:

$$d\frac{\theta}{dl}=\frac{T}{GI_0} \tag{12}$$

where T is the torque value (the z part of force moment in k-cross-section) and GI_0 represents the torsional rigidity of the module

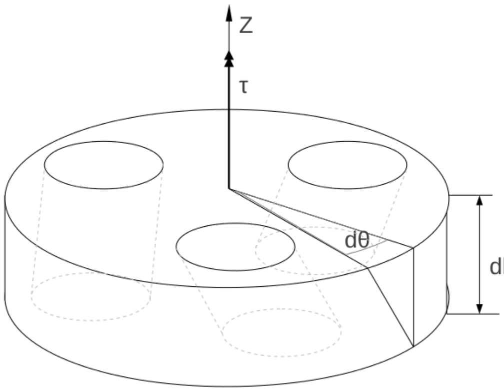

Fig. 10 Twist of the module fragment dl

Shape of the module can be determined by integrating the elongation, twist and bend of every point along the module axis.

6 Implementation

The model described in this paper has been implemented in order to use in the Stiff-Flop project system. For more convenient development, Matlab had been used. For determining the overall shape of the arm, equations presented earlier are applied to all modules of the manipulator, starting from the last module. Elongation, bending and torsion are calculated in a fixed number of cross sections of the module in the direction from the tip to the base. At each iteration, coordinates (position and orientation) of the current cross-section in terms of the module's tip frame are used to calculate moments and forces. The coordinates of next iteration cross-section frame are calculated using the bending, elongation and twist of the current fragment. When next module is reached, the process is repeated , but the forces and moments from previous module are taken into account. The method of calculation used in the model causes the results to be expressed in terms of the module's tip frame. During the calculations, the resulting values have to be transformed between frames several times. For transformation of vectors between the frames Euler angles are used (**Fig. 11**)

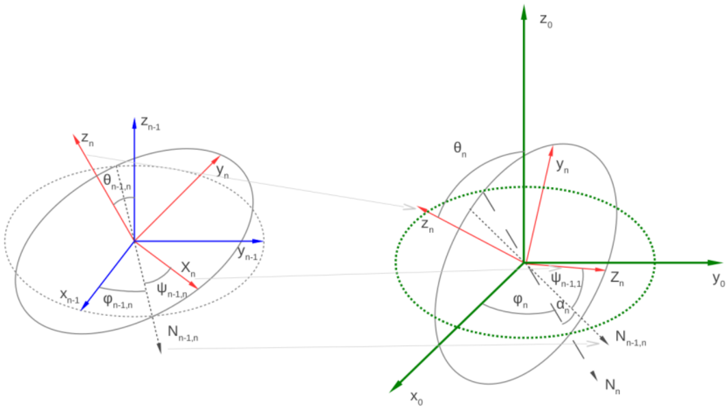

Fig. 11 Euler angles between n and n-1 cross section frame; n-th cross section frame shown with the global frame

Results are presented on **Fig. 12**

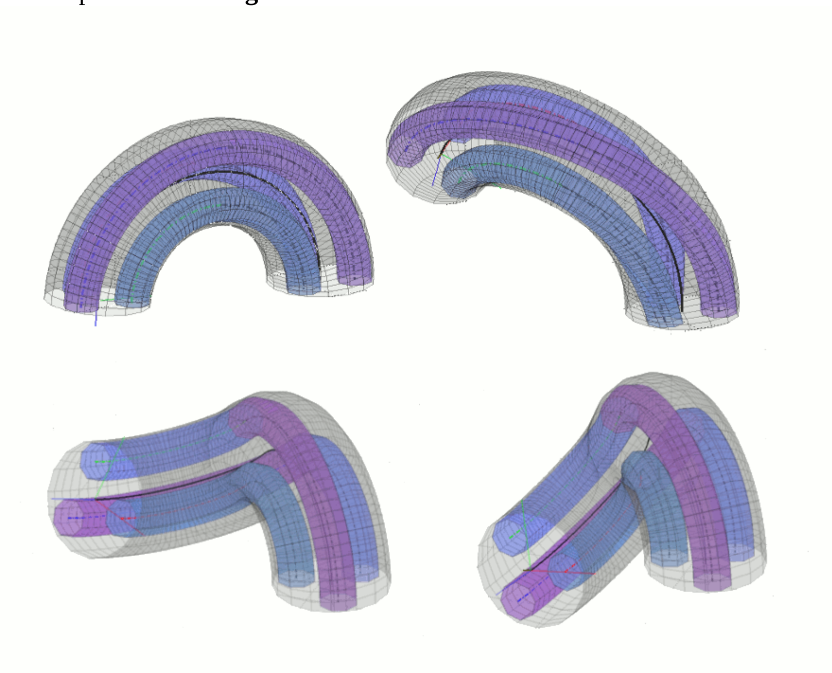

Fig. 12 Visualization of the simulated arm

7 Conclusion

The model described in this paper allows estimation of the continuum robot's shape. It has been successfully used as a simulation platform to work on data fusion in the Stiff-Flop project. Adjusting the number of calculation iterations allows choosing between high precision and low computation time. More research about the optimal number of iterations for the task of estimating the Stiff-Flop manipulator shape is still to be carried out. The possibility of adjusting the model to describe the dynamic behavior of the arm is being explored.

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