Optimizing Continuum Robot Tendon Routing for Minimally Invasive Brain Surgery

Margaret Rox[1], Aidan Copinga[2], Robert P. Naftel[3], Robert J. Webster III[1], and Alan Kuntz[2]

[1] *Department of Mechanical Engineering, Vanderbilt University*
[2] *School of Computing and Robotics Center, University of Utah*
[3] *Department of Pediatric Neurosurgery, Vanderbilt University Medical Center*
margaret.rox@vanderbilt.edu

INTRODUCTION

Tendon-driven continuum robots are compliant and capable of assuming complex curves, making them ideal for minimally invasive surgery in confined spaces with obstacles. These robots can achieve an infinite family of curves, determined by both actuation and design considerations, such as the tendon routing paths of tendons along the robot. Design optimization of surgical continuum robots has been studied (see [1] for review), but the idea of variable and complex tendon routing is newer, and although it has been modeled [2], it has yet to be used to design a practical surgical device. For tendon-driven continuum robots in general, design optimization has thus far focused on multi-segment robots that use straight (i.e. parallel to the backbone) segments of different lengths, where tendons terminate at various arclengths along the robot [3], [4]. The advantage of designing with nonlinearly routed tendons is the potential to enable a much more expressive family of shapes during actuation [2]. However, it has thus far been challenging to design nonlinear tendons because one is working in an infinite design space with mechanics-based models that require solving differential equations to compute robot kinematics.

Toward solving this problem, this paper presents a new tendon routing parameterization for tendon-driven robots and leverages it to optimize the routings for a design objective drawn from a practical neurosurgical application: choroid plexus cauterization for hydrocephalus [5]. This application was an early motivating example in the development of concentric tube robots, extended in [6], although physical size, achievable curvatures, and stiffness constraints have thus far limited practical fabrication of the robots designed in simulation. The endoscopic approach to choroid plexus cauterization requires maneuvering through tight spaces in the ventricles, which is challenging with traditional constant curvature endoscopes (see Fig.1). Further, even in "successful" procedures, surgeons often want to cauterize more of the choroid plexus than they can currently reach and simply settle for what they can reach. Thus, a robot with nonlinear tendon routing that can access more of the choroid plexus would be a valuable tool.

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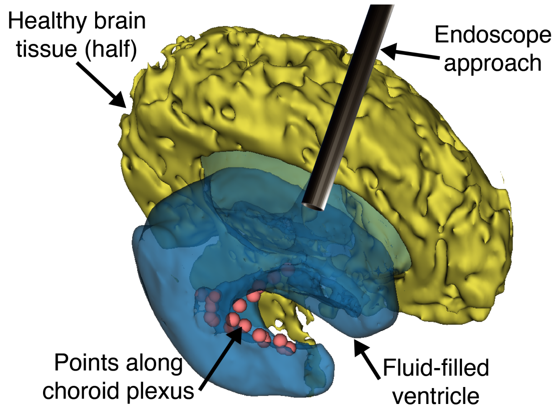

Fig. 1 Choroid plexus cauterization for hydrocephalus is a neurosurgical procedure where an endoscope is inserted into the open, fluid-filled ventricle, and then must reach points around the curvature of the ventricle.

MATERIALS AND METHODS

According to the model defined in [2], we can describe the tendon routing for a given robot by a vector in attached frame coordinates as a function of s: $\boldsymbol{r}_i(s) = \left[x_i(s)\ y_i(s)\ 0\right]^T$. Note that one can arbitrarily set x and y to any value (constrained by a maximum radius of the robot), but x and y do not have to be integer values. One can use any shape equation to define the tendon routing, as long as it is physically realizable.

To use this framework in designing an optimal robot for a given application, we propose a new way of parameterizing tendon routing which will enable complex routings in the design space, such that one does not have to assume a priori that the only candidates are lines or helices. We parameterize a given tendon routing path using polynomials in cylindrical coordinates, i.e., a polynomial describing the tendon's angle around the

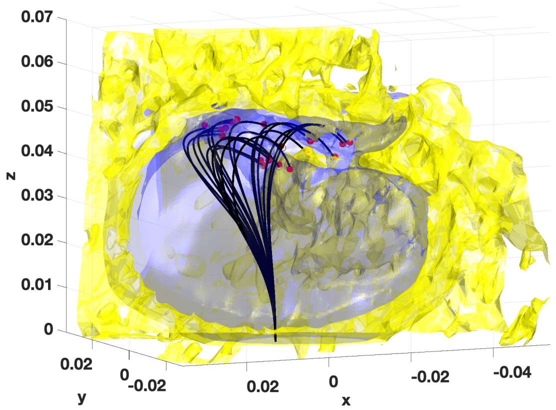

Fig. 2 After optimization, the robot is able to reach the desired points, which are shown in red. Also shown: the backbone of the tendon robot (black), brain tissue (yellow), and open ventricle space (blue).

backbone as a function of the backbone's arc length and a polynomial describing the tendon's distance from the backbone as a function of arc length.

This results in a set of polynomial basis functions with coefficients:

$$\begin{aligned} \varphi_i(s) &= C_{0i}s^0 + C_{1i}s^1 + C_{2i}s^2 + \ldots + C_{ni}s^n \\ \rho_i(s) &= D_{0i}s^0 + D_{1i}s^1 + D_{2i}s^2 + \ldots + D_{ni}s^n \end{aligned} \tag{1}$$

where s is arc length, φ is the angular position of the tendon on the projection plane located at s, ρ is the radial position of the tendon with respect to s, and with i indexing the i^{th} tendon. With the tendon routing formulated in this manner, we are now able to optimize the coefficients of these functions, searching over an expressive set of non-linear, generalized tendon routings. We can then convert the cylindrical equations back to a Cartesian frame using the standard conversion equations to be fed back into the model.

To apply this framework to hydrocephalus, we assumed a robot with 3 tendons and limited $\varphi_i(s)$ to 3 coefficients while keeping $\rho_i(s)$ fixed. We model the backbone with the physical properties of a nitinol tube of OD .686 mm and ID 0.533 mm, with an assumed disk diameter of 8 mm. We made these choices only as a proof-of-concept, and none are intrinsic to the approach. A pediatric neurosurgeon (co-author Naftel) selected targets defining the desired choroid plexus surface to be cauterized in an MRI scan of a brain from a hydrocephalus patient. He also selected the entry vector he would use for the endoscope if treating this patient, which defined the entry path for our robot. Next in our optimization, for a given tendon routing, we computed the forward kinematics of the robot at each combination of a discretized set of tension values (spanning 0 - 4.5 N) for each tendon. We then found the minimum distance from the tip of the robot to each desired point in the choroid plexus across all tension values. We tasked the optimizer with minimizing the sum of squared error for these distances, optimizing C_0, C_1, and C_2 for all 3 tendons (9 parameters total). We used MATLAB's `fminsearch` function with random initialization to perform the optimization.

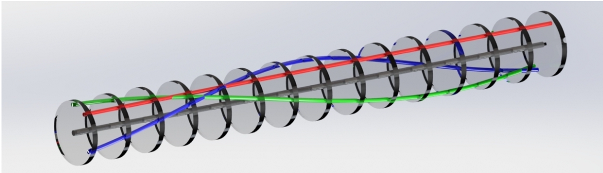

Fig. 3 Post-optimization tendon routing.

RESULTS

Our method found a set of tendon routings that enabled the robot to reach all 20 points with less than 0.8 mm of error and a mean error across all points of 0.5 mm (see Fig. 2). The optimization produced:

$$\begin{aligned} \varphi_1(s) &= -0.121 + 70.697s + 0.096s^2 \\ \varphi_2(s) &= 3.260 + 0.168s + 25.459s^2 \\ \varphi_3(s) &= 0.107 + -53.325s + -0.141s^2. \end{aligned} \tag{2}$$

with our fixed value of the radius set to $\rho_i(s) = 0.035$ for all tendons, which results in the nonlinear routing for each tendon shown in Fig. 3.

DISCUSSION

This paper presents a parameterization for nonlinear, expressive tendon routing for continuum robots. This parameterization results in a vector of coefficients that can be optimized using standard design optimization methods. We demonstrate the first generalized tendon routing optimization, while showing proof of concept in an example neurosurgical application in simulation. In future work, we plan to optimize not only the angle, but also include the radial distance from the backbone. We also intend to include either motion planning or another form of obstacle avoidance into the framework when evaluating design capabilities. We further intend to leverage the method to reduce the radius of the robot while maintaining capabilities and addressing physical fabrication feasibility. Lastly, we believe the method can be extended to many other surgical scenarios that involve touching a sequence of target positions.

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