Workspace Characterization for Hybrid Tendon and Ball Chain Continuum Robots

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INTRODUCTION

Continuum robots have attracted considerable attention for applications in minimally invasive diagnostics and therapeutics over the past decade [1]. The primary reason is their ability to navigate narrow and tortuous anatomical passageways, while guaranteeing safe interaction with the anatomy.

In designing such robots, an important goal is create a robot with a workspace appropriate for the clinical task. A significant limitation of many continuum designs relates to the minimum radius of curvature that a particular design can achieve. While multiple bending sections can be concatenated to provide more degrees of freedom, the orientations by which a point in the workspace can be approached are often limited.

To overcome this limitation, this paper investigates a hybrid design that combines the advantages of tendon-actuated [2] and magnetic ball chain robots [3] as shown in Fig. 1. In this hybrid design, a proximal tendon-actuated section positions the robot with respect to the goal tip location while a distal ball chain section orients the robot tip with respect to the goal location. This abstract describes how the hybrid kinematics can be modeled and illustrates how the hybrid design possesses a dexterous workspace of finite extent.

MATERIALS AND METHODS

While beyond the scope of this abstract, a complete physics-based hybrid model can be derived by applying the distributed and magnetic forces and torques of the ball chain [3] to the tendon-actuation model of [2]. Assuming that magnetic loading does not significantly deflect the proximal tube, a simplified workspace characterization can be derived using a constant curvature assumption for the tendon-actuated segment [2] and a straight line approximation for the ball chain segment [3]. The latter assumption holds when the strength of the applied field is high enough to straighten the chain. Given these assumptions, the following approximate kinematic model can be used for a qualitative workspace analysis.

A ball chain robot is assumed to extend, for a length $l = n_s d$, as a straight line; here n_s is the number of spheres (balls) and d their diameter. Given their base position and orientation in global reference frame, ${}^0\boldsymbol{p}_b$ and ${}^0\boldsymbol{R}_b$, their tip position and orientation is

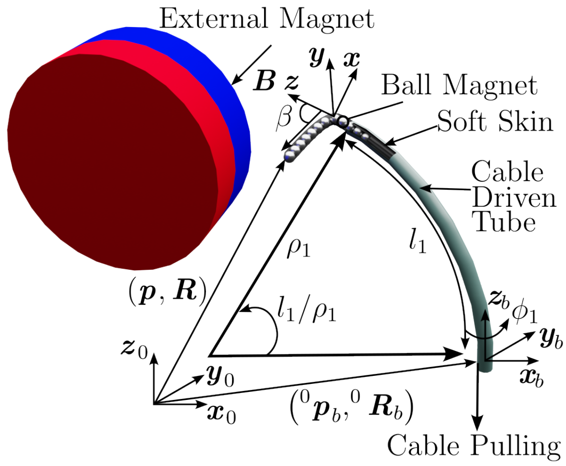

Fig. 1 Schematic representation of ball chain and tendon actuation.

$$\boldsymbol{p} = {}^0\boldsymbol{p}_b + n_s d\, {}^0\boldsymbol{R}_b \boldsymbol{rot}_{e_2}(\beta)\boldsymbol{e}_3 \tag{1a}$$

$$\boldsymbol{R} = {}^0\boldsymbol{R}_b \boldsymbol{rot}_{e_2}(\beta) \tag{1b}$$

with $\boldsymbol{e}_i \in \mathbb{R}^3$ i-th element of the canonical basis of $\mathbb{R}^3$, and $\boldsymbol{rot}_{e_i}(\beta)$ rotation of $\beta = \angle\boldsymbol{B}$ around the axis e_i; $\boldsymbol{B}$ magnetic field. We approximate a set of n_t telescoping cable driven tubes using piece wise constant curvature assumption,

$$\boldsymbol{p} = {}^0\boldsymbol{p}_b + {}^0\boldsymbol{R}_b \sum_{i=1}^{n_t} \boldsymbol{rot}_{e_3}(\phi_i)\boldsymbol{r}_i \tag{2a}$$

$$\boldsymbol{R} = {}^0\boldsymbol{R}_b \prod_{i=1}^{n_t} \boldsymbol{rot}_{e_3}(\phi_i)\boldsymbol{rot}_{e_2}\left(\frac{l_i}{\rho_i}\right) \tag{2b}$$

where $\boldsymbol{r}_i = \rho_i \left(1 - \cos(l_i/\rho_i)\ 0\ \sin(l_i/\rho_i)\right)^T$, ρ_i and l_i respective radius of curvature and length of the i-th section.

By combining (1) with (2), we obtain the kinematics of a ball chain magnetic robot extending from one cable driven tube

$$\boldsymbol{p} = {}^0\boldsymbol{p}_b + {}^0\boldsymbol{R}_b \boldsymbol{rot}_{e_3}(\phi_1)(\boldsymbol{r}_1 + n_s d \boldsymbol{rot}_{e_2}(\beta)\boldsymbol{e}_3) \tag{3a}$$

$$\boldsymbol{R} = {}^0\boldsymbol{R}_b \boldsymbol{rot}_{e_3}(\phi_1)\boldsymbol{rot}_{e_2}\left(\frac{l_1}{\rho_1} + \beta\right) \tag{3b}$$

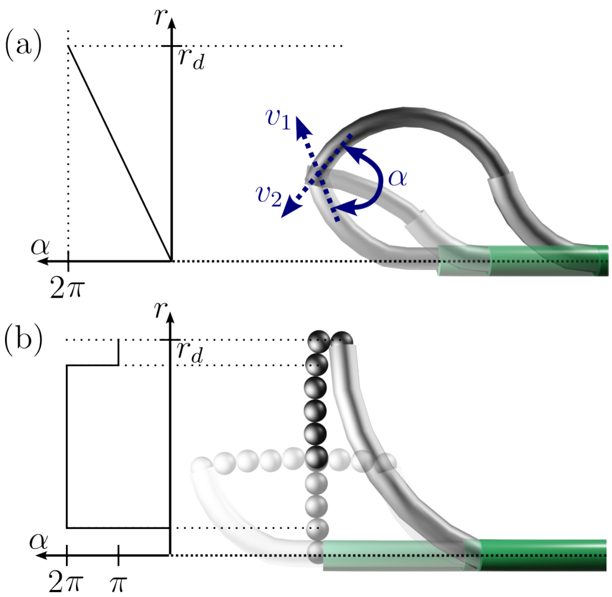

Fig. 2 Comparison of workspace dexterity for: (a) two-segment tendon-actuated robot; (b) tendon/ball-chain continuum robots. Plots on left indicate range of approach angles, α, as a function of distance, r, off of the longitudinal axis.

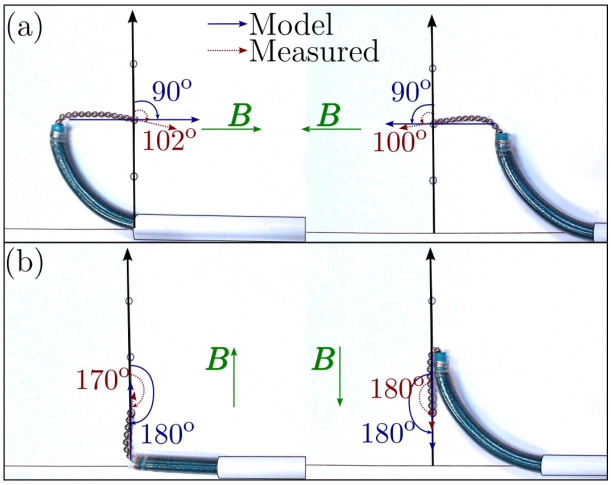

Fig. 3 Demonstration of dexterous workspace for hybrid tendon-actuated / ball chain continuum robot. Point at distance: (a) $r = r_d$; (b) $r \leq r_d - d$.

RESULTS

In Fig. 2, we compare the range of approach angles, α, spanned by a robot composed of 2 telescoping tendon driven sections with the proposed hybrid design, as a function of the distance, r, from the longitudinal axis of the proximal section at its base. For this comparison, we assume that the proximal and distal tendon-actuated sections have maximum bending angles of $\pi/2$ and π, respectively and that minimum radius of curvature of the distal tube is half that of the proximal tube. The minimum radius of curvature of the proximal tube is $r_d = 2l/\pi$. For any point located less than r_d from the base axis, the angle of approach is bounded by v_1 and v_2 (see Fig. 2). The former corresponds to the approach direction when the distal tube takes on its minimum bending radius while the latter corresponds to both tubes at their minimum radii of curvature. Any approach angle between these two extremes is possible as shown by the intermediate configuration. It can be shown that the range, α, increases linearly with r_d as shown on the left side of the plot with $\alpha = 2\pi$ only at $r = r_d$.

In contrast, since ball chains can achieve a very small radius of curvature as schematically depicted in Fig. 2 [3], the hybrid design can approach points from all directions, $\alpha = 2\pi$, for any r satisfying $d < r < r_d - d$. We see that the telescoping tubes achieve full dexterity only for $r = r_d$.

Fig. 3 provides an experimental validation of the dexterity of ball chain robots shown in Fig. 2. We consider the case $r = r_d$ (Fig. 3a) and the case $d < r \leq r_d - d$ (Fig. 3b), to validate the two extreme cases: $\alpha = \pi$ and $\alpha = 2\pi$, respectively. The tendon-actuated proximal segment is 76mm long and the ball chain is 38mm long with the latter composed of 3.175mm diameter balls (N52 magnets). Using a magnetic field of 40 mT, by positioning a permanent magnet (N52, diameter 76.2 mm, height 38.1 mm) in the directions indicated in Fig. 3, we show that the ball chain can achieve the full dexterity predicted in Fig. 2 with mean percentage error between approximated model and experiments of 7.5%.

While we only have space to analyze and report experiments for the planar case here, by revolution around the robot's main axis (z_b), these results can be generalized to 3D. Specifically, we can show any point within distance $r_d - d$ from the robot's main axis can be approached from any direction.

DISCUSSION

The hybrid design presented in this paper is characterized by a large dexterous workspace. The design method, consisting of the combination of tendon driven and magnetic ball chain robots is perhaps the only continuum design capable of approaching a large set of tip positions from an arbitrary direction. This workspace can be approximated using a simple kinematic model, which is validated experimentally on a benchtop setup.

In the future, we will demonstrate the dexterous workspace in 3D and create an actuation platform for concurrent control of the tendon driven robot and magnetic chain.

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