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Auto-Calibration for a Planar Epicardial Wire Robot

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Abstract

Gene therapies have emerged as a promising treatment for congestive heart failure, yet they lack a method for minimally invasive, uniform delivery. To address this need we developed Cerberus, a minimally invasive parallel wire robot for cardiac interventions. Prior work on controlling the movement of Cerberus required accurate knowledge of device geometry. In order to determine the geometry of the device *in vivo*, this paper presents work on developing an auto-calibration procedure to measure the geometry of the robot using force sensors to move injector. The presented auto-calibration routine is able to identify the shape of the device to within 0.5 mm and 0.9°.

I. INTRODUCTION

Cerberus is a planar parallel wire robot developed for minimally invasive myocardial injections [1]. The device is inserted using a subxiphoid approach that accesses the heart while avoiding the lungs. Flexible arms then allow the device to expand into a triangular shape and adhere to the surface of the beating heart with suction on its three bases, providing a stable platform with no motion relative to the heart. Wires from each base connect to an injector head that moves within the triangular support structure by changing the wire lengths. This design has the typical advantages of parallel wire robots, namely a large workspace and the ability to move quickly within this workspace [2]. These advantages give the device the potential to deliver multiple injections accurately within the entirety of the workspace to the beating heart.

Previous work on Cerberus has focused on adapting previously developed control methods for parallel cable manipulators [1]. Under simplifying assumptions about the geometry of the robot and neglecting the curvature of the heart, inverse kinematics that yield the wire lengths were successfully derived, and a control system was developed and tested *in vivo* using only position feedback that required knowledge of the geometry.

Errors in the geometry can cause wires to be too loose, resulting in loss of injector control and accuracy, or too tight, potentially interfering with heart activity or breaking the device. Such errors are amplified by the fact that the kinematics require accurate knowledge of the geometry which becomes altered once deployed on the heart to the point where position feedback alone will not suffice.

With the long-term goal of Cerberus to be in the operating room, it is crucial to have accurate measurements of the robot for the purposes of calculating wire lengths. The addition of force sensors allows the injector to be moved without prior knowledge of deployed geometry or location by measuring the tensions in the wires under the assumption that the device is frictionless and non-inertial. Further, wires can only exert force by pulling [2, 3]. In this paper, an auto-calibration algorithm that estimates the geometry of the device is constructed which allows the injector to start anywhere once deployed and move independent of location knowledge using force sensors and encoder values.

II. METHODS

A. System Hardware

The existing electrical control system [1] was adapted to incorporate three load cells using a pulley system and calibrated to measure the tension in each wire. For the purposes of this experiment, a desktop set-up was designed, capable of fixing the three bases of the robot to a planar surface while allowing variation of the lengths and angles of the arms at known values, as shown in Fig. 1. A Pixy camera was mounted directly overhead to capture all possible configurations within the camera's field of view. The camera was used to establish ground truth using the camera's color-tracking software via markers on the bases and injector, but not to control the robot.

B. Kinematics

Kinematic equations were adapted to fit this system from previous work for general parallel wire manipulators with one degree of actuation redundancy [2]. No closed-form solution exists for the forward kinematics because the system is a parallel manipulator. Inverse kinematics can be found by drawing concentric circles around each base that intersect at the injector to find the Euclidean distances between bases, assuming that the middle base is set as the origin under Cartesian coordinates (Fig. 2). As provided by Costanza et al. [1], the lengths of the wires are given by:

$$\begin{bmatrix} r_l^2 \\ r_m^2 \\ r_r^2 \end{bmatrix} = \begin{bmatrix} (x_0 + L_l \cos \theta_l)^2 + (y_0 - L_l \sin \theta_l)^2 \\ x_0^2 + y_0^2 \\ (x_0 - L_r \cos \theta_r)^2 + (y_0 - L_r \sin \theta_r)^2 \end{bmatrix} \quad (1)$$

Note that this depends on knowledge of the desired injector position and the geometry of the robot. However, the deployed geometry of the device is difficult to predict due to compliance in the arms and irregularity of the surface. The next section will discuss a solution to this problem using an auto-calibration procedure.

C. Auto-Calibration

Obtaining visual confirmation of robot using medical imaging, though possible, would take extra time and be more expensive. Other research has explored alternative methods of calculating cable lengths from geometric properties [3]. The method previously used by Cerberus involved manually adjusting wire lengths until the user felt that the injector was at a base given that that base's wire was fully taut. The encoder values at said base were then recorded and the user would then manually position the injector to the next base. The lengths of the robots arms were then determined using these wire lengths.

In an effort to automate this process, an auto-calibration routine was developed that takes advantage of force measurements. Similar to the manual process, the auto-calibration begins by pulling the wire of a designated base as the other two wires maintain a minimum tension as to not inhibit the main wire. The robot will know that it is at the base when its designated wire cannot be pulled further without exceeding the maximum tension, while the other wires are within the minimum range. This process is repeated to record the encoder values at each base. The encoder values are then converted into wire lengths based on the reel's diameter. The differences between bases will give the designated arm length as well as the angle between the left and right base using the law of cosines. Accuracy and precision of the auto-calibration algorithm were tested by running it while varying the geometry of the set-up and comparing the results to known geometric values.

III. RESULTS

Simulations and bench top experiments were conducted to verify the validity of auto-calibration results under operation conditions with various geometries. An example of the auto-calibration process in screenshots is shown in Fig. 3.

Auto-calibration was tested using various geometries to verify the accuracy of the procedure. Estimates of the left and right arm lengths and symmetric angle between the arms compared from the calibration procedure were compared to the actual measurements. The average absolute error of the left and right arm were 1.16 ± 0.38 mm and 1.31 ± 0.46 mm, while the average absolute error for the angle was $0.89^\circ \pm 0.30^\circ$ for 10 trials under various geometries.

IV. DISCUSSION

Current models of the device are simplified for ideal conditions. Future work could focus on improving the geometric assumptions made to better reflect realistic conditions. Particularly taking into account the base diameter will change both wire length and angles used to calculate target wire lengths.

The next step for this robot would be to translate the algorithm from the current planar model to a curved surface to replicate more realistic heart conditions. This would begin on an idealized sphere and then move onto irregular curved surfaces similar to the heart. Calculation of the arm lengths will need to be adjusted for a curved surface.

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Fig. 1. Desktop set-up with three bases fixed on a platform, where the left and right base can be set to various lengths, and a mounted camera.

Fig. 2.
Ideal kinematics diagram of the planar wire robot manipulator.

Fig. 3. Screenshots during auto-calibration (a)–(d). (a) Robot starts in any configuration. (b) Injector moves to middle base. (c) Injector moves to left base. (d) Injector moves to right base. Injector then moves back to middle base (b).