Effect of Path History on Concentric Tube Robot Model Calibration

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INTRODUCTION

A variety of models have been developed to describe the kinematics of concentric tube robots [1,2]. While some of these are based on mechanics-based modeling [1], others employ parametric [1] and nonparametric [2] models. Almost all modeling attempts neglect history-dependent effects, i.e., the dependence of robot shape and tip location on prior motion. Physically, these effects can arise from phenomena such as friction and hysteretic stress-strain. Furthermore, such state dependency has been observed experimentally.

While the neglect of these effects may be justifiable in order to simplify and speed kinematic computations for real-time control, it is worthwhile to understand the effect of unmodeled state dependency on the accuracy of state-independent models.

Consider the three-tube robot in Fig. 1 that consists of a proximal pair of tubes that rotate, but do not translate with respect to each other and a distal tube that can rotate and translate with respect to the proximal pair. The robot configuration (neglecting rigid body displacements) can be defined by two relative rotation angles and one translation. Considering only the two rotations, a specific configuration can be approached from four angular "directions," which actually result in four robot tip positions for the same configuration.

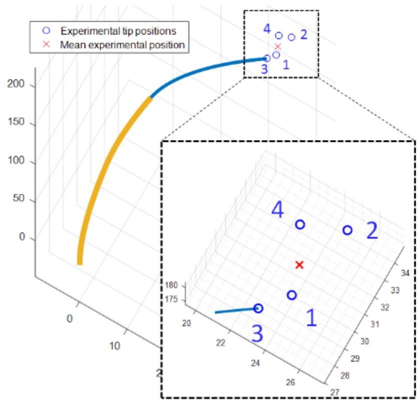

Fig. 1. Four experimentally measured robot tip positions corresponding to same relative rotation angles, but different directions of approach. Tube parameters in Table 1.

To calibrate a state-independent model of this robot, one could collect data in a number of ways. For example, one could sequentially increment each of the two relative angles through complete revolutions. Depending on the selected directions of rotation, that would correspond in Fig. 1 to collecting all data points in, e.g., configuration 1. Since for arbitrary robot motions, all four configurations are equally likely, this would introduce a systematic bias in the calibrated model and likely increase model error when tested against a verification data set – unless, of course, the verification data was collected with the same bias.

Alternately, one could design a data collection algorithm to select a random direction of approach for each sample configuration. This is an appropriate technique for acquiring a verification data set and, if also used to acquire training data, it would eliminate the dirctional bias and could reduce modeling error.

As a final alternative, consider the mean position of the four directional configurations, which is also shown in Fig. 1. A model trained on the set of mean positions for all configurations is likely to produce the smallest error when validated against data collected with random directions of approach. Such a calibration method is time consuming, however, since actual robot position must be measured 2^n times, where n is the number of rotational joints.

One can speculate, however, that the mean position corresponds to the position the robot tip would take if there were no state-dependency in the robot's behavior. This suggests that if there was a technique to shake a robot free of its history dependence as it approached a configuration, one could reduce collection of the calibration data set to one point per configuration while still reducing modeling error to what could be achieved using the mean of all potential configurations.

Dithering has long been used to reduce the effect of friction and we have also used a type of dithering to drive elastically unstable tube sets to configurations inside the major hysteresis loop created by the instability [3]. In this case, dithering refers to driving the tubes to the desired relative angles following an oscillatory path of decreasing amplitude in joint space.

MATERIALS AND METHODS

A three-tube robot, with parameters given in Table 1, was used with an electro-magnetic (EM) sensor to capture the tip position. This robot design is chosen as it possesses a large workspace relative to other designs [1]. Two kinematic models were used for calibration – the mechanics-based model of [1] and the truncated Fourier series model of [1].

To validate the calibration concepts proposed above, we collected and compared two different calibration data sets of robot tip positions. One dataset was acquired using dithering to minimize path history effects, while the other dataset included four measurements of tip position for each joint space configuration, corresponding to the four angular directions of approach. Each dataset included 512 joint space configurations (base rotations and translations) evenly distributed over the joint space.

In the data set acquired without dithering, the four measurements corresponded to the following rotation directions of the second and third tubes relative to tube 1: (1) CCW,CCW, (2) CCW,CW, (3) CW,CCW and (4) CW,CW. A third data set was collected for verification of the calibrated models that consisted of 500 random configurations. To reflect real-world conditions, the directions of approach for each configuration in this set were selected using a random number generator.

Table 1. Tube Parameters.

	Tube 1	**Tube 2**	**Tube 3**	
	Section 1	Section 1	Section 2	Section 1
Length (mm)	150	150	150	86.4
Radius of curvature (mm)	265	265	∞ (straight)	55
Relative stiffness	1	1	0.2857	0.2857

RESULTS

To verify if the dithered data set is equivalent to the data set that includes all four approach directions, we first computed the mean positions of the latter and compared them with the former. The dithering consists of a sequence of 20 angular offsets: $\{+40^o, -38^o, +36^o, \ldots, -2^o, 0^o\}$. The dithered positions are good approximations to the mean of the 4 undithered positions, with average and maximum distances between them of 0.5025mm and 1.4716mm, respectively. This provides some support for our hypothesis that dithering can average out path-dependent phenomena.

Next we calibrated the mechanics-based and truncated Fourier series models using four different subsets of our calibration data sets and compared them all using the verification data set. The first two training sets correspond to the complete dithered and undithered training data sets. We anticipate that these two sets will produce comparable errors. The third training set was the subset of undithered data associated with directions (1) CCW,CCW. This set corresponds to the typical approach one would use to collect data when neglecting path-dependent effects. The fourth training set was a subset of the undithered data set in which one of the four directions was selected randomly for each configuration.

The mean and maximum errors for the four training data sets and two models are given in Tables 2 and 3. As anticipated, the dithered data set and the full undithered data set give comparable results. The biased subset of the undithered data produces the largest errors. The use of a directionally-random subset of the undithered data produces smaller errors, but not as small as those provided by the dithered and full undithered data sets.

The choice of training data set also affects the comparison of the two kinematic models. Based on the biased undithered sets, which likely have been used in many prior papers, the accuracy of both models is comparable. When compared using the dithered and full undithered data sets, however, the truncated Fourier model significantly outperforms the mechanics-based model. The difference in modeling error is likely related to the relative expressive power of the two models as determined by the number of parameters (9, mechanics-based; 343, truncated Fourier series). A representative robot configuration is given in Fig. 3.

Table 2. Prediction errors of mechanics model on 500 random evaluation configurations.

Calibration data set (number of measurements)	Mean error (mm)	Max error (mm)
Dithered set (512)	3.3 (±1.6)	9.4
Full undithered set (2048)	3.3 (±1.6)	9.5
Biased undithered set (512)	4.5 (±2.4)	14.5
Random undithered set (512)	3.3 (±1.6)	9.0

Table 3. Prediction errors of truncated Fourier model on 500 random evaluation configurations.

Calibration data set (number of measurements)	Mean error (mm)	Max error (mm)
Dithered set (512)	2.3 (±1.3)	7.2
Full undithered set (2048)	2.3 (±1.3)	7.1
Biased undithered set (512)	4.1 (±2.5)	14.5
Random undithered set (512)	3.5 (±2.2)	12.8

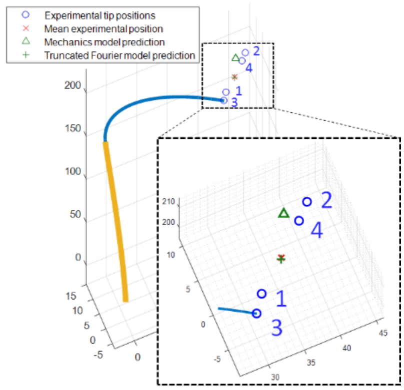

Fig. 3. Representative configuration illustrating large model errors. (Calibrations using dithered data set.)

DISCUSSION

We have demonstrated that standard approaches to calibration data collection introduce bias and increase modeling errors owing to the dependence of concentric tube robot configuration of path history. We have also introduced a dithering technique that can be used to avoid bias while also dodging the collection of multiple data points for each configuration. While we have only considered the path dependency of tube rotation here, tube translation should also be considered.

REFERENCES

[1] P. E. Dupont, J. Lock, B. Itkowitz, E. Butler, "Design and control of concentric tube robots", IEEE Trans. Robotics, vol. 26, no. 2, pp. 209-225, 2010.

[2] G. Fagogenis, C. Bergeles, P.E. Dupont, "Adaptive Nonparametric Kinematic Modeling of Concentric Tube Robots", IEEE/RSJ Int. Conf. Intelligent Robots and Systems, 2016.

[3] J. Ha, Park F.C., P.E. Dupont, "Optimizing Tube Precurvature to Enhance Elastic Stability of Concentric Tube Robots", IEEE Trans. on Robotics, vol. 33, no. 1, pp. 22-37, 2017.