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Task-Space Position Control of Concentric-Tube Robot with Inaccurate Kinematics Using Approximate Jacobian

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Abstract— **Many medical applications can benefit from the new technology of concentric-tube robot (CTR) due to its miniature size, superior steerability, and controllability of the end tool. However, the kinematic modeling of CTR is challenging because of complicated physical phenomena caused by the elasticity interaction between tubes. Existing control methods of CTR are based on inverse kinematics calculation and hence the control performance largely relies on the accuracy of kinematics model used. In this work, we propose a new control method from the actuator level and show that the control design of actuator input in task-space with approximate Jacobian matrix provides more flexibility and robustness in handling inaccuracy in kinematics model. It is shown through simulation study that the proposed control method presents better performance compared with traditional inverse kinematics based control method in face of kinematics inaccuracy.**

I. INTRODUCTION

The past few decades witness the evolution of surgical intervention from traditional open surgery towards Minimally Invasive Surgery (MIS), Single-Incision Laparoscopic Surgery (SILS) and Natural Orifice Translumenal Endoscopic Surgery (NOTES) due to their many advantages for the patient, such as less trauma and post-operative complications, reduced blood-loss and recovery time. On the other hand, this evolution makes the surgical procedures more challenging for the surgeon in terms of navigation to reach the clinical target and manipulation once the target is reached. To better assist surgeons in these surgical procedures, it is expected that new robotized surgical devices should be more flexible and more dexterous which allows safe navigation through sensitive anatomic obstacles inside the patient's body, and the device should keep sufficient manipulability and dexterity after reaching the surgical site.

The concentric-tube robot (CTR) is a new technology developed recently as a subset of continuum robots [1] [2]. Instruments used in MIS can be generally classified into three groups: straight flexible needles; straight and stiff shaft with articulated tool mounted at the tip; elongated and steerable devices (multistage microrobot, steerable catheters, etc) [3]. Compared to the aforementioned instruments, concentric-tube robot presents better tradeoff between steerability and controllability on the tip. CTR is miniature robot with small diameter and high dexterity which is composed of nested precurved Nitinol tubes actuated independently and hence its shape can be adapted to avoid anatomical obstacles and follow complex 3D paths. With cross sections comparable with

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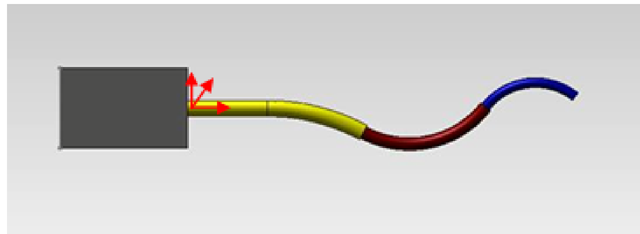

Fig. 1: concentric tube robot

needles and catheters, CTR is capable of both lateral motion and axial force exertion. All these characteristics make it suitable for minimally invasive and natural orifice surgery especially inside small body cavities [4]. Recent research works have shown the potential of using CTRs in different medical applications such as neurosurgery (endoscopic choroid ablation) [5], intracardiac surgery [4], endonasal skull base surgery [6] and lung biopsy surgery [7]. To realize real time control of the CTR, mechanics-based models with different assumptions have been developed to model the kinematics of CTR. The first model proposed assumes that the outer most tube has infinity stiffness compared to inner tubes [8]. Later on, more realistic physical phenomena previously neglected, such as bending and torsion, have been taken into consideration in order to improve the kinematics [9]. Based on the developed kinematics models, several motion planning algorithms have been developed [10] [11]. These motion planning algorithms resort to inverse kinematics calculation to obtain the actuator joint angles to achieve desired task space positions. However, the inverse kinematics calculation of CTR is not straightforward due to the nonlinear mapping between relative tube displacements and tip configuration as well as due to the multiplicity of solutions. A geometric approach is given for single and multiple sections in [12] by applying an analytical process to solve inverse kinematics based on modelling of each section with a spherical joint and a straight rigid link. Jacobian-based methods represent another approach to robot-independent inverse kinematics. In the Jacobian-based inverse kinematics strategy, it is possible to build actuator limits into the control law so that the robot's trajectory is always physically realizable [9], e.g. [13] for active cannula results.

It is noticed that existing works in literature on CTR position control are based on inverse kinematics calculation to get the necessary actuator joint angle in order to achieve control tasks that are usually defined in operational space (image space, Cartesian space, etc). Consequently, the con-

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trol performances are sensitive to the kinematic modelling inaccuracy. However, so far there exists no closed form kinematic of CTR when the number of tubes exceeds two, and the modelling challenge lies in the physical phenomena due to elasticity interaction between tubes such as bending, friction and torsion. With the existence of kinematics modelling errors, the inverse kinematics based control methods may suffer position errors and lead to safety problems. Although in teleoperation scenario this kind of positioning deviation could be partially compensated by the surgeon, it is not always guaranteed to work as the surgeon's intuitive manual correction command could be mis-interpreted by the inaccurate kinematics used in the inverse kinematics calculation.

To alleviate this problem, in this study we investigate the CTR position control from the actuator input level and it is shown that even if only approximate Jacobian matrix is available the position control task can be still accomplished with a simple PID form control torque input based on task space feedback position errors. The proposed control design is rigorously analysed through theoretical proof. This work presents a new method from the task-space control point of view which has not been explored for CTR motion control. Simulation studies based on a realistic experimental platform are shown to justify the advantage of proposed task-space control method over inverse kinematics based design method in handling kinematics modeling inaccuracy.

II. Kinematic Models of CTR

Since the concept of CTR was proposed in 2006 [1] [2], many research efforts have been made to study its kinematics model [14]. In this section the main existing kinematic models of CTR are introduced.

(1) The first idea was to consider the stiffness of the outer-most tube of the robot infinite compared to all the others inner tubes [8]. The limitation of this model is that if the stiffness of the outermost tube is not high enough to satisfy the assumption then the accuracy of the model will be degraded, otherwise the shape variation will be limited with less dexterity.

(2) Torsion-Free Model (TFM) takes into account the bending interaction between tubes, but the torsion is neglected. As the tubes are made of Nitinol, this assumption has an impact on the rotation angles of the tubes and in some cases the difference between the proximal and distal tubes angles can be significant which effects the estimation of the shape [1].

(3) Kinematics modeling of CTR is improved by including the transmissional torsion between actuators and the first curved link in the Transmissional Torsion Model (TTM) which reduces the error caused by torsion phenomenon in the straight part, but the torsion in the curved part of the tubes is neglected [15] [16].

(4) The most accurate model so far is based on Cosserat Rod Theory (Special Cosserat Rod Equilibrium Model). The torsion of the straight and curved parts of the tubes is included in the model, but the latter is described by a second order nonlinear differential equation causing problems of boundary conditions and computational cost in real-time. Another limitation is that the frictions are not included in the model [17].

The inverse kinematic model of CTR is more complicated compared to the other continuum robots. Analytically it's divided into two mappings: from the cartesian space to the arc parameters and then to the joint variables [9] [13]. The closed form solution exists only for the two tube case. Another way to solve the inverse kinematics problem is to use numerical root finding function since the forward kinematic model is nonlinear [18]. Inverse kinematic model can also be obtained using the Jacobian matrix [9].

In summary, there exists no kinematics model that describes precisely the effects of all important physical phenomena, and consequently existing inverse kinematics models used in motion control methods of CTR may lead to positioning errors in practice. Moreover, inverse kinematics calculation could be cumbersome due to the complicated and nonlinear mapping.

III. Formulation of CTR Position Control Task at Actuator Level

In literature, the position control of concentric tube robot is mostly formulated as a motion planning problem based on inverse kinematics calculation. Given the desired position or trajectory x_d in operational space, the corresponding desired joint positions or trajectories q_d are calculated by solving the inverse kinematics:

$$q_d = f_{InvKin}(x_d), \tag{1}$$

and it is assumed that the actuator for each joint will faithfully generate the desired joint motion q_d. However, if the robot kinematics is not accurately modelled the joint position obtained through calculation (1) may not achieve the desired operational space position.

In this work, we try to compensate the kinematics modelling error from the actuator control input level and bypass the inverse kinematics calculation, inspired by the works on uncertain kinematics task-space control for serial robot in literature [19] [20].

For existing CTR design, the joints are normally actuated by current driven motors which possess the following dynamics:

$$M_i\ddot{\theta} + C_i\dot{\theta} = K_i u_i - \frac{\tau_{ei}}{r_i} \tag{2}$$

where θ denotes the motor rotor shaft angle, M_i denotes the rotor inertia moment, C_i denotes the friction coefficient and K_i the torque constant. u_i is the control current input, τ_{ei} is the external load torque. $r_i = \theta_i/q_i$ is the transmission gear ratio from the motor angle θ to the CTR joint variables q, which is usually quite big and thus the effect of external load τ_{ei} could be neglected. Considering the linear relationship between actuator and joint variables $\theta_i = r_i q_i$ and, for simplicity of expression and without loss of generality, setting $\frac{K_i}{r_i} = 1$, the dynamic relationship between CTR joint variables and actuator input can be written from (2) as:

$$M\ddot{q}+C\dot{q}=u \tag{3}$$

where $M=diag([M_1,\cdots,M_n])$, $C=diag([C_1,\cdots,C_n])$ and $u=diag([u_1,\cdots,u_n])$.

Now the position control task could be specified at the actuator level: design the actuator current input u such that the tip position x of CTR can reach the desired operational space position ($\Delta x=x-x_d=0$) even with inaccurate kinematics model. Compared to joint level control which is directly influenced by the kinematics errors, the lower level control design provides another solution which possesses more flexibility to handle such kind of problem.

IV. Task-Space Position Control of CTR with Inaccurate Kinematics

The operational space velocity $\dot{x}$ and the CTR joint velocity $\dot{q}$ could be determined by Jacobian matrix $J(q)$ as [9]

$$\dot{x}=J(q)\dot{q}. \tag{4}$$

With the presence of kinematics errors, accurate Jacobian matrix is unknown and only estimated (best-guess) Jacobian $\hat{J}(q)$ is available.

In this study, it is assumed that the Jacobian estimation error $\|\hat{J}(q)-J(q)\|$ is bounded with an upper limit β as

$$\|\hat{J}(q)-J(q)\|\leq\beta. \tag{5}$$

Based on the approximate Jacobian matrix $\hat{J}(q)$, the control current input can be designed with the use of task-space position error as in the following form:

$$u=-\hat{J}^T(q)K_p\Delta x-K_d\dot{q}-K_i\int_0^t(\dot{q}+\alpha\hat{J}^T(q)\Delta x)d_t \tag{6}$$

where $K_p=k_pI$, $K_v=k_vI$ and K_i are positive definite control gains, α is a positive scalar.

Since the CTR joint velocities are not directly measurable and noting the fact that $\dot{q}=r^{-1}\dot{\theta}$, the control input is actually implemented using easily available and more accurate actuator joint velocity $\dot{\theta}$ as

$$u=-\hat{J}^T(q)K_p\Delta x-K_d'\dot{\theta}-K_i'\int_0^t(\dot{\theta}+\alpha'\hat{J}^T(q)\Delta x)d_t \tag{7}$$

which is equivalent to the control design in (6) with $K_d'=K_dr^{-1}$, $K_i'=K_ir^{-1}$, $\alpha'=r\alpha$.

It's seen from the proposed control input (6) or (7) that no inverse Jacobian calculation is required in this control method which is in general much more complicated than transpose Jacobian calculation. The task-space position error can be obtained online through camera, ultrasound, MRI, etc according to different clinical applications.

Next, we investigate the system performance through Lyapunov analysis. Substituting control input (6) into the dynamics equation (3), the closed-loop system dynamics has

$$M\ddot{q}=-\hat{J}^T(q)K_p\Delta x-(C+K_d)\dot{q}-K_i\int_0^t(\dot{q}+\alpha\hat{J}^T(q)\Delta x)d_t. \tag{8}$$

Propose a Lyapunov function candidate as

$$V=\frac{1}{2}\dot{q}^TM\dot{q}+\alpha\dot{q}^TM\hat{J}^T(q)\Delta x+\frac{1}{2}\Delta x^TK_p\Delta x+\frac{1}{2}z^TK_iz \tag{9}$$

where $z=\int_0^t(\dot{q}+\alpha\hat{J}^T(q)\Delta x)d_t$.

Rewrite V into the form

$$\begin{aligned}V=&\tfrac{1}{2}(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^TM(\dot{q}+\alpha\hat{J}^T(q)\Delta x)\\&-\tfrac{\alpha^2}{2}\Delta x^T\hat{J}(q)M\hat{J}^T(q)\Delta x+\tfrac{1}{2}\Delta x^TK_p\Delta x+\tfrac{1}{2}z^TK_iz\\=&\tfrac{1}{2}(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^TM(\dot{q}+\alpha\hat{J}^T(q)\Delta x)\\&+\tfrac{1}{2}\Delta x^T(K_p-\alpha^2\hat{J}(q)M\hat{J}^T(q))\Delta x+\tfrac{1}{2}z^TK_iz\end{aligned} \tag{10}$$

Since matrix $\hat{J}(q)M\hat{J}^T(q)$ is positive semi-definite, if α is chosen small such that the following matrix is positive definite

$$K_p-\alpha^2\hat{J}(q)M\hat{J}^T(q)>0, \tag{11}$$

then

$$V>\frac{1}{2}(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^TM(\dot{q}+\alpha\hat{J}^T(q)\Delta x)+\frac{1}{2}z^TK_iz>0 \tag{12}$$

which is positive definite in $\dot{q}+\alpha\hat{J}^T(q)\Delta x$ and z.

Differentiate V with respect to time, it has

$$\begin{aligned}\dot{V}=&(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^TM\ddot{q}+\alpha\dot{q}^TM\dot{\hat{J}}^T(q)\Delta x+\Delta x^TK_pJ(q)\dot{q}\\&+\alpha\dot{q}^TM\hat{J}^T(q)J(q)\dot{q}+(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^TK_iz\end{aligned} \tag{13}$$

Substituting the closed-loop system dynamics (8) into (13), it has

$$\begin{aligned}\dot{V}=&(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^T[-\hat{J}^T(q)K_p\Delta x-(C+K_d)\dot{q}-K_iz]\\&+\alpha\dot{q}^TM\dot{\hat{J}}^T(q)\Delta x+\alpha\dot{q}^TM\hat{J}^T(q)J(q)\dot{q}+\Delta x^TK_pJ(q)\dot{q}\\&+(\dot{q}+\alpha\hat{J}^T(q)\Delta x)^TK_iz\\=&-\dot{q}^T\hat{J}^T(q)K_p\Delta x-\dot{q}^T(C+K_d)\dot{q}-\alpha k_p\Delta x^T\hat{J}(q)\hat{J}^T(q)\Delta x\\&-\alpha\Delta x^T\hat{J}(q)(C+K_d)\dot{q}+\alpha\dot{q}^TM\dot{\hat{J}}^T(q)\Delta x\\&+\alpha\dot{q}^TM\hat{J}^T(q)J(q)\dot{q}+\Delta x^TK_pJ(q)\dot{q}\\=&-k_p\dot{q}^T(\hat{J}(q)-J(q))^T\Delta x-\alpha\Delta x^T\hat{J}(q)(C+K_d)\dot{q}\\&+\alpha\dot{q}^TM\dot{\hat{J}}^T(q)\Delta x-\dot{q}^T(C+K_d)\dot{q}+\alpha\dot{q}^TM\hat{J}^T(q)J(q)\dot{q}\\&-\alpha k_p\Delta x^T\hat{J}(q)\hat{J}^T(q)\Delta x\end{aligned} \tag{14}$$

By using the Jacobian estimation bound (5), it has

$$\begin{aligned}\dot{V}\leq&-\{\lambda_{min}[C+K_d]-\alpha\|M\hat{J}^T(q)J(q)\|\}\|\dot{q}\|^2\\&-\alpha k_p\lambda_{min}[\hat{J}(q)\hat{J}^T(q)]\|\Delta x\|^2+\{k_p\beta\\&+\alpha[\|\hat{J}(q)(C+K_d)\|+\|M\dot{\hat{J}}^T(q)\|]\}\|\dot{q}\|\|\Delta x\|\end{aligned} \tag{15}$$

where $\lambda_{min}[\cdot]$ denotes the minimum eigenvalue of a matrix.

Since

$$\|\dot{q}\|\|\Delta x\|\leq\frac{1}{2}(\|\dot{q}\|^2+\|\Delta x\|^2) \tag{16}$$

Inequality (15) can be further written as

$$\begin{aligned}\dot{V}\leq&-\tfrac{1}{2}\{2\lambda_{min}[C+K_d]-k_p\beta-\alpha[2\|M\hat{J}^T(q)J(q)\|\\&+\|\hat{J}(q)(C+K_d)\|+\|M\dot{\hat{J}}^T(q)\|]\}\|\dot{q}\|^2\\&-\tfrac{1}{2}\{k_p[2\alpha\lambda_{min}[\hat{J}(q)\hat{J}^T(q)]-\beta]\\&-\alpha[\|\hat{J}(q)(C+K_d)\|+\|M\dot{\hat{J}}^T(q)\|]\}\|\Delta x\|^2\end{aligned} \tag{17}$$

So if α is chosen small enough, k_p and k_d are chosen large enough, the following conditions can be satisfied for a certain range of kinematics estimation error β:

$$2\lambda_{min}[C+K_d] - k_p\beta - \alpha[2\|M\hat{J}^T(q)J(q)\| + \|\hat{J}(q)(C+K_d)\| + \|M\dot{\hat{J}}^T(q)\|] \geq 0 \quad (18)$$

$$k_p[2\lambda_{min}[\hat{J}(q)\hat{J}^T(q)] - \frac{\beta}{\alpha}] - [\|\hat{J}(q)(C+K_d)\| + \|M\dot{\hat{J}}^T(q)\|] \geq 0 \quad (19)$$

such that $\dot{V} \leq 0$. Considering that V is positive definite, according to Invariant Set Theorem [21], it can be concluded from (17) that $\dot{q} \to 0$ and $\Delta x \to 0$ asymptotically.

Remark 1: From conditions (18) and (19), it can be seen that the proposed method can handle kinematics error but with certain range. When the kinematics estimation error is too big, meaning β is big, the two conditions may no longer be satisfied and the system performance is not guaranteed, which is logical that automatic controller cannot handle infinite large modeling errors without online updation or adaptation that lead to more complicated control design. On the other hand, it should be noted that the Lyapunov analysis is very conservative and so are the conditions deduced meaning that in many cases even if conditions (18) and (19) are not satisfied the control task could be still achieved.

Remark 2: Although the proposed actuator current control input also possesses a PID form, it is totally different from the PID control of the actuator which is used to generate the calculated joint position as in inverse kinematics based methods. The difference lies in that the proposed PID actuator controller takes no desired actuator joint position through inverse kinematics as reference but the direct operational space positioning error as feedback signal, and this makes the difference between joint-space controller and task-space controller.

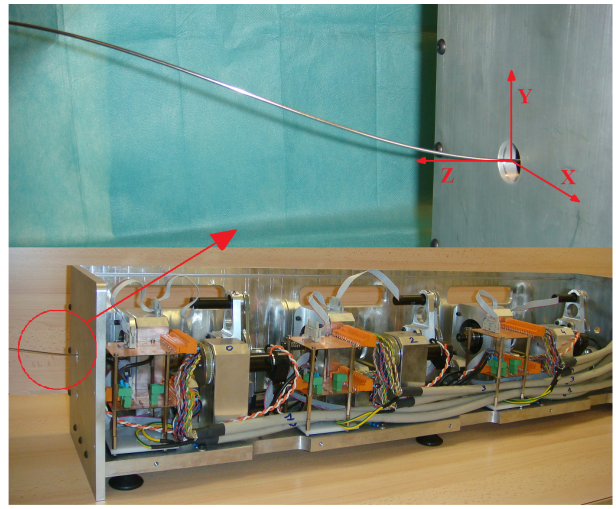


Fig. 2: CTR Prototype: (top) Zoomed in picture of the concentric tubes (bottom) Whole system with actuators

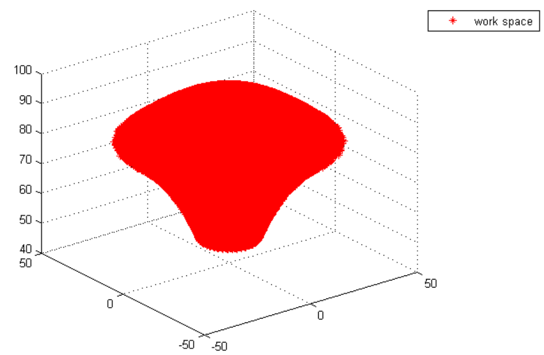


Fig. 3: workspace

V. Simulation Studies

Simulation studies have been carried out based on the mechanical design of our recently developed prototype of concentric-tube robot as shown in Fig. 2. The prototype is composed of three pre-curved Nitinol tubes with each driven by two motors for 2 DOFs (rotation and translation). As the prototype is not yet fully functional, simulation study is carried out instead to evaluate the performance of the proposed control method in this paper. In this simulation study, we investigate the position control task with the first two tubes. The workspace of the two-tube CTR is shown in Fig.3. As accurate model for the CTR kinematics is not available in practice so far, in the simulation we use the Transmissional Torsion Model (TTM) as the true kinematics model for forward kinematics calculation. In order to simulate the case of inaccurate modeling, the simpler and less accurate Torsion-Free Model (TFM) is assumed to be the model that is known to the designer and used to carry out the inverse kinematics based control. And also, based on TFM the Jacobian matrix is calculated which represents the inaccurate Jacobian used in the proposed actuator current input design. Here the more accurate but more complicated Special Cosserat Rod Equilibrium Model (SCREM) is not used as the true kinematics model since the purpose of this simulation study is to investigate the capability of the proposed control method in handling kinematics inaccuracy, in this sense the choice of true model doesn't make real difference as both are simplified approximations of the reality.

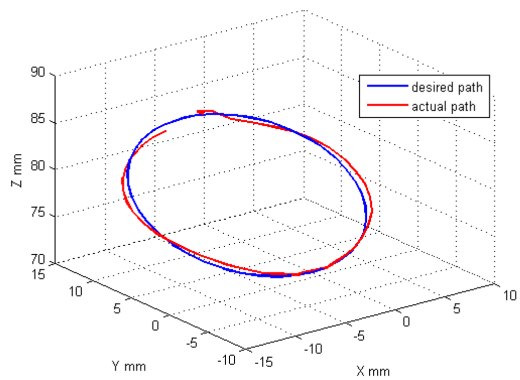
For the position control task, we define 40 points in cannula base frame (as seen in Fig. 2) along a circular trajectory of 10 mm radius which is within the workspace and defined by:

$$x_d = 10cos\phi, y_d = 5\sqrt{3}sin\phi - 40, z_d = 5sin\phi + 40\sqrt{3}. \quad (20)$$

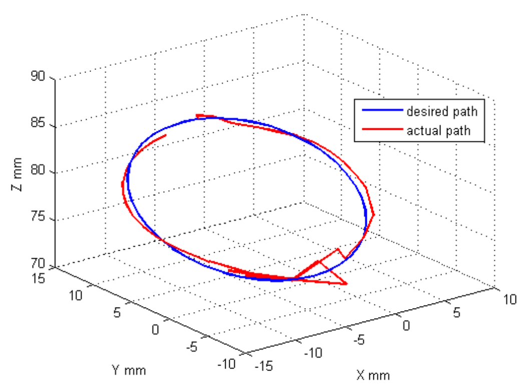
A position sensor is assumed to be available to provide online update of task-space positioning errors.

Two simulation studies are provided here to compare the performances of the traditional inverse kinematics based control method and our proposed one in face of different kinematics uncertainties. For inverse kinematics based control method, the desired joint variables for the first specified point on the defined trajectory as by (20) are calculated through inverse kinematics based on the less accurate model

TFM, and the corresponding actual task-space positions are calculated through the TTM forward kinematics which is considered as the true model, and then task-space positioning errors are fedback to update the joint variables through TFM inverse kinematics in order to reach next specified point. One situation with smaller kinematics modeling inaccuracy and one with bigger kinematics inaccuracy are considered. The performances of this control method are illustrated in Fig. 4 for these two cases with different kinematic uncertainties.



(a) Smaller Modeling Inaccuracy



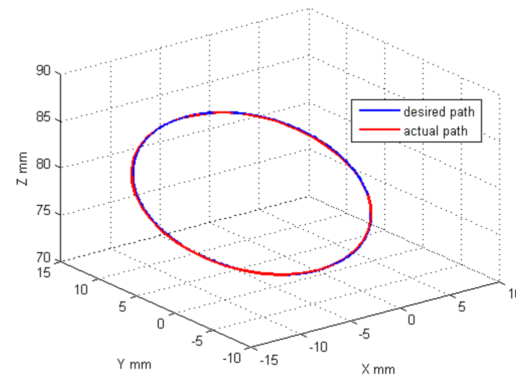
(b) Bigger Modeling Inaccuracy

Fig. 4: Inverse Kinematics Based Control

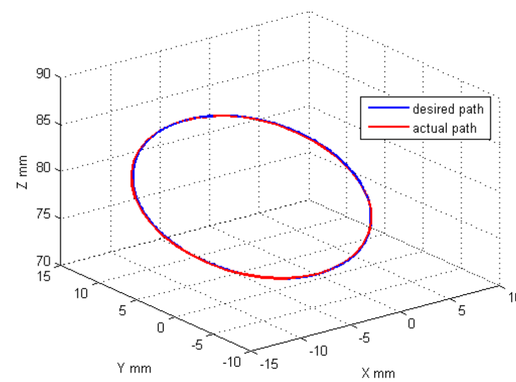
By using the control algorithm proposed as (6), the control performances of the task-space approximate Jacobian position control method with the same kinematic uncertainty settings as for inverse kinematics based control method are illustrated in Fig. 5. The actuator dynamics parameters used are the same as calibrated from the real prototype.

To have a quantitative evaluation of the control performances, the means of L_1 norm of the position errors for two simulation studies are provided in Table I for the inverse kinematics based method (IK) and proposed task-space control method (TC).

From Fig. 4, Fig. 5 and Table I, it can be concluded that with the presence of kinematics modeling error the task-space approximate Jacobian control method provides



(a) Smaller Modeling Inaccuracy



(b) Bigger Modeling Inaccuracy

Fig. 5: Task-Space Control with Approximate Jacobian

TABLE I: Comparison of Position Errors (mm)

	X	Y	Z
IK1	3.5705	3.3006	3.3568
TC1	0.7066	0.4367	0.4383
IK2	7.3717	6.6883	3.5222
TC2	0.7127	0.4572	0.4445

better positioning performance over inverse kinematics based control method.

Fig. 6 shows the CTR shape evolution (only 6 shapes chosen) along the circular trajectory for one simulation study of the proposed control method. The shapes are numbered following the time sequence.

Discussions: (1) Although in this simulation study the inverse kinematics based control performance using TFM model is shown for comparison, it doesn't mean that we are comparing the proposed method to this specific model. In fact, through the simulation study we want to show the fact that with the existence of kinematics modeling error, which is the case for all existing kinematics models, the proposed method can provide automatic compensation at the actuation level to achieve the control task. As mentioned

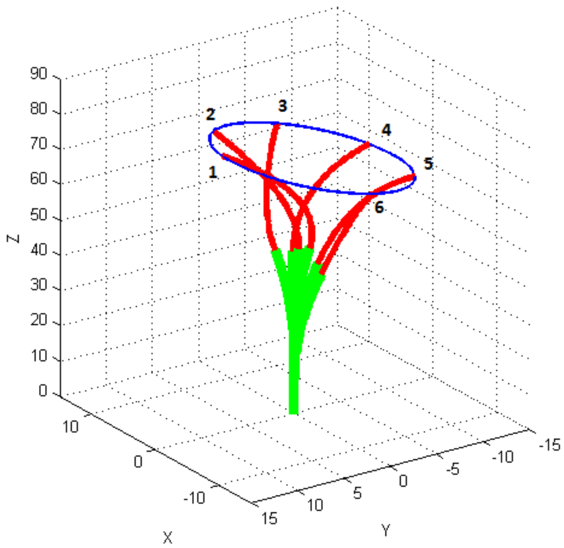


Fig. 6: CTR Shape During Control

in the introduction, although with manual compensation of the surgeon existing models may be enough for current teleoperated control task, it is still desirable if this manual compensation work could be left to the lower level motion controller such that the surgeon can operate in more intuitive way. To achieve that, the control design should provide the robotic instrument capabilities to tolerate uncertainties and disturbances within certain extent.

(2) The proposed control method relies on Jacobian matrix of the concentric-tube robot. It is noticed that for most existing kinematics models the Jacobian matrix, i.e. the mapping from the operational space velocity to joint velocity, can be obtained. For very complicated models (existing or to come), an optimized approximation could be used for the Jacobian matrix. In any case, as shown in this work, the proposed control method may work with only an approximated Jacobian without need of exact kinematic information.

VI. Conclusions

Existing motion control methods for concentric-tube robot are mainly based on inverse kinematics calculation which is prone to inaccuracy in kinematics modeling. Through this work, we show that this problem can be tackled by using the approximate Jacobian matrix and direct measurement of operational space error in the actuator control input design. The positioning errors are guaranteed to converge asymptotically through rigorous Lyapunov analysis given the control parameters are properly chosen to satisfy certain conditions. This result presents a new task-space control method that has not been explored for concentric-tube robot motion control. It is verified through simulation study that the control performance of the proposed method with the presence of kinematics inaccuracy is better than inverse kinematics based method. Experimental evaluation is currently in progress.

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