Experimental Validation of Concentric Tube Robot Control for Surgical Application with Uncertain Kinematics

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Abstract: The concentric-tube robot (CTR) is a medical robotics technology developed in the last decade as a subset of continuum robots. Compared to existing minimally invasive surgery (MIS) instruments, CTR presents better tradeoff between steerability and controllability on the tip. The majority of its existing control methods are based on inverse kinematics. However, the kinematics modeling of the CTR is very complicated in general and thus leads to the difficulty of precise inverse kinematics calculation. We proposed a task space control method for CTR without using the inverse kinematics but approximate Jacobian matrix. Preliminary simulation study showed remarkable improvement in control accuracy of the proposed method over inverse kinematics based methods. An experimental platform has been built to simulate a surgical task and to verify the effectiveness of proposed control method in real practice.

Keywords: Medical Robot, Uncertain Kinematics, Motion Control, Surgical Application

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1. 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 patients, 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. The concentric-tube robot (CTR) is a new technology developed as a subset of continuum robots (Sears and Dupont (2006)). 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 micro-robot, steerable catheters, etc) (Dupont et. al. (2010)). Compared to the aforementioned instruments, concentric-tube robot presents better trade-off between steerability and controllability on the tip. CTR is miniature robot with small diameter and high dexterity which is composed of nested pre-curved Nitinol tubes actuated independently and hence the robot shape can be adapted to avoid anatomical obstacles and follow complex 3D paths. With cross sections comparable with 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 (Bedell et. al. (2011)).

Recent research works have shown the potential of using CTRs in different medical applications such as neurosurgery (endoscopic choroid ablation), intracardiac surgery, endonasal skull base surgery and lung biopsy surgery. To realize real time control of the CTR, mechanics-based models with different assumptions have been developed to model the kinematics of CTR (Burgner et. al. (2013)). 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.

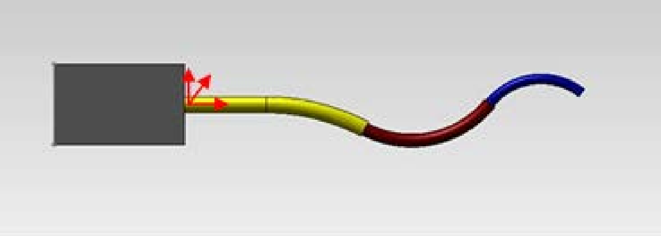


Fig. 1 Concentric tube robot

It is noticed that existing works in literature on CTR position control are based on inverse kinematics calculation to compute the necessary actuator joint angles in order to achieve control tasks that are usually defined in operational space (image space, Cartesian space, etc). Consequently, the control performances are sensitive to the kinematics modelling inaccuracy. 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 misinterpreted by the inaccurate kinematics used in the inverse kinematics calculation. To alleviate this problem, we have proposed a method with approximate Jacobian matrix and construct control input at the actuator level based on task space feedback position errors (Boushaki et. al. (2014)). Simulation studies justified the advantage of proposed task-space control method over inverse kinematics based design method in handling kinematics modelling inaccuracy. In this work, the effectiveness of the proposed control method is to be experimentally validated in a lab set-up surgical environment based on our CTR prototype platform.

2. *TASK-SPACE CONTROL METHOD WITH UNCERTAIN KINEMATICS*

In the proposed control method (Boushaki et. al. (2014)), the kinematics modelling error is compensated at 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 (Liu and Cheah (2005)).

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

$$M\ddot{\theta} + C\dot{\theta} = Ku - \frac{\tau_e}{r} \qquad (1)$$

where θ denotes the motor rotor shaft angle, M denotes the rotor inertia moment, C denotes the friction coefficient and K the torque constant. u is the control current input, τ_e is the external load torque. $r = \theta/q$ 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_e could be neglected.

The actuator control current input is proposed in the following form:

$$u = -\hat{J}^T(q)K_p\Delta x - K_d\dot{\theta} - K_i\int_0^t(\dot{\theta} + \alpha\hat{J}^T(q)\Delta x)dt\,, \qquad (2)$$

where $J(q)$ is the true Jacobian matrix relating operational space velocity $\dot{x}$ to the CTR joint velocity $\dot{q}$ ($\dot{q} = r^{-1}\dot{\theta}$) as

$$\dot{x} = J(q)\dot{q}. \qquad (3)$$

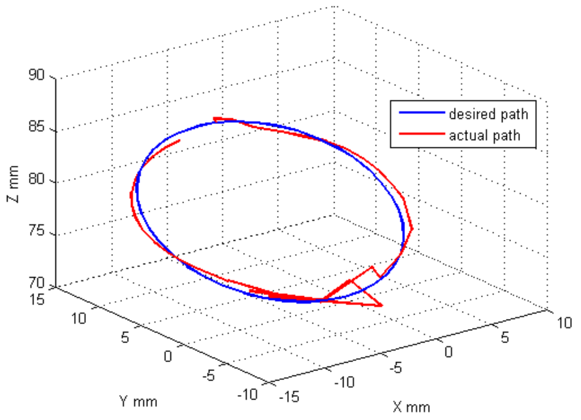
With the presence of kinematics errors, accurate Jacobian matrix is unknown and only estimated (best-guess) Jacobian $\hat{J}(q)$ is available and it is reasonable to assume that the Jacobian estimation error $\left\|\hat{J}(q) - J(q)\right\|$ is bounded as:

$$\left\|\hat{J}(q) - J(q)\right\| \le \beta\,. \qquad (4)$$

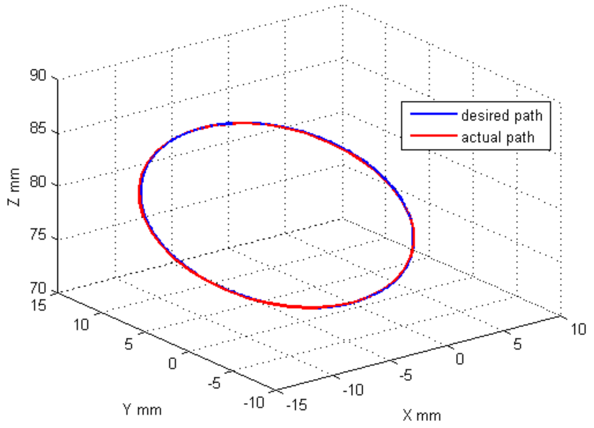
It has been proved through rigorous Lyapunov analysis that the task-space regulation error converges asymptotically even with the approximate Jacobian matrix (uncertain kinematics).

3. *SIMULATION STUDY*

In (Boushaki et. al. (2014)), simulation studies have been carried out to investigate the control performance of traditional inverse kinematics based control method and the proposed task-space control method with inaccurate kinematics information, where Torsion-Free kinematics model has been used (Sears and Dupont (2006)). It is seen that with the presence of kinematics modelling error the task-space approximate Jacobian control method provides better positioning performance over inverse kinematics based control method as shown in Fig. 2.



(a) Inverse kinematics based control method



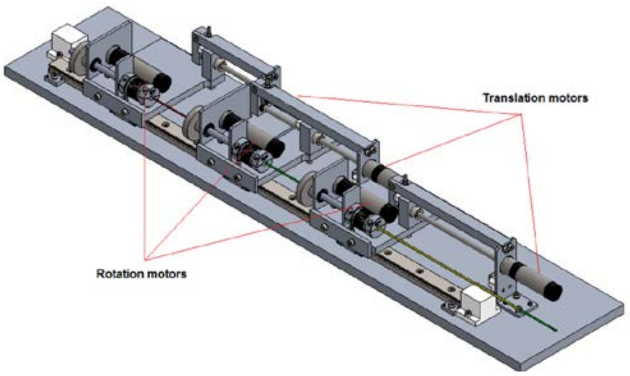
(b) Proposed task-space control method

Fig. 2 Control performance comparison

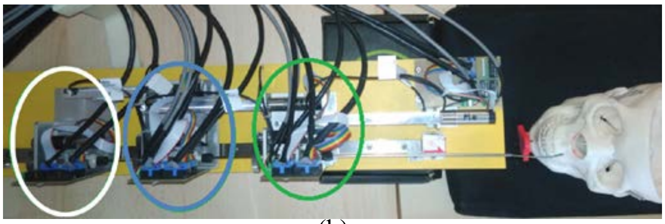
4. *EXPERIMENT SET-UP*

4.1 CTR Prototype

We have developed a three-tube CTR prototype in collaboration with University Catholic of Louvain (Belgium) that is compact enough to fit in the real operating room (OR) as shown in Fig. 3.



(a)



(b)

Fig. 3 Three-tube CTR prototype

The CTR prototype is composed of three blocks with one for each tube. Note that for the proposed actuation unit and for each tube, the rotation and translation are decoupled. Thanks to this decoupling, each rotation is controlled by one dedicated motor, which improves the control performance, facilitates the calibration procedure and reduces the modelling complexity.

4.2 Targeted Surgical Application

The targeted surgical application of the method under validation is removal of deep frontal lobe brain tumor (Fig. 4). Usually for anterior skull base surgery, the procedure is transcranial, the access is created by severing a portion of the cranium. Following this procedure, the brain will swell up after the operation, which creates a brain pressure and causes a large trauma for the patient. An endonasal approach could alleviate this problem by resorting to CTR which is flexible and adaptable with the anatomical complexity.

Fig. 4 Transcranial intervention for frontal lobe tumor

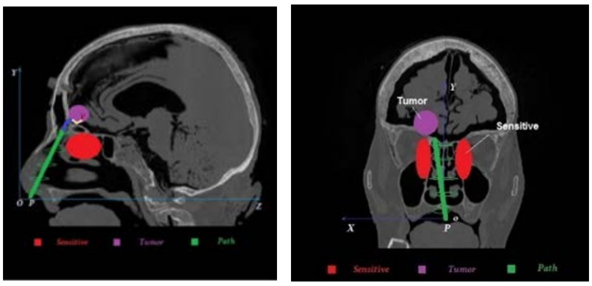


Fig. 5 Workspace characterization

Based on CT scan images and with more clarification and orientation of the surgeon, the space of the passage used to introduce the CTR from the nostril to the frontal sinus is identified roughly as a straight tunnel with variable diameter (from ≈ 10mm for smaller ellipse diameter to ≈ 30mm for bigger ellipse diameter) and a length of ≈ 72mm for the patient sample studied. These allowed workspace borders are illustrated by six green ellipses in Fig 5. These anatomical constraints (orbits, nerves...) should be considered in the tube design.

4.3 Tube Design

The objective of tube design is to maximize the range of motion that can be covered by the CTR tip and at the same time to avoid the elastic instability (bifurcation) problem which happens when the joint angle difference approaches value π. To this end, Pareto method has been used to select the optimal values of the tube parameters based on the surgical task workspace characterization as indicated in Fig. 6 (Boushaki et. al. (2016)).

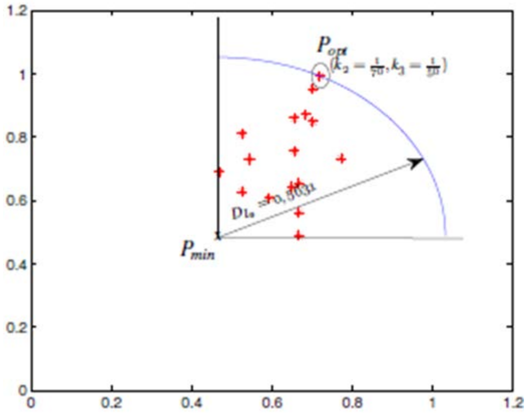
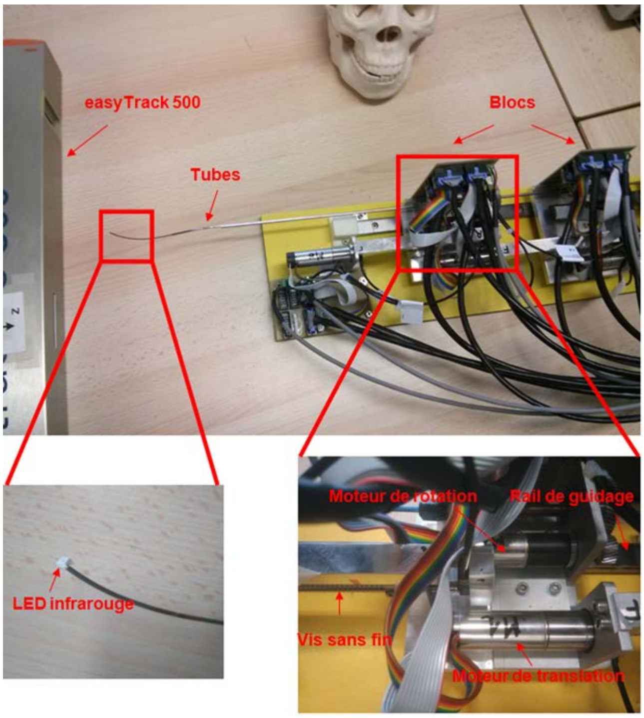


Fig. 6 Tube curvature selection

4.4 Experiment Platform



(a) Optic sensor and tracking system

(b) Actuator control system (EPOS3)

Fig. 7 Overall experiment system

The overall experimental system is constructed as shown in Fig. 7. In this set-up, the CTR tip motion is captured by easyTrack500 system (Atracsys, Switzerland) using LED as active marker. The robot is driven by 6 maxon motors through EPOS3 controllers (Maxon Motor AG, Switzerland) for the translation and rotation motions of the 3 tubes.

4.5 Experiment Objectives

Through the experimental study, the main objective is to implement the proposed task-space controller on our developed CTR prototype and evaluate its control performance to regulate the robot tip motion. Regulation and tracking errors are to be compared with traditional inverse kinematics based control method. The second objective is to examine the workspace covered by the selected tubes as in Section 4.3 in an artificial skull environment and thus to evaluate the feasibility of using CTR as intervention tool for the targeted surgical application of deep frontal lobe brain tumor removal.

5. CONCLUSIONS

This work is to integrate a complete experimental platform for concentric tube robot (CTR) in order to validate the effectiveness of a novel control method proposed to solve the inaccurate CTR kinematics problem. Based on an optimized tube design, the motion range of developed CTR system is to be evaluated and check its feasibility to be used as an alternative method for the surgical application of deep frontal lobe brain tumor removal. If the experimental results support both targeted objectives, convinced evidences could be generated to support the task-space CTR control design without inverse kinematics calculation and the new robotic surgical technique of using CTR for deep brain intervention. Thus further efforts would be encouraged to be made towards these new directions. Future works would include tests on animals in collaboration with the University Hospital of Montpellier (CHU, Montpellier).

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