Adaptive Decoupling Control of a Serial Redundant Robot for Teleoperated Minimally Invasive Surgery

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***Abstract*— In this paper, we present an adaptive decoupling control scheme using a serial redundant robot for teleoperated Minimally Invasive Surgery (MIS). In presence of uncertain interaction between the surgical tip and the patient body during teleoperated surgery, the accuracy of the end-effector position should be secured, while guaranteeing a Remote Center of Motion (RCM) constraint. Adaptive fuzzy approximation is adopted to estimate the dynamical uncertainties in physical interaction between the surgical tip and the abdominal wall to enhance the accuracy and keep the RCM constraint. The effectiveness of the proposed control approach was verified in a lab setup environment by using the LWR 4+ (KUKA) slave robot and Sigma7 (Force Dimension) master device.**

I. INTRODUCTION

To serve as the surgical arms for laparoscopic surgery, the end-effector of the manipulator must go through small incisions on the patient's abdominal wall, which is commonly known as the Remote Center of Motion (RCM) constraint. Various studies have been conducted with serial robots for MIS tasks for RCM constraint [1][2]. Sandoval et al. proposed an improved dynamic control approach for redundant robots with Cartesian Admittance Control (CAC) in the task-space and RCM constraint [3]. However, the control scheme is only validated with simulation and is not competent for practical application. Furthermore, in presence of uncertain disturbances during human-robot interaction, the accuracy of the surgical tip and the RCM constraint should be secured. Direct fuzzy adaptive controllers are known to estimate a large uncertainty or unknown variation in plant parameters and disturbance [4][5]. The unknown time-varying periodic disturbances from physical interaction can be compensated online. In this paper, we proposed an adaptive decoupling control scheme to enhance the accuracy and keep the RCM constraint for the teleoperated laparoscopic surgery.

II. METHODOLOGY

A. Modelling of the serial robot

The dynamic model of n-DoF serial manipulator in the Lagrangian formulation can be expressed as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \tau_{\mathbf{C}} - \tau_{\mathbf{e}} \tag{1}$$

where $\mathbf{q} \in R^n$ is the joint values vector, $\mathbf{M}(\mathbf{q}) \in R^{n\times n}$ is the inertia matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \in R^{n\times n}$ is a matrix representing the Coriolis and Centrifugal effects, and $\mathbf{g}(\mathbf{q}) \in R^n$ is the vector of gravity torques. The torque vectors $\tau_{\mathbf{C}} \in R^n$ and $\tau_{\mathbf{e}} \in R^n$ represent the control torques and the external torque vectors, respectively.

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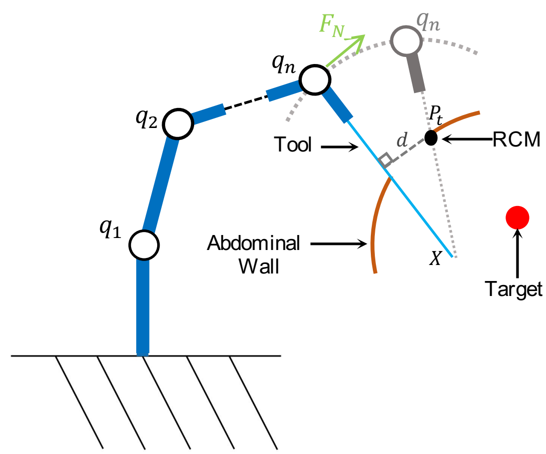

Fig. 1. Minimally Invasive Surgery scenario: d is the distance between the RCM point ($\mathbf{P_t}$) and the tool (the small incision is zoomed for a better understanding). The tool tip position $\mathbf{X}$ is controlled by teleoperation to reach the target in the patient's abdomen.

B. Adaptive decoupling control scheme

To drive the tool tip, the torque controller is defined as:

$$\tau_{\mathbf{C}} = \tau_{\mathbf{d}} + \hat{\mathbf{C}}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \hat{\mathbf{g}}(\mathbf{q}) + \hat{\tau}_{\mathbf{e}} \tag{2}$$

where $\tau_{\mathbf{C}} \in R^n$, $\hat{\mathbf{C}}(\mathbf{q}, \dot{\mathbf{q}}) \in R^{n\times n}$ and $\hat{\mathbf{g}}(\mathbf{q}) \in R^n$ are the estimated compensation terms, $\hat{\tau}_{\mathbf{e}}$ is the filtered torque computed from external torque sensors, and $\tau_{\mathbf{d}} \in R^n$ is the term introduced to conduct the desired surgical task.

1) Main task control: The end-effector position $\mathbf{X} \in R^3$ is utilized to reach the desired position. The task control torque $\tau_{\mathbf{T}}$ can be defined as

$$\tau_{\mathbf{T}} = \mathbf{J}^{\mathbf{T}}(\mathbf{K_X}\tilde{\mathbf{X}} - \mathbf{D_X}\dot{\mathbf{X}}) \tag{3}$$

where $\mathbf{J}(\mathbf{q}) \in R^{3\times n}$ is the Jacobean matrix from the base to the end-effector, $\tilde{\mathbf{X}} = \mathbf{X_d} - \mathbf{X}(\mathbf{q}) \in R^{3\times n}$, $\mathbf{K_X} \in R^{3\times 3}$ is the diagonal stiffness matrix, $\mathbf{D_X} \in R^{3\times 3}$ is the diagonal damping matrix, and $\dot{\mathbf{X}} \in R^3$ is the actual Cartesian velocity.

2) Null-space control: The null-space controller $\tau_{\mathbf{N}} \in R^n$ can be utilized to achieve the RCM constraint:

$$\tau_{\mathbf{N}} = (\mathbf{I} - \mathbf{J}^{\mathbf{T}}(\mathbf{q})\mathbf{J}(\mathbf{q})^{+}_{\mathbf{M}})\mathbf{J_2}(\mathbf{q})^{\mathbf{T}}\mathbf{F_N} \tag{4}$$

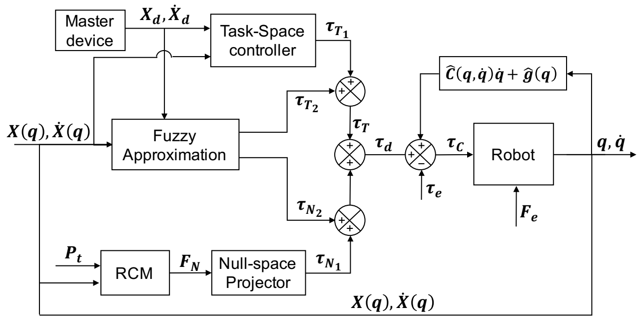

Fig. 2. Block diagram representing the proposed control architecture: The "Task-space control" block is used to achieve the desired pose of the end effector, the "RCM Constraint" calculates the virtual force applied on the null space, the "Null-space Projector" maps the virtual force to joints torque, the "Fuzzy Compensation" compensates the unknown disturbance in both task space and null-space, the "Robot " is robot arm dynamic model with uncertain physical interaction.

where $\mathbf{J_2(q)} \in R^{3\times n}$ is the Jacobean matrix from base to the last joint, $\mathbf{J(q)_M^+}$ is the inertia-weighted pseudo-inverse matrix [6], $\mathbf{F_N} \in R^3$ in Fig. 1 is the force applied on the last joint to keep the RCM constraint:

$$\mathbf{F_N} = (k_s d - k_d \dot{d})\overrightarrow{F}_{\mathbf{N}} \quad (5)$$

where $d = \|(\mathbf{P_t} - \mathbf{X}) \times \mathbf{u}\| \in R$, $\mathbf{P_t} \in R^3$ is the RCM point, $\mathbf{u} \in R^3$ is the tool tip vector, $k_s, k_d \in R$ are stiffness and damping parameter, $\overrightarrow{F}_{\mathbf{N}} = \frac{\mathbf{(X-P_t)\times u \times u}}{d}$ is the direction vector of the force. In addition to the decoupled control torque, adaptive fuzzy approximation is introduced to estimate the uncertain physical interaction, enhancing the task accuracy and keeping RCM constraint. The whole control diagram can be seen in Fig. 2.

III. EXPERIMENTAL EVALUATION

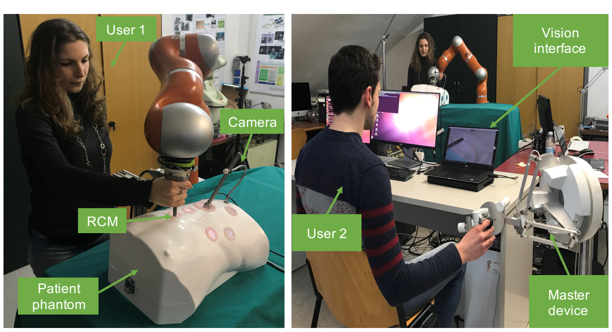

Fig. 3. Experimental setup procedures: Firstly, hands-on control is utilized to allow user 1 locate the RCM constraint by hand on the patient phantom; then user 2 use the master device to control the tool tip for surgical tasks.

As it is shown in Fig. 3, two subjects were enrolled to setup the experimental scene with the developed teleoperated MIS system implemented with Fast Research Interface (FRI) [7]. The proposed adaptive decoupling control method (ADC) was compared with the method (DCAC) [3]. The accuracy of the effector and the RCM constraint error are recorded and shown in Fig. 4.

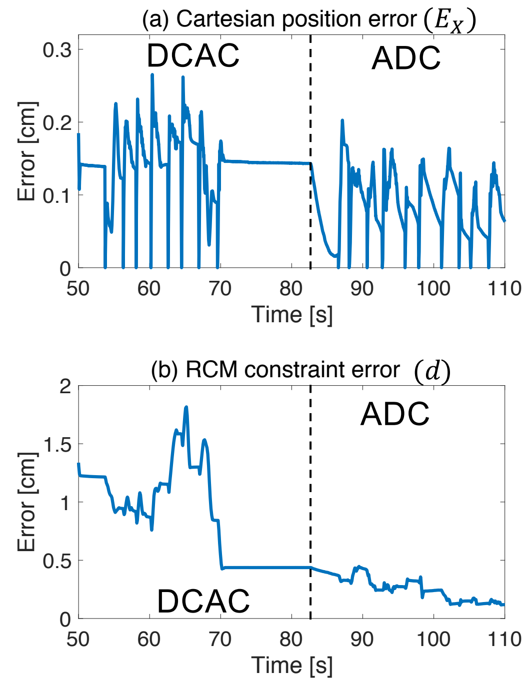

Fig. 4. Performance comparison between DCAC and ADC

IV. CONCLUSIONS

This paper proposes an adaptive decoupling control scheme using a serial robot for teleoperated laparoscopic surgery. Compared with the method proposed in [3], it shows promising accuracy improvement of the surgical tip in static error, and the error of RCM constraint also was converged into a smaller area.

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