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Generalized Framework for Control of Redundant Manipulators in Robot-Assisted Minimally Invasive Surgery

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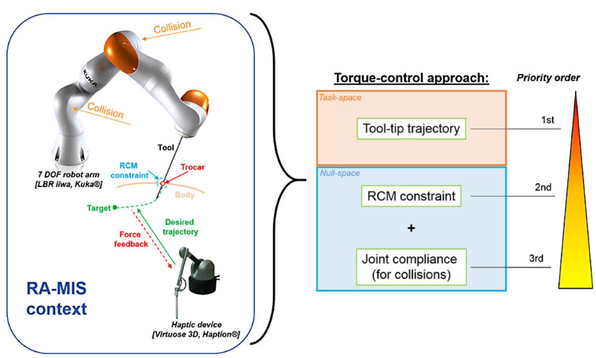
Highlights

- A generalized Framework for RA-MIS using serial redundant robots is proposed.
- A strict priority torque-controller allows to simultaneously execute the tasks.
- Performance of the surgical task is preserved during contact with the robot's body.

Graphical abstract



Abstract

Background: During a Robot-Assisted Minimally Invasive Surgery (RA-MIS), a robot inserts a surgical tool into the patient's body through a surgical device placed at the incision position, known as the trocar. A kinematic constraint, known as Remote Center of Motion (RCM) constraint, is then generated since the tool axis must always pass through the trocar position while the tool-tip executes the surgical task. When a serial manipulator is used, the RCM constraint must be guaranteed by the control system. In this paper, we provide a generalized framework for the dynamic control of redundant manipulators used for RA-MIS. Moreover, we consider the event of desired or unexpected collisions between the robot's body and its environment, e.g. medical staff or operating room equipments.

Methods: In order to guarantee the accomplishment of the surgical task in the event of collisions, we propose a joint compliance strategy, by exploiting the Jacobian null-space. The proposed control framework deals simultaneously with the surgical tool-tip trajectory, the RCM constraint and collisions in the robot's body.

Results: Simulations were conducted to validate the effectiveness of the proposed formulation, using the dynamic model of a Kuka LBR 7 iiwa R800 robot arm. Results showed that the distance between the tool axis and the trocar position never increases more than 0.5 mm, even in case of collisions.

Conclusions: The results showed the capacity of the proposed framework to simultaneously comply the three tasks: the tool-tip trajectory, the RCM constraint and joint compliance in case of collisions in the robot's body, always respecting the priority order between the tasks.

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1. Introduction

In Robot-Assisted Minimally Invasive Surgery (RA-MIS), a surgeon tele-operates one or more robots inserting surgical tools into the patient's body through surgical devices, i.e. trocar, placed on each small incision cut. Besides the benefits given by the MIS compared to classical open surgery [1], e.g. reduction in recovery time, low risk of infection or minimization of scars, the robot-assisted system increases the workspace of the surgeon, usually considerably constrained in classical MIS and enables to cancel his trembling and to enhance accuracy, among other advantages.

During a RA-MIS, such as in gynecology, urology or general surgery, the robot tool-tip performs a task inside the patient's body. Simultaneously, the tool movements are constrained by the trocar where the contact forces must be minimized, in order to avoid any injury to the patient. The kinematic constraint generated by the incision point is commonly known as the Remote Center of Motion (RCM) constraint. Several "RCM mechanisms" have been specially designed to mechanically define a RCM point and then to calibrate it with the trocar [2,3]. Some commercialized systems for RA-MIS, such as the *Da Vinci surgical system*, includes a fixed RCM point for each robotic arm [4]. Before starting the surgical procedure, the RCM point is synchronized with the trocar position, in such a way that the surgical tool always goes through the trocar. Then, the surgical robot can safely perform an autonomous or tele-operated task into the patient's body. However, no specific strategy is planned to prevent a degradation of the surgical task or a physical interference on the robotic system when collisions between the robotic arms and the environment occur.

Instead of considering a robot with a mechanically fixed RCM point, a serial manipulator can also be used for RA-MIS, where the RCM constraint must be guaranteed by a software control approach, e.g. *MIRO robot* from *DLR* [5]. The use of serial manipulators gives versatility to the system, since the robot is not restricted to be used in applications with a fixed incision point. Moreover, when the robot is kinematically redundant, other secondary tasks can eventually be performed. Different control approaches have been proposed to effectively combine the surgical task and the RCM constraint using serial redundant manipulators. For instance, *Aghakhani* [6] provided a general kinematic characterization of the RCM constraint for MIS. *Hyo-Jeong* [7] proposed to minimize the constraint force at the RCM by considering the manipulator as a closed chain; however, a non-redundancy property of the manipulator is required. *Michelin* [8] proposed the application of the conventional operational space formulation, developed by *Khatib* [9,10], by choosing the objective function such as the square of the minimal distance between the insertion position and the surgical tool axis. Additionally, in this las work, a trajectory-following control is applied to the end-effector's motion. In a previous study, we improved the null-motion performance of the control system proposed in [8], by implementing an extended-based formulation with null-motion feedback [11]. However, the control approaches proposed in [8] and [11] are performed at the acceleration level and, consequently, are highly dependent of an accurate information or estimation of the robot inertia matrix.

The null-space of the robot's Jacobian can be exploited to perform other secondary tasks, improving the performances of the surgical procedure. Redundancy can be conveniently used to execute obstacles avoidance strategies [12], to optimize manipulability [13], to minimize gravity torques [14] or apparent mass and frictions [15]. If we consider that the robot shares a common workspace with the medical staff and the operating room equipments, collisions with the robot's body may occur during the surgical procedure, degrading the performances of the surgical task. In this context, a contact might happen due to multiple reasons: accidental collisions between the robot and the environment, e.g. staff or medical equipments, desired contacts by the medical staff to modify the robot joint configuration, and so on. Therefore, an interesting way to exploit the redundancy of the robot is to implement a compliant motion strategy in the robot's body, in order to preserve the surgical task performances in the event of collisions. Numerous compliance strategies applied in the null-space of the robot can be found in the literature. For instance, *Sadeghian* [16] proposed a null-space compliance strategy at the acceleration level using observers to estimate the external torques. A multi-priority impedance controller without using external forces sensor at the end-effector was proposed in [17], where the first level of priority is given to the Cartesian impedance control, whereas the joint impedance control is performed in a secondary level. Nevertheless, the control approaches proposed in [16] and [17] are highly dependent on the accuracy of the estimated inertia matrix. A simplified compliance control approach is proposed in [18], using the potential function of a virtual spring and adding an appropriate damping term, to avoid to shape a desired inertia matrix and without using the estimated/measured external forces.

In this paper, a generalized torque-control framework for RA-MIS is proposed using kinematically redundant manipulators. The proposed framework allows to simultaneously integrate the surgical task performed by the tool-tip while guaranteeing the RCM constraint as well as dealing with collisions with the robot's body. A strict hierarchy redundancy resolution method is applied [19] in order to define the priority order of these different tasks. In this strict hierarchy approach, a higher priority task is never disturbed by a lower priority task. In the proposed control framework, we define the surgical task performed by the tool-tip in the first level of priority, by implementing a Cartesian compliance control approach. A kinematic formulation of the RCM constraint, that we previously proposed in [20], is exploited in the second level of priority, in order to constraint the tool movements by the trocar position.

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