Multi-task control strategy exploiting redundancy in RMIS

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INTRODUCTION

Intrauterine fetal surgery allows a minimally invasive surgery (FMIS) approach to the treatment of congenital defects. This surgical technique allows the correction of the Twin-to-Twin Transfusion Syndrome (TTTS) [1]. TTTS is a severe complication in monochorionic twins' pregnancies that occurs when there is communication (anastomoses) between the fetuses' blood systems, which leads to cardiovascular disturbances and results in their death in 90% of cases. A minimally invasive approach is less harmful and allows the preservation of the tissues of the amniotic sac. Fetoscopic Laser Photocoagulation (FLP) is a MIS intervention to ablate all the intertwin anastomoses to make independent the twins' vascular systems from each other [2].

A single master single slave teleoperation platform was developed to assist the surgeon during FLP, Fig. 1. The master is composed of a 6DoF haptic device and an interactive user interface containing fetoscopic view, interactive navigation map, etc. The slave is composed of 6DoF robot holding a fetoscope, an active trocar insertion depth control and an automated coagulation laser control system. The platform has been tested by 14 surgeons with different fetoscopic surgical experience, obtaining the face validity. Two main issues have been detected. First, the need of a redundant robot to overcome the kinematic restrictions imposed by the Remote Center of Motion (RCM) and the workspace placement, defined by the placenta position. Second, the need of active human-robot interaction during pre and post-operative phases (insertion and extraction of the fetoscope) and during surgery to enable a safe shared workspace between medical staff (e.g. auxiliary surgeon with an echographer probe) and robot.

Following the generalized framework for control of redundant manipulators in RMIS proposed in [3], this paper proposes a multi-task control strategy exploiting redundancy to improve dexterity and reachability as well as enable human-robot interaction to deal with human-robot collisions and co-manipulation while performing the surgical task. This work is based on a 7 DoF KUKA LWR 4, a redundant and collaborative robot.

MATERIALS AND METHODS

FLP surgery can be described with a Finite State Machine (FSM) with five main states: System Set-up (SS), anastomoses localization (AL), coagulation (AC), review (AR) and tool removal (TR). The developed multi-task control modulates the behavior of the system according to the specific requirements of each state. A hierarchical multi-layer control ensures the control of the tool tip pose (main task) guided by co-manipulation (SS and TR) or telemanipulation (AL, AC and AR). Three secondary tasks are active when necessary: dexterity optimization using redundancy (all states), joint compliance (all states) and obstacle avoidance (AL, AC and AR). Fig. 2 shows the multi-layer control schema for the different phases.

Two robot guidance modes are proposed: telemanipulation and co-manipulation.

Robot redundancy is obtained adding an extra joint (q3) to the kinematic chain. Redundancy allows the use of the

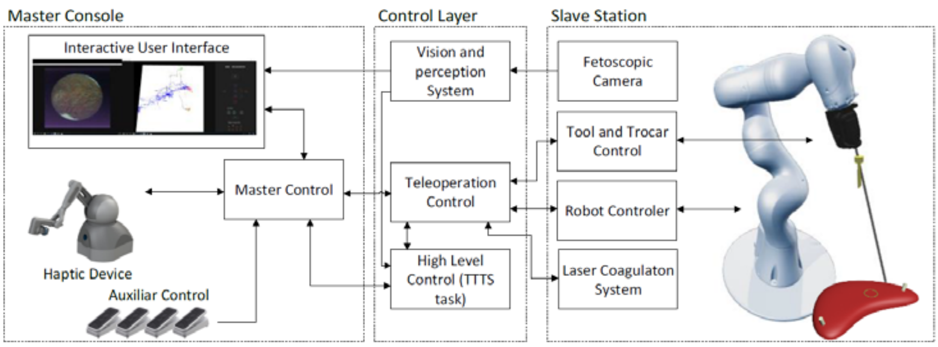

Figure 1. Schematic representation of the robot-assisted TTTS surgery-oriented teleoperation platform

Jacobian's null-space projection, where the proposed subtasks can be performed without modifying the main task (tool position). The subtasks performed in null-space have a strict priority hierarchy. From highest to lowest: joint compliance, obstacle-avoidance and dexterity optimization.

Joint compliance control allows safe human-robot interaction. This admittance-based control allows the surgeon to free occupancy space (passive behavior) and react safely to unintended collisions (active behavior) by changing the stiffness parameter. The obstacle-avoidance control defines lateral boundaries that represent the allowed lateral occupancy space of the robot. The lateral boundaries are modelled as masses attached to a spring-damper system, affected by repulsive forces. The medical staff is treated as obstacles that generate a repulsive force to the boundaries based on the distance. The joint configuration of the robot must remain inside the lateral bounds. Finally, as redundancy offers infinite configurations for a given tool pose, it can be exploited to increase the reachability workspace and maximize dexterity, within the joint limits defined by the higher priority subtasks. The proposed dexterity optimization method dynamically finds the joint configuration that gives the maximum manipulability from a set of redundant configurations around the current joint position $q3(t) \in [q3(t-1) - \Delta max, q3(t-1) + \Delta max]$, where Δmax is the maximum allowed joint movement at each control step. To maintain a coherence in the movement around the workspace, *q3* upper and lower boundaries are set proportional to the radial distance to the RCM in the XY plane. This policy forces the robot to decrease its q3 value near the centre, allowing it to escape local maxima that would compromise the robot's performance.

RESULTS

Several scenarios have been used to test the proposed control, simulating different realistic placenta positions: posterior and lateral. The workspace of the robot is constrained by the RCM, which defines a cone-shape workspace. In posterior placenta the tool is inserted (origin of the tool orientation) in vertical whereas lateral placenta forces the tool to enter with some inclination. The joint compliance control has been tested in simulation with different stiffness parameters, where the robot dynamics behave as expected upon an external force. The obstacle-avoidance control has been tested in simulation with an obstacle trajectory of approaching and retreating. The robot's lateral occupancy space is reduced when the obstacle is close. A performed reachability workspace analysis proved that in posterior placenta the reachability (points reached inside the workspace) increases a 30% using redundancy, but there is not a significant volume increase (<5%). In the lateral placenta, the reachability increases up to an 80% and the volume up to 70%. The dexterity optimization algorithm is tested for a set of randomized paths. The results show that the manipulability increases up to 600% in some regions with respect to the results of the same test with a 6 DoF robot, whereas isotropy increases up to 80%. Best results are obtained in the vicinity of a singularity where the use of q3 avoids falling into a singularity. None of the subtasks performed in the null space compromised the main task, which in all tests reached all destination points with an error less that 1 mm.

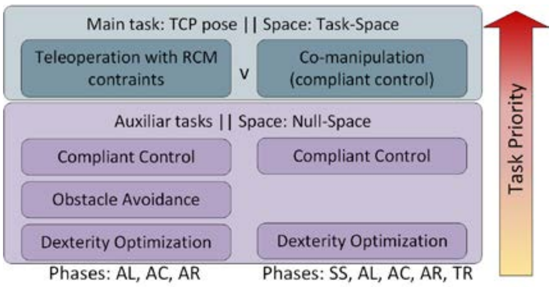

Figure 2. Multi-Layer control schema

CONCLUSION AND DISCUSSION

The inclusion of a redundant and collaborative robot in the FMIS teleoperation platform has demonstrated a noticeable improvement of the system in several aspects. The hierarchical multi-task control strategy enables an adaptive system behavior depending on the specific requirements of each phase of the surgical procedure. The main task ensures the correct fetoscope position using any of the two tool guidance modes: co-manipulation and teleoperation. The secondary tasks are applied depending on the desired robot behavior. Redundancy increases the reachable workspace, optimizes dexterity (local optimization) and singularity avoidance, ensuring the applicability of the system independently of the placenta position. Dexterity improvement eliminates singularities inside the workspace. In addition to redundancy the collaborative capabilities offer benefits in two aspects. First, enables the system to be implemented in real surgical environments, where the robot occupancy volume is shared with medical staff (e.g. the echographer). The ability to measure the forces exerted on the arm enables the possibility to change its position to free up working space while the main task (fetoscope position) is accomplished. Second, improves the set-up and tool removal phases, reducing the surgery room occupancy time. Finally, the obstacle avoidance and compliant control ensure the safety of the medical staff during surgery. The new multi-task control schema jointly with the use of Kuka LWR 4 will speedup the process to start tests with animal models.

REFERENCES

[1] Gratacos E., Deprest J., Current experience with fetoscopy and the Eurofoetus registry for fetoscopic procedures, Eur J Obstet Gynecol Reprod Biol. 2000, vol. 92 pp. 151-159.

[2] WAPM consensus group on Twin-to-twin transfusion syndrome, Baschat A., et al., Twin-to-twin transfusion syndrome (TTTS)*, Journal of Perinatal Medicine, 2011, 39(2), 107-112

[3] Sandoval J., Vieyres P., and Poisson G., Generalized Framework for Control of Redundant Manipulators in Robot-Assisted Minimally Invasive Surgery, IRBM, 2018, vol. 39(3) pp. 160–166