# Hybrid controllers for middle ear surgery: towards efficient cholesteatoma removal

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## INTRODUCTION

Modern-day robots are required to operate autonomously in unknown, unstructured and dynamic environments with sufficient accuracy and repeatability. They are also expected to share the workspace with humans or other robots in a safe and secure manner. To this extent, external sensors like force, position, vision etc. play a prominent role. For instance, force sensors provide local contact information while vision sensors such as cameras provide rich and global information of the environment. This brings up to the question, whether it is possible to effectively combine several modes of perception (e.g., force and vision) within the same control scheme to benefit from their complementary advantages? Of course, this does not concern the sequential controllers that are usually reported in the literature [**?**]. Combining several information of different nature and geometry in the same control scheme can benefit many robotic applications, including surgical robotics to which the work described in this paper belongs. This work is part of an overall effort to improve the current surgical procedure, which consists of removing a pathological tissue that develops in the middle ear cavity, called cholesteatoma [**?**], [**?**]. This will involve the development of a minimally invasive robotic solution and adapted control modes to ensure exhaustive, accurate and safe cholesteatoma resection from the middle ear cavity.

In this paper, we investigate new control modes for middle ear surgery. The main contributions lie in the formulation of new hybrid controllers by consistently combining two physical quantities in the control loop. This allows separating the linear degrees of freedom (DoF), which are controlled in tele-operation (respectively, comanipulation) while the rotational DoFs are intuitively controlled by a vision-based controller.

## MATERIALS AND METHODS

As depicted in Fig. 1, the developed robotic setup consists of a 7 DoF cobot from FRANKA EMIKA on which a 6 DoF Force-Torque (F/T) sensor (ATI MINI-40) is attached at the end-effector. Additionally, a 3D printed tool of 2mm diameter mimicking a typical surgical instrument used for surgery inside the middle ear cavity is fixed on the robot's end-effector. A AVT Guppy PRO F033b camera is mounted in an *eye-in-hand* configuration on the robot end-effector. A head phantom at scale 1:1 is positioned in order to simulate the position of a patient on

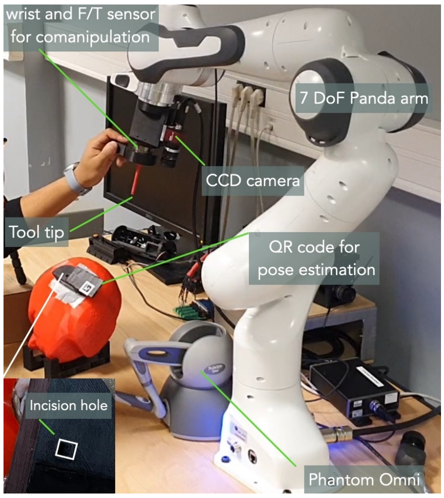


Fig. 1: Overview of the developed robotic setup.

the operating table during intervention. Finally, a tunnel (having the shape of the 3D tool) is drilled on the head representing the operator channel. The size of the drilled hole is slightly larger than that of the tool to have a tolerance of 0.5 mm during the tool insertion (Fig. 1).

Different control methods are developed and evaluated using the robotic setup. Firstly, a classical end-frame tele-operation mode using position-based controller with a Sensable Phantom Omni, as well as a comanipulation mode using the integrated F/T sensor are implemented on the robotic setup [**?**]. Secondly, to improve the peg-in-hole style insertion task of the surgical tool into the middle ear cavity and through the operating channel with respect to the ergonomics, intuitiveness, precision and safety of the procedure, particularly in minimally invasive surgery, we have developed a new generation of controllers. These controllers consist of two shared control laws, which combine proximal (local) and global measurements (Fig. 2). More specifically, local measurements provided by position or force sensors are combined with globally observed visual information, which is acquired from the camera attached to the robot end-effector in an *eye-in-hand* setting.

The first shared controller we developed in this work is called hybrid parallel (Fig. 2(a)). It consists of the parallel juxtaposition of two internal loops. The first is a vision feedback loop to automatically manage the angular motion of the robot. The second is a position-based (in

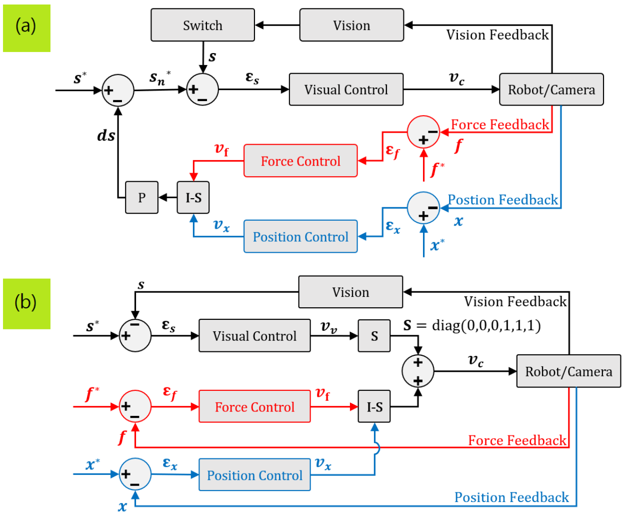


Fig. 2: Diagram of proposed shared control loops: (a) Parallel Hybrid force/vision comanipulation (in red) and position/vision teleoperation (in blue) control scheme (b) External Hybrid force/vision comanipulation (in red) and position/vision teleoperation (in blue)

case of tele-operation mode) or force-based (in case of comanipulation) loop to control the linear motion.

When both the force/position and vision-based controllers work in parallel, there is a risk that the tracked visual features (i.e., the *AprilTag*) are lost (i.e., goes out of the camera field of view (FoV)). This could jeopardize the accuracy of final positioning task. To tackle this issue, we have designed a new hybrid controller called external hybrid, as depicted in Fig. 2(b). The underlying idea is to express the control task as two hierarchical sub-tasks. The first task (priority sub-task) deals with maintaining the *AprilTag* at the center of the camera FoV, while the second one (secondary sub-task) is devoted to the regulation of the error between the current and the desired poses.

## RESULTS

The proposed controllers were validated and compared with each other by analysing the scenario where a 3D printed tool is inserted into an incision hole. Initially, the robot is placed in an arbitrary position, then the operator has to jog it in front of the incision and to insert the tool. A group of 5 participants (2 experts and 3 novices) carried out the positioning and insertion tasks using different tele-operation (classic, parallel hybrid and external hybrid) and comanipulation (classic, parallel hybrid and external hybrid) control modes. For each of the performed tasks, Cartesian errors (along each DoF) as well as the time required to achieve the tasks are recorded and analysed.

Fig. 3 summarizes the translation and rotation errors. For comanipulation modes, it can be noticed that the classical mode is slightly more accurate than the external hybrid one. The parallel hybrid is the most accurate with the mean linear error $e_t$ = 0.84 mm (2.15 mm and 2.17 mm for the classical and external hybrid methods, respectively). The mean angular error clearly shows that the parallel hybrid comanipulation gives the best result

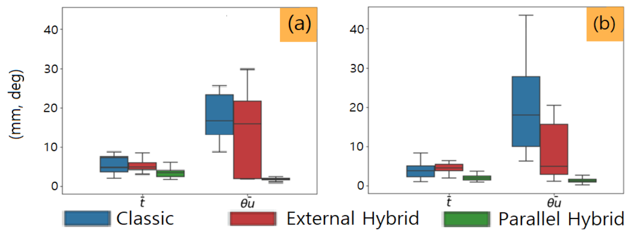


Fig. 3: Mean translation errors and rotation errors for the evaluated control laws. (a) tele-operation modes (b) comanipulation modes

with $e_r$ = 0.45° (6.67° and 3.07° for the classical and external hybrid methods, respectively).

For tele-operation modes, the result is similar to co-manipulation modes, parallel hybrid is the most accurate. The average linear error is $e_t$ = 0.67 mm (1.32 mm and 1.49 mm for the classical and external hybrid methods, respectively). Finally, one can point out that both shared control methods outperform the classical control laws.

Considering the required time to complete the defined insertion task, it appears that the hybrid parallel tele-operation approach needs in average 40.53 ± 10.09 seconds, which is 50% faster than the classical and external hybrid ones, when the hybrid parallel controller requires on average 29.03 ± 6.94 seconds to achieve the task, which is approximately 25% faster than the others control schemes.

## CONCLUSIONS AND DISCUSSION

The objective of this study was to provide surgeon, ergonomic, intuitive and accurate control method for the tool positioning at the early stage of a cholesteatoma surgery. To do so, a new generation of hybrid position/vision and force/vision were proposed and evaluated using a robotic setup under a scenario of inserting a surgical tool through a millimetric incision hole performed behind the ear lobe. This study demonstrated that the shared control laws outperform the classical tele-operation and comanipulation modes, both in accuracy and time required to perform the predefined task.

Future work will focus on the implementation of the proposed controllers in clinical situation. Senior and junior surgeons will be recruited to evaluate the benefit of such approaches in the operating room.

## ACKNOWLEDGMENT

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