A Computational Framework for Complementary Situational Awareness (CSA) in Surgical Assistant Robots

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A paper review summary by Zhaoshuo Li
Computer Integrated Surgery II, 2019

Project Overview and Introduction

Some anatomies are very fragile, and it is extremely undesirable to contact or even damage those tissues during surgery. For example, during skull drilling process of mastoidectomy, the facial nerve is very close to the surgical field. Any contacts with the facial nerve can cause paralysis. Therefore, the goal of this CIS II project is to develop complex virtual fixtures to protect critical anatomies such that the burden of surgeons can be reduced. In this project, the virtual fixtures will be developed for the Mark I robot from the company Galen Robotics Inc. This robot is a platform robot that can be used for many surgeries, mostly head and neck ones, which makes it a suitable robot for this project.

Paper Selection

Initially, the goal of the project is to enable bimanual teleoperation of the EyeRobot with the dVRK, which are both developed at the LCSR, JHU. Thus, the paper “A Computational Framework for Complementary Situational Awareness (CSA) in Surgical Assistant Robots” is selected since it provides a general framework to telemanipulate different robots with the dVRK. However, due to many factors, the goal of the project has changed after the paper review presentation. Therefore, in this report, the summary of previous review is given. Though this paper by Dr. Chalasani et. Al [1] is not related to the current project goal, this paper still provides a good insight of how to set up a software framework for advanced robot manipulation.

Problem and Key Results

Currently, the telesurgical robots, such as the da Vinci surgical robot (Intuitive Surgical Inc.), have provided more intuitive interaction and enhanced dexterity to surgeons performing minimum invasive surgeries (MIS). Nonetheless, the surgeons’ situational awareness is limited by the spatial separation. The missing information of patient’s anatomy and surgical environment can lead to surgery complication and prolong the treatment duration. Therefore, the goal of this paper is to enhance the teleoperation procedure for MIS by providing the surgeons complementary situation awareness (CSA). In the paper, the author has demonstrated the feasibility of using the proposed algorithmic software framework can improve the human-robot interaction by providing the missing sensory feedback.

Methods

Currently, teleoperation has been mostly human-in-the-loop system to correct any errors the slave robot experiences. In some extreme cases, solely relying on visual feedback can be impractical. The CSA framework aims to resolve this issue by providing more information through two key steps,

1) the teleoperation is mediated by a virtual model, and
2) the update of the virtual model by the interaction information of the slave robot.

The software consists of several high-level and mid-level controllers, which is illustrated below.

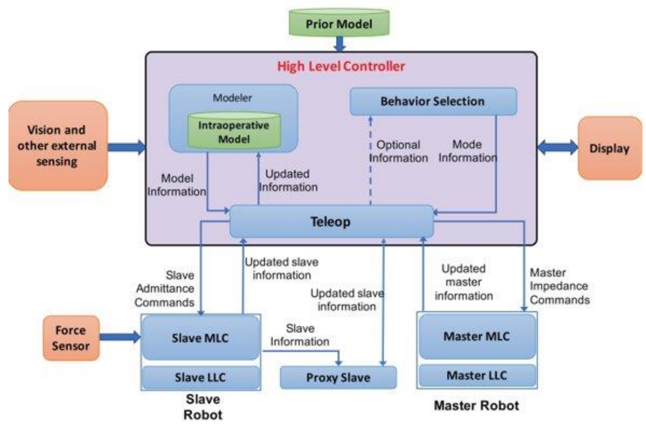

Fig. 1 The components of proposed CSA framework (figure 2 in [1])

Master Middle-Level Controller

The master middle-level controller is illustrated in the figure below. It is implemented as a torque controller, which provides user haptics feedback with some defined compliance gain setting. The detailed algorithm can be found in the paper. The compliance wrench is calculated with respect to the compliance frame $F_c = [R_c, p_c]$, as

$$g = g + k\epsilon + bv, f = R_C g$$

$$\tau = \tau + k_o\theta, T = R_C\tau$$

where ϵ and θ are the translational and orientational difference between the master frame and compliance frame.

$$\epsilon = R_c^{-1}(p - p_c), \theta = \text{Rodriguez}(R_C^{-1}R)$$

The *k* is translational elastic constant, *b* is damping constant, and k_o is the orientational constant.

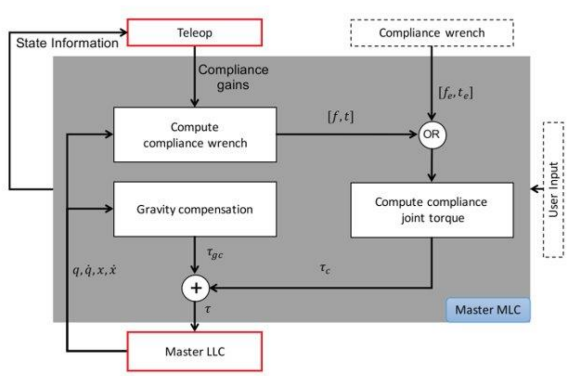

Fig 2. Master Middle-Level Controller block diagram (figure 3 in [1])

Slave Middle-Level Controller

The slave middle-level controller is illustrated in the figure below. It is implemented as a admittance controller following the hybrid force motion control law. The slave will follow the teleoperation command in the later direction of the force vector and tries to maintain the desired force in the normal direction of the force vector, which can be summarized as

$$\delta x = K_a K_g (F_c - F_d)\delta t + K_p (x_d - x_c)$$

with joint velocity constraint

$$v_l \le \frac{\delta q}{\delta t} \le v_u,$$

and

$$\delta q = min \, ||J \, \delta q - \delta x||$$

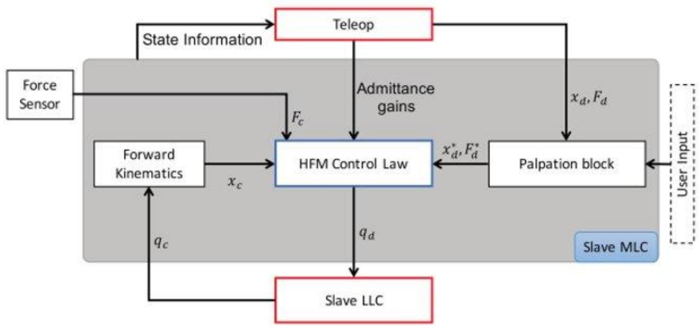

Fig 3. Slave Middle-Level Controller block diagram (figure 4 in [1])

Two motion primitives are also supported in the CSA framework, sinusoidal force reference and sinusoidal motion reference, during which either a constant force of a constant motion is maintained. The primitives can be used as palpation for stiffness information.

Proxy Slave

Proxy slave is used to interact with the model and update the model when necessary by the interaction information. The proxy slave is implemented as a position controller only.

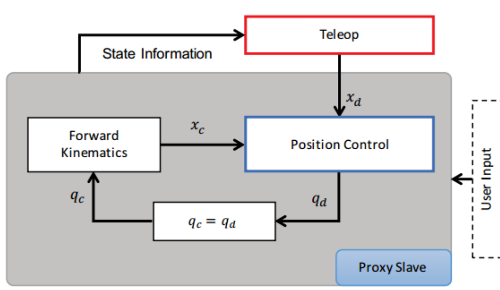

Fig 4. Proxy Slave block diagram (figure 6 in [1])

Teleoperation High-Level Controller

Teleoperation controller is a high-level component which is the central communication node. It is also responsible for drift correction of the virtual environment by using the interactin information of the actual slave and physical phantom.

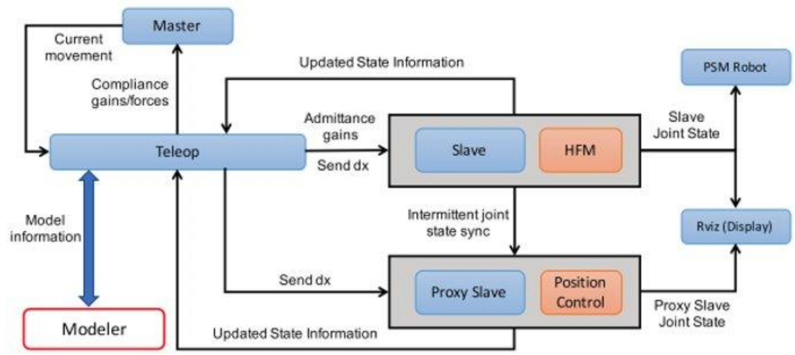

Fig 5. Teleoperation High-Level Controller block diagram (figure 8 in [1])

Modeler

The modeler is implemented using MATLAB, which deformably registers the virtual organ to the GP estimated shape. Optionally, there is a trajectory optimizer that optimizes the trajectory of the motion for the estimation.

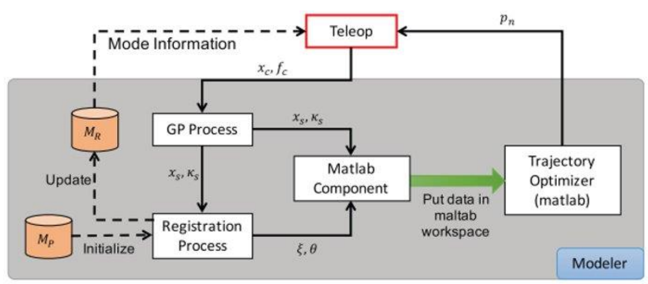

Fig 6. Modeler block diagram (figure 10 in [1])

Experiment and Results

One feasibility test is done to evaluate the proposed software framework. The user uses the dVRK to explore a phantom with some stiff lesions (made of hard plastic). The user therefore can move the slave laterally without the need of palpating the organ themselves. However, no numerical evaluation of the proposed system is provided.

Assessment

Pros

There are several points of this paper making it outstanding. First of all, the paper provided very detailed and structured description of its software framework, which has made it easy to follow and understand. Moreover, the paper provided enough visual supports for the user by using block diagram, flow charts, simple sketches to illustrate the algorithmic logic. Lastly, the proposed framework is very well-thought-out to tackle the existing the challenges in MIS. The effort on developing model-mediated teleoperation and online model updating removes the constraints of having a static organ, which is the assumption of many other papers.

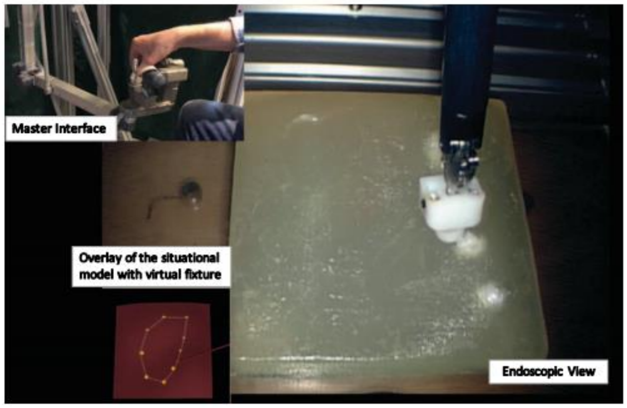

Fig 7. Experiment setup (figure 12 in [1])

Cons

However, there are some drawbacks of the paper as well. First, the experimental section of the paper is very short without many analyses of the proposed system. If there are more studies other than feasibility test, the paper will be much more convincing. Second of all, even if the framework proposed a online registration procedure to avoid misalignment of model and real organ, this still requires a very close initial alignment of the two organs, which can be hard to obtain in some way. Lastly, the proposed framework cannot be adapted to the clinical setting since the force sensor is directly placed under the organ phantom. Smaller force sensor that can be attached to the surgical tool will be ideal, though its force sensing accuracy and sensitivity can be worsened.

Relevance to the Current Project

As discussed before, there is a shift in the project goal due to some unexpected events. Thus, the relevance of the paper being reviewed and the current project goal may not be direct. However, there is still many features of the proposed software framework that can be adapted to the current project. For example, the proposed framework used a high-level teleoperation controller that communicates directly with the middle-level controller of the robots to enable complex robot manipulation. The same design strategy can be adapted for the virtual fixture project, since there should be a high-level controller determining the most relevant virtual fixture constraints of the robot based on its kinematics. Moreover, the modeler node of the proposed framework can be adapted to collision detection node of the current project by removing the registration step but keeping the Principle-directional Tree structure.

References

[1] Chalasani, P., Deguet, A., Kazanzides, P., & Taylor, R. H. (2018). A computational framework for complementary situational awareness (CSA) in surgical assistant robots. Proceedings - 2nd IEEE International Conference on Robotic Computing, IRC 2018, 2018–Janua, 9–16.