Critical Summary: A dual-user tele-operated system with Virtual Fixtures for robotic surgical training

Minimally invasive surgery (MIS) has become increasingly popular over recent years. The benefits of faster recovery times, less scarring and permanent landmarks as well as fewer complications arising form the procedures all speak to its effectiveness. Along with this popularity, naturally the training of surgeons and residents to use these new machines is of vital importance not only for the proliferation of their usage but to maintain the safety and effectiveness of these tools. Current dual control training systems, although increasingly sophisticated have been noted to be quite simplistic in their formulation, which contributes to their easily understand platforms but also hinders their intuitiveness and overall modularity. This can effect not only the quality of the training being given but also the time it takes to fine tune different dual control systems for specific scenarios. Therefore, a more modern, adaptable and intelligent system is of great interest to the field of surgical robotic training. This paper decides to tackle this problem by utilizing the concept of virtual fixtures already prevalent in robotic surgical systems but applying an added layer of adaptive functionality to them in order to evolve the use of virtual fixtures for training purposes.

The paper itself uses the concept of guidance virtual fixtures to create an adaptive dual control system, which changes the influence a trainee has over the overall motion of the physical instrumentation of surgical robot based on their demonstrated level of expertise in its usage when compared to that of the expert simultaneously controlling the robotic system. The researchers summarize this goal in equation 1 below.

$$x_{sd}(T) = \alpha_{adp}(t)x_{m_1}(t) + \alpha_{adp-T}x_{m_2}(t) \qquad (1)$$

This equation essentially states that the overall position of the slave physical tools as a function of time ($x_{sd}(T)$) is composed of the position of the expert's virtual position at some time t time ($x_{m1}(t)$) multiplied by some adaptive factor at time t ($\alpha_{adp}(t)$) plus the position of the trainee's virtual position at t ($x_{m2}(t)$) multiplied by the complementary adaptive factor ($\alpha_{adp\text{-}T}(t)$), where $\alpha_{adp\text{-}T} + \alpha_{adp} = 1$. This system allows for a flexible dual control system where at any given point in time either the trainee or expert have more or less control over the positions and state of the robot. The next step for the researchers was then determining how this adaptive factor $\alpha_{adp}(t)$ would change over time and they decided to change it based on the real-time demonstrated expertise of the trainee in manipulating the robot. To do this they determined expertise to be represented by 4 factors: the total path length a trainee is taking, the orientation of the tools the trainee has, the smoothness of the trainee's motions, and finally, the virtual fixture force felt by the trainee at any given moment. These 4 factors can be summarized by the follow 4 parameterizations, respectively:

$$\alpha_{\Gamma}(T) = 1 - \left| \frac{\Gamma_{m_2}(t) - \Gamma_{m_1}(t)}{\Gamma_{m_2}(t) + \Gamma_{m_1}(t)} \right| \qquad (4)$$

$$\alpha_{\Theta}(t) = 1 - \left| \frac{\Theta_{m_2}(t) - \Theta_{m_1}(t)}{\Theta_{m_2}(t) + \Theta_{m_1}(t)} \right| \qquad (5)$$

$$\alpha_{\Psi}(t) = 1 - \left| \frac{\Psi_{m_2}(t) - \Psi_{m_1}(t)}{\Psi_{m_2}(t) + \Psi_{m_1}(t)} \right| \qquad (6)$$

$$\Xi_{m_2}(t) = 1 - \exp\left(-\left(\frac{F_{GVF}(t)^2}{\delta_{GVF}^2} \right)^{m_{GVF}} \right) \qquad (7)$$

$$\alpha_{\Xi}(t) = 1 - \Xi_{m_2}(t) \qquad (8)$$

Equations 4-6 all follow similar patterns of being entirely relative to the motion of the expert and are bound between the values of 0 and 1. Simply, put these functions measure the trainees performance in comparison to those of the expert and depending on the trainees ability change in value to reflect how closely they are following the expert's motion. If the trainee is demonstrating proficiency then the value of the function approaches 1 while approaching 0 if they are not. For equations 7 and 8, its slightly more complicated but the general concept remains the same, the only difference being that instead of a straight comparison method between trainee and expert performance, what is being measure is how much for the trainee is experiencing based on the existence of a spherical virtual fixture around the virtual tools of the expert. The farther outside the trainee if from this sphere, the stronger the force they will experience, thus driving function 8 to 0 or 1 if the trainee is experiencing no force, implying they are within an acceptable radius of the expert's tools. Combining these 4 factors, the researchers arrived at the following function (10) for the adaptive factor, where each function is multiplied and an added 5th term, $\alpha_{\aleph}$ (t), is a chooser value to represent the maximum influence the trainee is allow to have. This can range from 0 for no influence at all to 1 where the trainee is capable of having total control over the system if they demonstrate perfect proficiency.

$$\alpha_{adp-T}(t) = \alpha_{\aleph}(t).\ \alpha_{\Gamma}(t).\ \alpha_{\Theta}(t).\ \alpha_{\Psi}(T).\ \alpha_{\Xi}(t) \qquad (10)$$

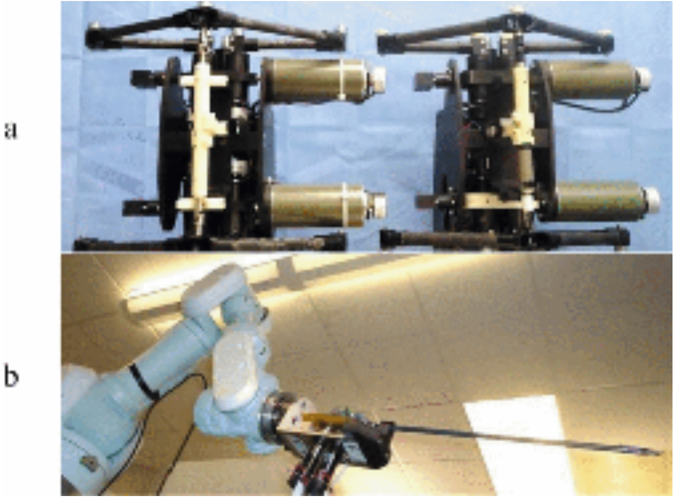
As for the virtual fixture itself, it can be quickly summarized by the following equations:

$$(x_{m_{2x}} - x_{m_{1x}})^2 + (x_{m_{2y}} - x_{m_{1y}})^2 + (x_{m_{2z}} - x_{m_{1z}})^2 \leq R_{VF} \qquad (11)$$

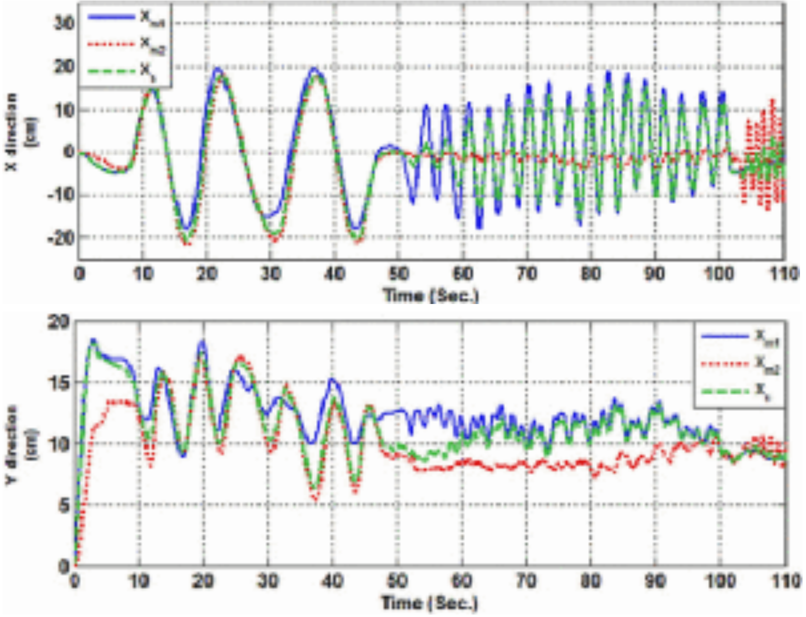
$$R_{VF} = R_0 - G_0 ln(1 - \alpha_{adp-T} + \epsilon) \qquad (12)$$

Equation 11 is the parameter used to determine whether a force is exerted on the trainee or not depending on their position relative to the virtual fixture sphere around the virtual tools of the expert of radius R_{VF}. This radius itself is the adaptable and expands or contracts whether the trainee is demonstrating proficiency or not, respectively. R_0 and G_0 are predetermined values for the minimum radius of the guidance VF and some factor by which one wants to change the size of the sphere.

Using this construction for the dual control system, researchers then tested their implementation with a simple experiment where a trainee and an expert were both given consoles controlling a singular physical robotic arm.



From there they calibrated their system to allow the trainee to have a maximum control of .9 ($\alpha_{\aleph}$ = .9) and a VF spring stiffness of 30N/m. Trainees where the told to follow the experts motion for 50 seconds (t = 0 —> t = 50) and then firmly hold their controls in one place while the expert continued to move their controls (t > 50). Although several different metrics were recorded and used for results analysis the two which most holistically exemplify the trail are shown below.



These charts show the x and y positions, respectively, of expert's (x_{m1}) and trainee's (x_{m2}) virtual tools as well as that of the slave robot they are both controlling (x_s). These charts clearly show how when the trainee if following the motion of the expert, the slave follows their trajectory identically, at time following that of the trainee more closely, but when the trainee begins to diverge from the motions of the expert the system quickly shifts to give control back to the expert making the movements of the trainee almost irrelevant. This clearly demonstrated the effectiveness of the system as an adaptable platform for dual robotic control.

In this experiment, however, there were several aspects of which I believe the researchers overlook. The first being that the method they chose to adapt the virtual fixture radius with, although sound in it reasoning, does not necessarily reflect a training usage for this system. For training, it is always about practicing, overcoming, and eventually perfecting of the task. The method they chose of an expanding virtual fixture as the trainee demonstrates proficiency goes against this logic as it does not push an experienced user to perfect their manipulations, instead granting them added leeway because they are adhering to other, potentially unrelated criteria. Instead, I would propose that the function work in the opposite manner, giving inexperienced users more freedom to explore the motion of the control console and tool while increasing restrictiveness as they demonstrate greater ability in order to push experienced users to be more deliberate and precise in their motions, so ultimately, when all assistance is removed they then have already perfected the exact manipulations they need to perform. Another, oversight of the paper was the lack of testing of their system during the performance of an actual task as opposed to generic motions. This would better demonstrate not only the applicability of their system but would also help reveal some initial shortcomings of their system such as intuitiveness for the trainee and how varying control may serve to assist or confuse the user when trying to perform a task. Finally, I believe that their treatment of force feedback as being an essential component to their system too restrictive and that perhaps being able to remove that element may help with the adaptability of the platform. This is a problem we encountered in or project and found that not having force feedback is just as viable a control scheme as one that does have it and may actually have some benefits of its own.

This paper help the development of our project not only by providing an innovative example of a possible dual console control scheme but also by how they chose to quantify expertise during surgical training scenarios. This provides us with new metrics to measure and consider in our own project for determining the effectiveness of different control schemes for training as these new criteria can be measured during experiments with and without an expert in order to quantify the progression of a users ability in using these surgical robot consoles.

References

M. Shahbazi, S. F. Atashzar and R. V. Patel, "A dual-user teleoperated system with Virtual Fixtures for robotic surgical training," *2013 IEEE International Conference on Robotics and Automation*, Karlsruhe, 2013, pp. 3639-3644.