Haptic Guidance in Comanipulated Laser Surgery for Fetal Disorders

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Abstract:
The current techniques in minimally invasive surgery allow treating fetal disorders. Treatment in an earlier stage increases the chance or level of recovery. However, fetal interventions require precise instrument manipulation from the surgeon. For instance, in the treatment of the twin-to-twin transfusion syndrome (TTTS) the surgeon needs to bring a laser in close vicinity to the placenta. It is crucial that the surgeon maintains a specific distance between the tip of the employed instrument and the placenta, while lasering target sites on the placental surface. To facilitate this procedure, we suggest a new approach where the surgeon comanipulates the instruments together with a robotic stabilizer arm. The stabilizer arm provides haptic guidance to the surgeon, augmenting the surgeon's precision and helping him maintain a desired lasering distance. The benefit of this approach is demonstrated experimentally.

Keywords: comanipulation, haptic guidance, fetal surgery, twin-to-twin transfusion syndrome

Introduction

Current surgical techniques allow treatment of fetal disorders in a minimally invasive surgical (MIS) manner. In such procedures, the surgeon enters the uterus with a small diameter – typically 3mm – endoscope through a small incision in the patient's womb in order to perform the necessary diagnostic and therapeutic steps. Most endoscope manipulations require a considerable amount of dexterity and high precision from the surgeon, as the surrounding structures are very delicate. As such, this type of surgery requires highly skilled surgeons [1].

One particularly challenging intervention aims to treat the twin-to-twin-transfusion syndrome (TTTS), a pathology where unwanted blood vessel connections, anastomoses, in the placenta of monochorionic twins cause an unbalanced blood flow [2]. If left untreated, this condition can be lethal for both fetuses. The treatment of TTTS is a non-contact laser-coagulation procedure. The surgeon manoeuvres the endoscope, equipped with a laser fibre, over the placenta to coagulate all anastomoses. Alternatively or additionally he/she will laser a continuous coagulation line over the vascular equator of the placenta, in order to separate the blood circulation of both twins [3].

During the lasering, it is essential to maintain a minimum distance between the placental surface and the laser, i.e. the tip of the fetoscope. A larger distance would render the laser process ineffective, while a smaller distance introduces the risk of undesired and dangerous contact.

TTTS treatment is a highly demanding task for the surgeon, not only due to this distance criterion, but also because of the scale, the required precision and the fulcrum effect, typical to MIS [4]. To facilitate this task, we suggest an approach where a robotic stabilizer arm provides haptic guidance to the surgeon. A comanipulation approach, where both the surgeon and the stabilizer arm hold the instrument and jointly determine the instrument pose, was preferred over a teleoperation approach, as comanipulation can be more readily integrated into the current surgical practice and it allows the surgeon to remain in close vicinity to the patient.

In this paper we investigate to what extent a robotic stabilizer arm can improve safety and precision during a lasering task.

Method

For the proposed application the requirements for the robotic stabilizer arm are that it is highly back-drivable, has a very large workspace and can display fairly large levels of stiffness throughout its workspace. The back-drivability of the stabilizer is crucial as the surgeon must be able to move the instruments in an unhindered fashion. The workspace of the stabilizer has to be sufficiently large to be able to cope with the variability in the location of the incision point on the patient's womb. The reachable stiffness (Z-width) is important for comanipulation as it allows providing effective haptic guidance, e.g. keeping the surgeon (instrument) away from contact. [5]

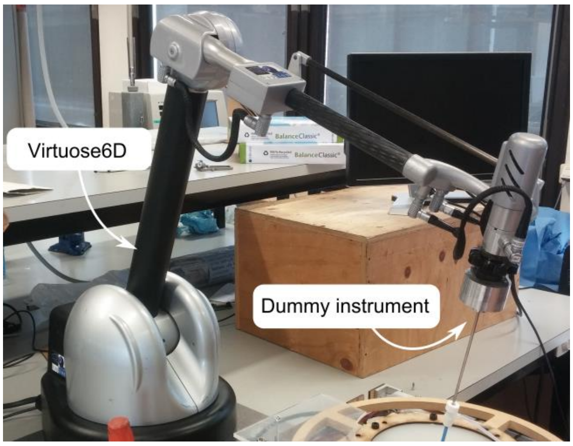

***Fig. 1:** Robotic stabilizer*

The haptic manipulator Virtuose6D (Haption S.A., Laval, France) fairly well meets the above requirements and was consequently selected as the robotic stabilizer arm. Its default end effector was replaced by a custom-made dummy tool (Fig. 1).

A controller was developed for the stabilizer to help the surgeon maintain a desired distance d_d between the instrument and the placenta. If frame $\{i\}$ is a frame rigidly attached to the instrument tip, with $\boldsymbol{z}_i$ along the instrument axis, and if frame $\{p\}$ is the placenta frame, with $\boldsymbol{z}_p$ orthogonal to its surface (Fig. 2), then the distance d between the instrument and the placenta can be expressed as:

$$d = \frac{{}^{p}\boldsymbol{O}_i \cdot {}^{p}\boldsymbol{z}_p}{{}^{p}\boldsymbol{z}_i \cdot {}^{p}\boldsymbol{z}_p},$$

where $\boldsymbol{O}_i$ refers to the origin of the instrument frame {i} and leading superscript p designates the reference frame.

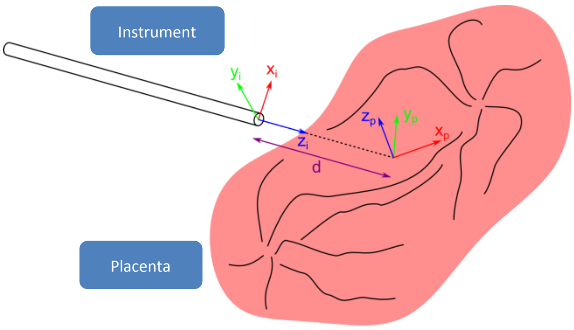

***Fig. 2:** Distance **d** between instrument tip and placenta*

The following PD force control law was implemented:

$$\begin{cases} {}^{i}F_{rep} = K_p(d - d_r) + K_d \dfrac{d}{dt}(d - d_r), & d < d_r, \\ {}^{i}F_{rep} = 0, & d > d_r, \end{cases}$$

where F_{rep} is a repulsive force applied along the instrument's axis. This control law can be interpreted as a virtual compression spring-damper of rest length d_r that is permanently attached to the tip of the instrument (Fig. 3). This spring will generate repulsive forces along the instrument axis $-\boldsymbol{z}_i$ whenever $d < d_r$. With such a controller, the robotic stabilizer provides haptic cues to the surgeon when he is approaching the placenta too close with the instrument tip.

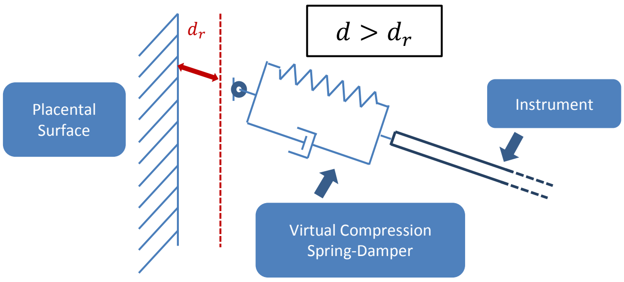

***Fig. 3:** Physical interpretation of the control law*

For safety reasons d_r is chosen larger than the proximity limit for safe lasering d_d. This ensures that the controller exerts sufficiently noticeable forces on the surgeon when he/she is at the desired distance d_d and thus increases safety. Practically, for our controller with a stiffness of 1000 N/m, d_r was set to 15 mm for a target d_d of 10 mm. Consequently, the surgeon had to provide a force of 5 N during the lasering in order to enter the no go zone.
Note that, the stability of this controller has to be carefully investigated. Especially in configurations where $\boldsymbol{z}_i \cdot \boldsymbol{z}_p \to 0$, the distance d is very sensitive to changes in $\boldsymbol{z}_i$ or in ${}^{p}\boldsymbol{O}_i \cdot {}^{p}\boldsymbol{z}_p$. The system could in such case become easily instable. To solve this issue, the force and its rate were saturated. Proper values were determined to ensure the stability of this system.

Experiments

A test setup, shown in Fig. 4, was created and consists of three main elements: the robotic stabilizer arm holding a dummy instrument, a simple womb mockup and a virtual reality system [6]. During the experiments the surgical tool was inserted through the incision point in the womb mockup to recreate the fulcrum effect.
The virtual reality system serves to replace the real placenta and laser by simulated ones. After calibration, it is possible to estimate the pose of the instrument tip from the encoder measurements of the Virtuose6D. This information is used to set the camera position in the virtual reality environment rendering a simulated endoscopic view upon a virtual placenta. The user can freely inspect the placenta, while receiving an additional indicator in

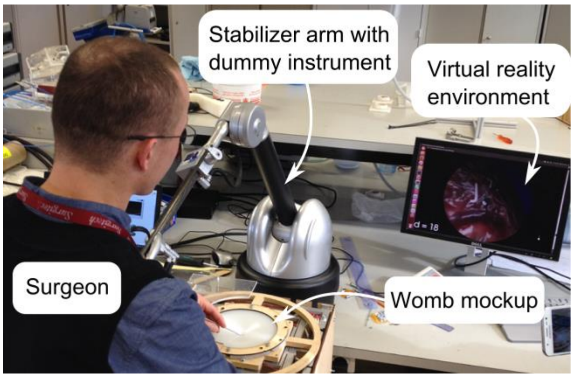

Fig. 4: *Experiment setup*

the corner of the screen that provides the distance information. If the user has identified a target to laser coagulate, he/she can press a foot pedal to generate a virtual burn mark on the placenta, thus replicating the course of events in a real TTTS procedure.
The user is asked to complete a laser task in the virtual environment. The task consists of tracing (and lasering) a line on the virtual placenta, while ensuring that the distance d, displayed with the endoscopic view, deviates minimally from a desired distance d_d, set here to 10 mm. This procedure is performed with and without haptic guidance from the robotic stabilizer. For the cases with haptic guidance, the user was able to turn it on and off, but all users preferred to have it constantly on, as soon as the line tracing began.
The experiments were carried out with novice users which didn't have any experience in MIS. Fig. 5a and 5b depict the results of the lasering, without and with haptic guidance respectively. The timeline of the distance d is shown in Fig. 6. Finally, Fig. 7 shows the frequency spectrum of the distance timeline.

Discussion

The results from Fig. 6 show a clear difference in the task performance without and with haptic guidance. Without haptic guidance the user was able to obtain an average distance of 11.2 ± 3.2 mm between the instrument tip and the placenta, while with the haptic guidance this was reduced to 10.6 ± 0.8 mm. Similar results were observed for different users. Furthermore, the motions of the user were more stable, and thus more controlled and safe, when the haptic guidance was enabled. This can clearly be seen from Fig. 6 and is also supported by Fig. 7 showing the frequency spectrum of the distance d during the lasering task. Human movements executed by the hand typically go up to a maximum frequency of 4.5 Hz [7]. If the energy spectral density for frequencies up to 4.5 Hz is computed from the data in Fig. 7, the resulting ratio of the case

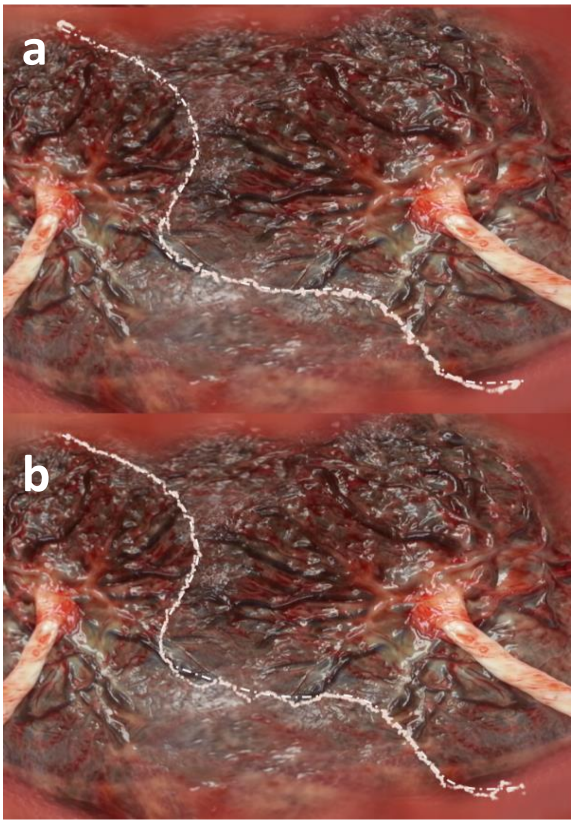

Fig. 5: *The lasering results without haptic guidance (a) and with haptic guidance (b).*

with haptic guidance to the case without is 5.2 %. This clearly shows the stabilizing feature of the robotic arm.

However, if one compares the lasering results (Fig. 5), the tracking quality should still be improved when haptic guidance is activated. This approach experiences some overshoots while following the line. This problem is directly linked to the chosen haptic guidance method, based on user feedback. It was preferred to apply forces only along the instrument axis, which corresponds to the vision direction of the scope. Forces applied on the instrument in other directions lead to a feeling of "losing complete control of the instrument". This design choice leads to two problems.
First, despite this intuitive haptic guidance, the price to pay is having forces not always related with the instrument motion and thus giving the impression that slippage occurs. Second, the sensitivity of distance d is non-homogeneous. It varies more strenuously when the instrument is being tilted rather when it is moving along the instruments axis.
An approach for improving the haptic guidance would be to add frictional forces along the plane parallel to the placenta. This would decrease the tendency of overshooting while moving over the line. Another solution is to apply an adaptive gain in the

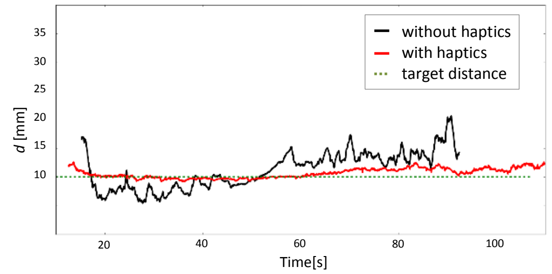

***Fig. 6:** The evolution of distance **d** when a novice surgeon lasers with and without haptic guidance.*

control law which would take into account the sensitivity of d when tilting, e.g. multiplying K_p by $\boldsymbol{z}_i \cdot \boldsymbol{z}_p$. The consequences for the feel of the user would have to be carefully studied.

This set of experiments showed promising results. Future works will focus on developing more advanced haptic guidance methods combining efficient stabilization and intuitive user feeling. Regarding the set-up, the dummy instrument can be easily replaced by a novel instrument equipped with distal actuators and flexible parts. Its distal degrees of freedom could be used to help the surgeon maintain a perpendicular angle of attack for lasering when moving along a curved line, and thus increase the efficiency of the laser. Finally, a thorough analysis of the surgeon's skill, e.g. based on motion analysis, may be useful to add proof of the positive outcome of this comanipulation approach.

Conclusion

A haptic comanipulation approach for minimally invasive surgery to aid the surgeon in maintaining a predefined distance between the endoscope and a clinical target, in this case the placenta, has been developed. This technique was applied for a representative lasering task in a virtual reality environment. The results from these experiments show that assistance from a robotic stabilizer has promising advantages. The next steps of this work will be developing more advanced haptic guidance methods, adapting the set-up to integrate a novel instrument with distal actuated degrees of freedom and performing a thorough analysis of the surgeon's performance when assisted by haptics.

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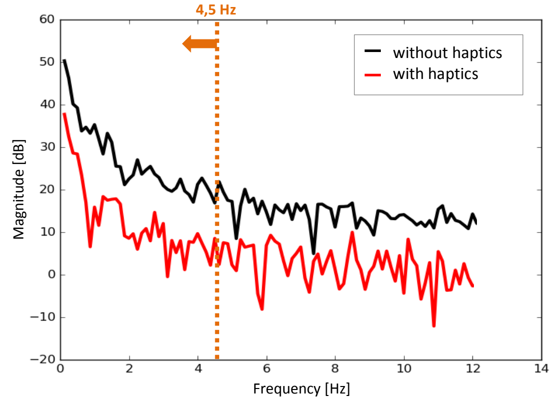

***Fig. 7:** The magnitude of the frequency response of the distance signal with and without haptic guidance.*

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