Design of a Haptic System for Minimally Invasive Cardiac Surgeries

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Abstract

In the present paper, we describe the mechanical design and working principle of a haptic device to be used during minimally invasive single port access cardiac surgeries. The details to hardware/software design and implementation to electronically actuate the device will be also presented. The viability of the design will be demonstrated by integrating the virtual representation of the left ventricle (as a simulation model) to define the unilateral constraints and find a safe corridor for haptic guidance and control of the surgical robot.

1 Introduction

In a conventional surgery, the surgeons apply translational force for the translational movement of the surgical tool with their wrist and/or arm movement. They may also apply rotational movement with their fingertips, which is necessary to rotate the tool tip inside the vessel, and hence to navigate through the junctions and curves of the vessel or the heart. They may also apply both translational and rotational movement at the same time. The main objective of the present work is to design a device which can assist the surgeon by feeding back the forces acting on the end effector of the catheter or other medical tools during the operation while maintaining the necessary translational and rotational movements. In order to maintain an effective force feedback, the designed haptic device should give all the necessary rotational and translational forces to the surgeon’s hands and/or fingertips, yet it should be a modular system, so that in case of a complication, which requires an open surgery, it allows surgeon to move freely. Considering these constraints, our proposed design avoids using any additional device, electronics or sensors attached to the surgeon’s hands or body, and yet it maintains all the necessary force feedback and movements; it is a separate device through which the surgical tool or catheter passes through (see Figure 1).

2 Methods

Mechanical Design: Figure 1 depicts the working principle of the device, which consists of three DC motors. Two of the motors are used to actuate the medical tool in translational direction, and the third one is to rotate the inner disc mechanism along with the medical tool that is in contact with the first two motors. The two motors are placed such that they prevent any unbalanced mass in the inner disc mechanism. At the tip of the translational motors, a soft material with high friction coefficient is placed to prevent the slipping of the medical tool while giving it force feedback. Using the measurements from the end effector position of the surgical tool, these motors can hold the tool, or simulate a virtual environment as if the tool is moving in a highly viscous environment. This is necessary in order to prevent the operator from moving the end effector to an unsafe operating region, which will be identified by a real-time image analysis algorithm using the MRI images, as sensed by the control algorithm as a future mistake. The viscous effects are zero in the safe zone, and gradually increase corresponding to an increase in the penalty coefficient which depends on the divergence of the end effector from its pre-defined path or workspace.

Prototyping: Having the components of the device modeled in a Computer Aided Design (CAD) software with exact dimensions, we used a 3D printer to manufacture the device. It is designed to be a compact device to assure the maximum user comfort and mobility. The overall dimensions of the device are 17 cm in length, 12 cm in width and 12.8 cm in overall height (including the inner disc mechanism). Figure 2 shows the components of the prototype in detail.

Hardware and Software Implementation: To control the device, a dSpace®1103 real-time data acquisition system is used. The control algorithm is developed using Matlab/Simulink®. DC motor drivers, which are commanded from the real-time data acquisition system, are used to supply the necessary currents to the motors.
The virtual representation of the heart is used as a virtual environment that the user feels the contact force feedback from. The dynamically changing boundaries of the safe operating region is fed to the control algorithm as constraints. Inside these boundaries, the operator is able to position the end effector without feeling any force feedback from the system. In fact, we compensated for the friction coefficients of the haptic system by introducing a virtual environment with negative friction. Using this virtually friction-less environment within safe boundaries allows user to control the haptic device with minimum effort. When the operator moves the end effector toward the safe boundaries and it reaches within the distance $\epsilon$ from the walls, the control algorithm applies a force in opposite direction of the force that the operator is already applying.

3 Results

The virtual environment is defined as the model of the left ventricle. This model and the safe boundary extracting algorithm is developed in [2]. The model is programmed in C$^\#$ programming language, and the safe boundary data from the C$^\#$ code are integrated by the dSpace real time data acquisition and control system. While actuating the prototype, the operator follows the end effector position of the rod (medical tool) inside the dynamically changing left ventricle in real time. The C$^\#$ code was integrated with dSpace by calling the Matlab engine from the C$^\#$ code. This is done by defining Matlab engine as a COM object. On the Matlab side, we developed a Matlab function for reading data from and writing data to the dSpace using the MLIB library that the dSpace company provided.

The virtual representation of the left ventricle is taken from Yeniaras et. al. [2], in which a realistic model was achieved by using MRI images of the heart taken from the healthy volunteers. They used a standard CINE pulse sequence that collected 24 frames of eight short axis and three long axis planes [2]. An access corridor was generated based on the criterion that it should not contact the endocardium (Figure 3), i.e., the innermost layer of tissue that lines the chambers of the heart, for all slices. The implemented algorithm determined a base surface ($S_{base}$) common to all slices and frames that satisfied the above criterion. The method described above can be summarized with the following four steps [2]:

1. The left ventricle is segmented and the endocardial boundary is extracted in all frames of short and long axes slices with manual tracing and ITK functions.
2. For each time frame, the common volumetric access corridor is determined by superimposing the access area for all seven slices.
3. The process in step 2 is then repeated for all the time frames to find the common access areas for all times sampled with the CINE sequence. The result from steps 2 and 3 gives the surface $S_{base}$. In practice, the algorithm in steps 2 and 3 is equivalent to superimposing the segmented left ventricles for all short axis slices and for all time frames.
4. The 3D access corridor is then generated by extending the surface $S_{base}$ from the apical to the basal short axis slices.

As a result, the workspace of the robot (shown in Figure 3 in shade) is determined using the steps described above and shown in Figure 4. The three plots illustrate the segmented left ventricle contraction at three different time instants. The shaded vertical region in subplots of Figure 4 shows the safe operating region for the haptic device end effector. We used the dynamically changing safe boundaries as the input to the control algorithm (not discussed here) developed for providing the haptic effects to the operator.

4 Summary

In this paper, we presented the details of the design of a novel haptic robotic system. The haptic device is designed to assist the surgeon during the delicate minimally invasive cardiac interventions via trans-apical access. First, the details and the working principle of the design were described by introducing the 3-D scaled design of the system. The details of the prototype was also discussed, where first we introduced the components of the prototype followed by a description of the software codes and hardware needed to be able to actuate the system and to collect sensory information. The virtual representation of the left ventricle were finally used to define the unilateral constraints for haptic guidance and control of the robot.

References

Fig. 1: Working principle of the medical haptic device

Fig. 2: Haptic prototype components

Fig. 3: Structure of the human heart and the left ventricle (edited from [1])

Fig. 4: Segmented representation of the left ventricle