Haptics-Constrained Motion for Surgical Intervention [1]

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Abstract. Current open-heart procedures requiring the use of a medial sternotomy and a heart-lung machine can potentially be performed by entering the heart through the cardiac wall. A new procedure in cardiac surgery involves introducing an ablation tool through the appendage of the left atrium. This method, intended for the treatment of atrial fibrillation, septal defect repair and valve replacement, provides increased control over the ablating instrument [1]. It is believed that this procedure will ultimately be performed under robotic control and image-guidance provided by intra-cardiac ultrasound. However, the intra-cardiac guidance presents several drawbacks, such as limited field of view, temporary loss of signal, and, in some cases, difficulty with interpreting the signal. We believe that the introduction of haptic feedback into this environment will enhance the procedure by providing tactile cues to assist in the location of the surgical targets. Keywords. Artificial potential fields, haptic feedback, sigmoid functions

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1. Introduction

In minimally invasive surgery, many safety and precision issues can be addressed through the use of haptic virtual fixtures. Recent literature reveals a great diversity in the application of studies concerning haptic fixtures [1,2]. In particular, one trend involves moving virtual fixtures closer to the operating room (OR). To this extent, we have proposed the use of dynamic 3D virtual fixtures generated directly from MR data of a beating heart in order to guarantee safety and improve precision by constraining the operator's motion relative to the target surface through haptic feedback.

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2. Background

Our ongoing lab work is focused on augmenting surgical guidance with haptic feedback in order to complement the intra-operative environment that is designed to guide intervention based on pre-operative MR or CT images and intra-operative ultrasound (US) images. To achieve this goal, we need to perform the following steps, which are shown in the block diagram in Figure 1

- Acquire pre-operative MR/CT images to construct a three-dimensional map
- Build a force model using MR/CT images and create a combined virtual visual/haptic model.
- Register this virtual visual/haptic model to the patient and synchronize this model to patient using the ECG as a time reference
- Acquire intra-operative US images and map them to the haptic model to provide real-time force feedback to the surgeon during the surgical procedure

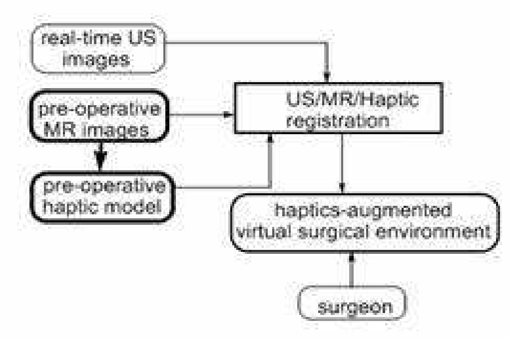

Figure 1. Haptics-augmented intra-cardiac intervention

Our primary objective in this study is to build a force model using MR/CT images and to create a combined virtual visual/haptic model. We apply a potential field-based force model to generate constrained motion on a beating heart phantom. The algorithms uses to generate the surface model and to register MR with US images have been described previously [5,4].

3. Method: Constrained Motion Using Gaussian Functions

In this section, we consider generating virtual fixtures to constrain the surgeon's motion to a predefined region. In this case, the region chosen is the surface of the heart. If we define $q = (x, y, z)$, the potential field based on generalized Gaussian functions can be written as,

$$f(q) = 1 - exp\left(-(\frac{q^2}{2\delta^2})^m\right) \tag{1}$$

where δ and m are adjustable parameters.

Although continuity in the force model is helpful in order to eliminate undesired oscillations in the surgeon's motion, an ideal virtual fixture should be imperceptible to the operation when the tool is within the desired region. Rather, the user should only feel constraint forces when the tool is about to stray outside the boundary of the desired zone. In practice, this means that both the slope of the constraint forces through the boundary zone and the location of the boundary zone should be adjustable. By changing the slope, we can change the magnitude of the constraint force that the surgeon feels as the tool approaches the boundary. Altering the location of the boundary zone ensures that the desired region can be made as large as possible, thereby allowing the magnitude of the constraint forces to increase. In our formulation, both of these adjustments are possible through changes to the two parameters m and γ.

Figure 2 illustrates that the feedback force can be easily localized to the boundary of the confined region by adjusting the parameter m. In Figure 2, 0 represents the surface, and $[-11]$ is the planned workspace that is defined by the parameter γ. When we set parameter $m = 1$, the operator will still perceive force even when the surgical tool is close to the surface. This condition can be improved by increasing parameter m. However, an extremely large value of m may result in oscillations near the boundary because the behavior of $f(q)$ is similar to that of an on-off switch control.

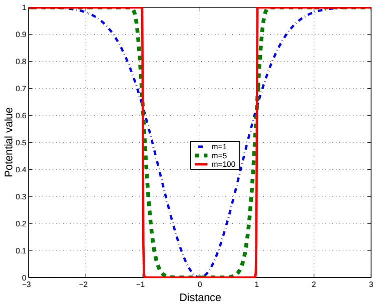

Figure 2. Effect of adjusting m

The parameter γ can be used to adjust the size of the confined area, which ensures that the surgeon does not feel force if the motion of the surgical tool is within the desired area. At the same time, any attempt to move the tool outside the desired area are restricted. Figure 2 illustrates variation in the workspace as a function of γ.

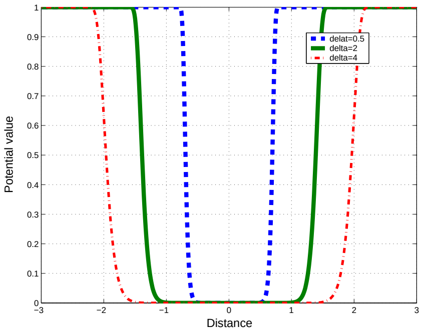

Figure 3. Effect of adjusting δ

The force can be defined as,

$$F_q = f_q(m)\frac{F'_q(m)}{\|F'_q(m)\|} \tag{2}$$

Figure 4 illustrates the potential force model, showing the potential fields for one slice of a heart surface model. The potential fields acquire a value of zero on the heart surface and increase as they move away from the surface.

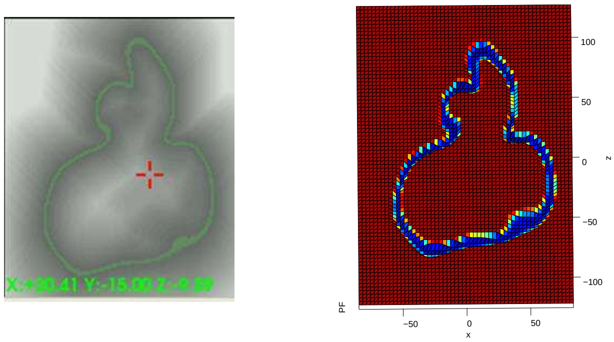

Figure 4. One slice of a heart surface model and its potential fields.

3.1. *Evaluation*

During robot-assisted cardiac surgery, surgical tools are often inserted to the workspace through small holes and surgeons need to operate with aid of image recorded by endoscope, and displayed in a video monitor. Poor hand-eye coordination, the restricted surgical field, and the low quality of image guidance make it difficult to perform even common procedures such as moving a surgical tool in a straight line or suturing.

However, these challenges can be addressed by our proposed force model. Using our model, we can generate an attractive force around the heart surface. As the user moves away from the pre-defined work area, the vicinity of the heart surface, he/she feels a force pushing the hand back. The force increases as the tool moves further away from the surface, and conversely, it decreases as the tool moves back towards the surface. The force model generates a fixture that is both continuous and soft; it is intended to provide guidance to the surgeon, rather than to restrict the motion of the instrument.

To illustrate the effectiveness of this constrained force, we perform a series of simulated tissue dissection procedures. These procedures use a surgical tool passing through a fixed pivot point in order to simulate the problem of poor hand-eye coordination, which results from the unnatural relationship between the user's hand movements and the motion of the instrument tip during laparoscopic minimally invasive surgery. Figure 5 illustrates a heart with ten pellets close to the surface. Each pellet represents a block of artificial tissue that needs to be removed from a location close to the heart. The goal of this procedure is to remove the tissue rapidly using a rod-like surgical tool.

Two subjects performed this procedure, yielding the results shown in Figure 1. We observe that without force guidance, the users finish the task in more than 3 minutes. However, when employing a virtual fixture, the users can remove all ten blocks of tissue

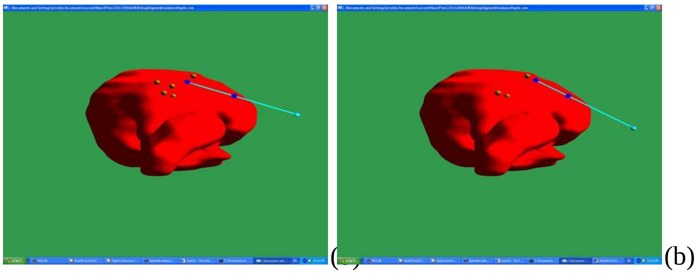

Figure 5. Evaluation on a simulated tissue dissection task

Table 1. Computation time comparisons

	(no force)	(with force)
1st Person	3’31"	1’30"
2nd Person	3’45"	1’26"

in less than half this time. Each observer performed the task ten times over a period of 10”

This decrease in the time to complete the task demonstrate the utility of the haptic-enhanced task. Figure6 illustrates constrained motion on a beating heart surface. Haptic force models are matched and superimposed on US images through the registration of intra operative US and pre-operative MR images. Soft constraints on the heart guide the tip of the tool to the surface and thereby help the user to perform delicate cardiac procedures without restricting their freedom of motion.

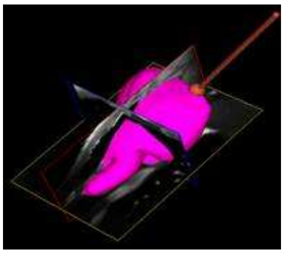

Figure 6. Constrained motion on the beating heart surface

4. Surgical Tools of Non-Point Shapes

In this preliminary work, we simplified the surgical tool to the shape of a point. However, in many applications, it is more reasonable to model the surgical tool as a generic shape rather than as a point: for instance, a cylinder can accurately represent the needle in brachytherapy and a torus is a more realistic model for the valve in mitral valve replacement. In this section, we extend our prior work as it applies to a surgical tool of a generic shape. This approach involves a three-step process; first, we divide the tool into multiple line segments and find the center point of each segment. Secondly, the feedback force is computed for the center point of each segment using the previously described method for points. Finally, we use the tip position to generate feedback force to the operator.

The exact method used to divide the surgical tool into multiple line segments depends on the specific application, and it is important to achieve a balance between accuracy and computation time. In order to validate our method, we used a MR data set. The results from this research can be directly used for surgical training and planning. Figure 7 shows a toroidally shaped surgical tool.

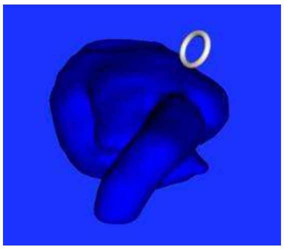

Figure 7. Constrained motion on the beating heart surface with a toroid-shaped tool.

5. Conclusion

In this paper, we have presented a method to augment a surgical guidance system with haptic feedback. Furthermore, we have described a procedure, based on Artificial Potential Fields, for generating constrained motion. Based on the results of our simulations, we believe that this approach has the potential to greatly increase the efficacy of robot assisted image-guided cardiac surgery. In our future work, we will integrate our approach with laboratory research into dynamically registered ultrasound and MR images, which will allow us to evaluate the utility of the virtual fixture model for intervention within the beating heart. We note however that effective utilization of this technique depends critically on robust spatial and temporal image registration of the model to the patient

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