A Computer Vision Approach to Virtual Fixtures in Surgical Robotics

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Abstract—This abstract paper proposes a novel method for implementing forbidden-region virtual fixtures in robotic surgery. In the absence of force feedback it is extremely important to prohibit the robot from accidentally colliding with sensitive organs and causing unwanted damage. A forbidden-region virtual fixture acts as a virtual protective region around the organs. The proposed method uses the streaming data from an RGB-D camera to build a virtual model of the surgical site and adds the virtual fixture to this virtual environment. The method can be implemented in real-time. It can be applied to streaming camera images and requires no pre-processing.

I. INTRODUCTION

Robotic surgery is rapidly becoming the standard of practice for many surgeries such as prostatectomy and hysterectomy. During the surgery, the surgeon has visual feedback but no haptic feedback (no sense of touch). It would be ideal if the surgeon would perceive the same kind of sensations as if the surgery was performed laparoscopically. In addition to this, additional force cues (haptic virtual fixtures) could be added.

A virtual fixture can be thought of as a virtual ruler guiding the tool motion in tele-operation [3]. A common virtual fixture is the forbidden-region virtual fixture which acts as a protective zone around objects of interest. In prior work on virtual fixtures for surgical robots, these protective zones have been defined from preoperative imaging. However these are difficult to register in a dynamic environment.

It has been noted that force feedback can result in fewer errors for certain tasks such as palpation [2]. A straightforward approach to force feedback is to mount a force sensor on the tool tip of the robot. This is however not desirable with respect to issues regarding biocompatibility, sterilization and sensitivity to temperature.

Instead we suggest using a RGB-D (video plus depth) camera to obtain depth data of the environment around the surgical robot in real-time. This depth data will then be used to generate dynamic forbidden-region virtual fixtures as well as a ‘sense of touch’ for the surgeon.

II. HAPTIC RENDERING FROM STREAMING POINT CLOUDS

We have developed a method for haptic interaction with streaming point clouds from an RGB-D camera [4]. The haptic device controls the Haptic Interface Pointer (HIP) in a virtual environment and can move freely. The HIP can be thought of as a mouse pointer for the haptic device. The HIP is attached to another virtual object (the haptic proxy) by a virtual spring-damper coupling. The force on the haptic device is then based on the vector between the HIP and the proxy.

When the HIP is not penetrating any objects, the proxy can match the HIP position perfectly. But when the HIP passes through an object, the proxy stays on the boundary of the object. That is, the proxy can never move through objects. Haptic interaction with polygons using this method has been described by several authors, e.g., [5]. In this work, we address the problem of moving the proxy in a streaming point cloud under the influence of noise. Fig. 1 illustrates the similarities and differences between polygon haptic rendering and point cloud haptic rendering.

When moving the point cloud, the proxy can be in either free motion, in contact or entrenched (see Fig. 2). When the proxy is entrenched, it is about to pop-through the point cloud. Our haptic rendering method can be summarized in the following steps:

1) Capture depth data using an RGB-D camera. Transform data from the camera frame to the Cartesian frame (the virtual world frame).
2) Read the position of the haptic device and update the HIP.
3) Move the proxy iteratively towards the position locally minimizing the distance between the HIP and the proxy.
in the direction of the estimated normal vector to get out of entrenchment.

4) Calculate the force on the haptic device as a spring-damper coupling between the HIP and the proxy.

III. VIRTUAL FIXTURES IN ROBOTIC SURGERY

In robotic surgery, the surgeon sits at a console and controls the motion of the surgical robot at the patient side. The surgical console can be in the same room as the robot or at a remote location. In the existing surgical robotic systems the force feedback is limited to tool-on-tool collision. This is mainly due to the problems that arise in the stability and transparency of force feedback at the tissue layer. In the absence of force feedback, the surgeon has to pay close attention to the visual feedback in order to prevent the robot from touching or damaging unwanted tissue.

Forbidden-region virtual fixtures [1] prohibit the robot end effector from entering a certain region in the workspace and causing accidental damage to the tissue. This can be thought of as a 'no-fly-zone' for the robot. Prior work on forbidden-region virtual fixtures requires this forbidden region to be defined by meshes or implicit functions prior to the operation. The haptic rendering method described in Section II eliminates the need for prior computations and enables the implementation of forbidden-region virtual fixtures from streaming point cloud data in real time.

In order to better distinguish the multiple environments present we use the following definitions:

- **Proximate Physical World** refers to the surgeon’s side including the surgical console, haptic devices, etc.
- **Remote Physical World** refers to the environment remote to the proximate physical world including the patient’s side, surgical robot, etc. The camera is present in this environment.
- **Virtual World** is the 3D virtual model of the remote physical environment as seen by the camera. The virtual fixtures exist in this world as well. A visualization of this 3D environment and the virtual fixture can be provided to the user as a visual aid.

Fig. 3 illustrates the three environments defined above as well as the flow of data between the environments. The RGB-D camera builds a 3D virtual model of the remote physical environment. The virtual fixture is added to the virtual environment. The position of the haptic device, which was earlier used as the position of the HIP, would now be used as position commands to control the surgical robot as well. If the operator tries to move the HIP and the robot into a forbidden region, the haptic rendering method calculates and applies the appropriate forces to prevent the user from driving the robot into the region. The virtual fixture can be built at a safe distant from the sensitive organs to protect them from any accidental damage. In addition to the forces, visual cues can be displayed to the surgeon to inform him/her of the collision with a forbidden region.

Fig. 3. A visual representation of the three worlds defined.

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REFERENCES


