Proof of Concept Implementation of Forbidden Region Dynamic Active Constraints in Minimally Invasive Surgery

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INTRODUCTION

Active Constraints (AC), also named as Virtual Fixtures (VF), are a strategy to provide anisotropic haptic guidance for surgeons during use so that motions that comply with safety requirements are permitted, while those that breach safety requirements are negated. AC can be helpful also in a teleoperative surgical scenario, in which surgeons operating on the surgeon-side interface are separated from the patient-side, where surgical instruments are held and manipulated by a robot. One challenging aspect of incorporating AC into a modern clinical setting is how to efficiently update pre-constructed AC geometries in real time to account for dynamic tissue movement. In this study, we designed a pipeline for implementing Forbidden Region AC (FRAC), where tissue movement is constantly captured by a depth-sensing camera. The effectiveness of the pipeline has been confirmed through *in vitro* trajectory tracking experiments along a deforming aorta phantom. Our experimental results demonstrate the capability of our method to provide timely corrective guidance when a violation of the safety region is detected.

MATERIALS AND METHODS

Bowyer *et. al* [1] proposed that the implementation of AC can be summarised into three stages: AC generation, AC evaluation and AC enforcement. In these processes, the tissue to be protected is represented using geometry, the violation of safety region is determined, and an AC force is generated. In the rest of this section, we present the design of each of these for our proposed dynamic AC pipeline.

A. AC generation

AC generation is the foundation of the AC implementation, where anatomical areas of interest must be geometrically represented, either through simple geometries such as lines and points or through complex geometries such as triangular or quadrilateral meshes. Although complex geometries provide a more accurate description of the anatomical structure, they come at the cost of higher computational requirements for the subsequent AC evaluation step. To enable real-time updates of AC when tissue undergoes deformation, we utilize a depth sensing camera, Acusense 3D (Revopoint 3D Inc.), with a resolution of 0.5mm at a working distance of 0.5m. The Acusense camera streams a point cloud representing the tissue surface at a rate of 10fps, which is then registered with a pre-scanned tissue model. Assuming that the deformation of soft tissue caused by the respiratory movements of a patient can be modelled as an affine transformation, we leverage the robust global registration method TEASER++ [2] to accelerate this step.

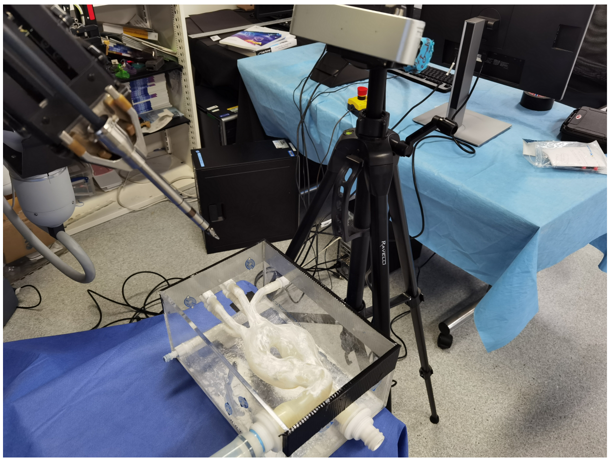

Fig. 1 Hardware setup, consisting of an Acusense 3D camera, an aorta silicon phantom and a pair of forceps held by dVRK Patient Side Manipulator1 (PSM1)

B. AC evaluation

AC evaluation is responsible for conducting a proximity query between a surgical instrument and the soft tissue to be protected. The returned minimum distance is compared with a safety distance to determine if a violation of the safety region has occurred. Different AC geometrical representations result in different levels of difficulty when performing AC evaluation. For mesh representations, proximity queries require a significant amount of computational effort. To accelerate the proximity query process, we incorporate the Deformation Invariant Bounding Spheres (DIBS) method [3] in our pipeline design.

C. AC enforcement

AC enforcement involves computing the magnitude and direction of an AC force/torque to be sensed by surgeons so that surgical tools can be retracted into the safety region promptly when a violation occurs. Although a simple elastic-plastic model is the most widely adopted for generating haptic cues, it is not always dissipative, which can introduce safety concerns. Therefore, in this study, we adopt a dynamic frictional constraint model [4] that is able to compensate for this shortcoming.

D. Experiment design

To test the effectiveness of the proposed AC strategy in assisting teleoperational surgical tasks, trajectory tracking experiments were designed and implemented on the first generation da Vinci Research Kit (dVRK) [5]. In this controlled study, we assume that when an AC force is generated, a surgical tool (Forceps 400036E) should be effectively pulled out of the forbidden region along the direction of the AC force by a "virtual surgeon". Specifically, instead of recruiting users to operate on the patient side, we directly feed the AC force into a hybrid force-position controller, which in turn generates positional commands to be received by the tool. Before the experiment, we defined a reference dynamic trajectory, consisting of 500 points in total, which is constantly updated as the tool moves above the surface of a pulsating phantom driven by a water pump, maintaining a safety distance of 8mm.

RESULTS

Throughout the experiment, a total of $N = 726$ points were gathered on the actual tool tip trajectory. The average distance between the tool tip and updated target point on the reference trajectory = $\frac{1}{N}\sum_{i=1}^{N}||P_i - Q_i|| = 13.28$mm, where P_i and Q_i denote the ith point on the actual tool tip trajectory and its corresponding target point on the updated reference trajectory, respectively. To demonstrate the effectiveness of the proposed AC strategy in assisting the task, 4 timestamps along the trajectory were selected, which are depicted in Fig.2 to show how the tool tip was retracted from the forbidden region when a safety condition was breached. The updated reference trajectory was also overlaid onto the updated phantom model at these four timestamps to illustrate the deformation of the phantom. Fig 3 provides a more detailed demonstration of the tool tip movement when a violation of the safety region is detected.

DISCUSSION AND CONCLUSION

The average distance between the tool tip and its corresponding target point on the reference trajectory is greater than the defined safety distance, which indicates the effectiveness of the proposed AC strategy in maintaining task safety. Our results also show that when the safety condition is breached due to dynamic tissue deformation, the proposed AC strategy is able to prioritize task safety and guide the tool tip to move out of the forbidden region. One limitation of this study is that a hybrid force-position controller was used to remove the human element from these initial experiments. Hence, the (virtual) surgeon was assumed to be able to perfectly act upon the

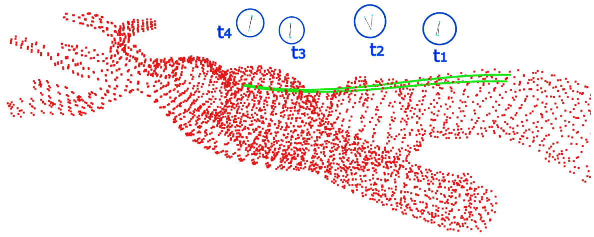

Fig. 2 Tool tip positions at four timestamps t_1, t_2, t_3, t_4. The green lines represent the updated reference trajectories at each timestamp, while the red points represent the updated phantom models. The misalignment between them indicates movement of the phantom. The blue circles represent the tool tip positions, with highlight in Fig.3

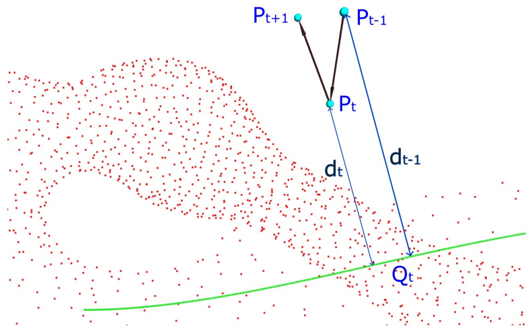

Fig. 3 Tool tip movement when safety condition is breached. At time $t-1$, the tool tip is located at P_{t-1}, and its distance from the phantom surface is greater than the safety distance ($d_{t-1} >$ safety distance), hence movement towards P_t is allowed. However, at P_t, when the minimum distance reduces to less than the safety distance ($d_t <$ safety distance), the AC controller generates an AC force to guide the tool tip away from forbidden region and towards P_{t+1}

generated AC force and respond promptly. Future work will involve conducting user studies and evaluating the effectiveness of the proposed AC strategy in assisting actual teleoperational surgical tasks.

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