An Instrumentation System with Force Feedback, Automatic Recognition and Skills for Cardiac Telemanipulation

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Abstract

In the last decade, the advancement of endoscopic and minimally invasive surgery has had a significant impact on patients and surgeons in various surgical fields. But in heart surgery the design of telemanipulators did not leverage endoscopic procedures. The focus is on building an experimental system for endoscopic and minimally invasive heart surgery which provides force feedback. In addition automating endoscopic surgical skills like knot-tying are implemented.

1. Introduction

Despite the obvious potential advantages of robot assisted MIS [1], most researchers in this area agree that the lack of haptic feedback is the most important drawback of currently available systems [2]. The inability of the operator to sense the forces applied causes increased tissue trauma and frequent suture material damage [3]. Another important limitation of current systems is the absence of Cartesian control over the end effector. It is not possible to drive the end effector to a defined position and orientation within the workspace, but only to apply relative displacements - the intended position being verified visually by the surgeon. A laparoscopically tied suture knot can take up to three minutes to complete, compared to one second for a manually tied knot. Given that knot-tying occurs frequently during surgery, automating this subtask would greatly reduce surgeon fatigue and total surgery time. For good knot-tying controller the 3D trajectories of multiple instruments must be precisely controlled. In order to release the workflow "learning by demonstration" paradigm is implemented in the system. Therefore a general learning machine is needed capable of generalizing examples shown by the user and building a control strategy.

2. Methods

System Setup. An experimental system is developed, which provides force feedback and full Cartesian control on each of the four end effectors. The system comprises four small robotic arms which are mounted on an aluminum framework (figure 1).

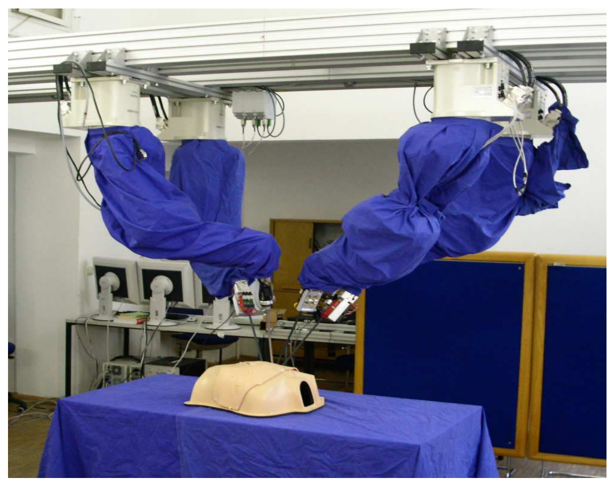

Figure 1. System setup with four robotic arms including force feedback.

Although there are four robots, it is easy to access the workspace due to a ceiling mounted setup. The arms are equipped with three force-feedback instruments and one endoscopic stereo camera system. Position and orientation of the manipulators are controlled by two haptic input devices.

Automatic Recognition of Suture Material. Surgery assistance like holding or tightening tissue or surgical material, or even more complex tasks like knot tying can be partially automated. But all these tasks can be achieved only if the system has an internal representation and basic semantics about the scene. Figure 2 left shows a heart mockup with a curved surgical thread in front of it. A thread is segmented out of the endoscopic image using a differential geometric approach for the extraction of curvilinear structures. The thread (dottet line) is segmented using a differential geometric approach for the extraction of curvilinear structures [4]. False matches (solid lines) are discarded using simple constraints like color, length and distance from the background. A dense disparity map is computed on the rectified stereo image pair using a normalized cross correlation (figure 2 right).

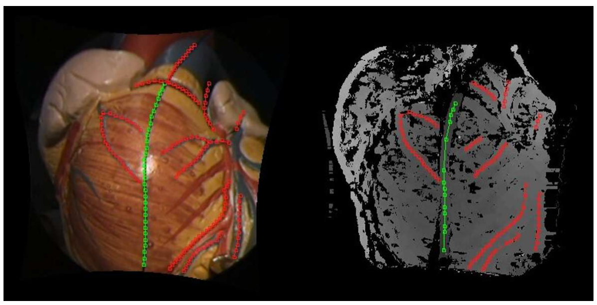

Figure 2. Thread recognition: segmented image (left) and disparity map (right).

3D coordinates are only computed for points in the disparity map, whose correlation scores are high, avoiding outliers caused by noise. The interpolation of a cubic spline through these points produces a smooth trajectory in 3D space. This allows furthermore an easy way to access arbitrary regions of the thread. The same is applied for the surface reconstruction: a texturized free-form surface (NURBS) interpolates prominent areas and models the background tissue.

Automatic Skills. Surgical assistance like holding or tightening tissue or surgical material, or surgical knot tying can be partially automated. “Learning by Demonstration” trajectories are included in the system. 25 example trajectories are recorded for the loop part of knot-tying, generalized with a neural network and included to the procedure. After the left gripper’s approach of the corresponding position, the network answers with an adequate loop-trajectory. The gripper continues from the end of the loop with a programmed part to complete the knot. It is possible to insert skills, learned in form of tasklets from the user, into the workflow. This will provide a comfortable opportunity for domain users (surgeons) to augment control programs with domain-specific knowledge.

3. Results

“Pre-programmed Knot-Tying” has been performed in reality with our system. It has been repeated several times and worked very reliably with no failures so far - in all cases, it successfully tied a knot. It turned out that this procedure benefits from thread tension which was first achieved with our third assistant arm. Previous experiments with two arms (and therefore no thread tension) often failed, because the loop around the gripper (in order to prepare the knot) was lost during the procedure.

Recently we also included the above mentioned **“Learning by Demonstration”** example into our system. We have recorded 25 example trajectories for the loop part of knot-tying, generalized them with a neural network and included the procedure into the workflow. Figure 3 left shows the trajectory with the pre-programmed loop while figure 3 right depicts the same trajectory with the learned loop in it: After the left gripper approaches the corresponding position, the network answers with an adequate loop-trajectory. After performing this, the gripper continues from the end of the loop with a programmed part to complete the knot. Like the “pre-programmed knot” this version also worked very reliably. It shows that it is possible to insert skills, learned in form of tasklets from the user, into the workflow. This will provide a comfortable opportunity for domain users (surgeons) to augment control programs with domain-specific knowledge.

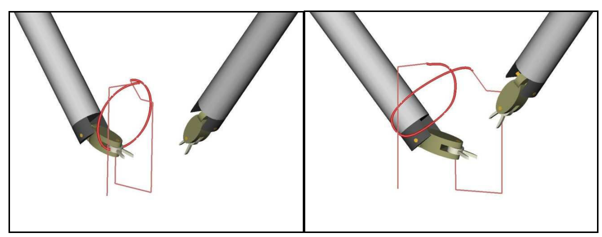

Figure 3. Original trajectory (left) and loop learned from examples (right).

4. Discussion and conclusions

We developed a novel robotic system for minimally invasive surgery that is capable of assisting a surgeon in tying knots. The defining features of this ceiling-mounted four-armed robotic system are its haptic feedback, its 3D vision system, its optical thread recognition and the automation of the surgical knot-tying procedure. The force feedback and user-friendly operating system lead to high-quality human control, which we exploit by applying state-of-the-art RNN-based supervised machine learning techniques in order to learn tasklets of the knot-tying procedure (learning by human demonstration). Initial results with learning to tie a knot are promising, and it is expected that future combinations of learned tasklets might be able to produce an entire knot-tying behavior, without any pre-programming. One step towards this is the integration of a reliable thread recognition algorithm as described in this paper. The next step is to combine thread recognition and automated knot-tying. I.e. the initial situation (grasping the thread) should be established automatically.

The force feedback and user-friendly operating system lead to high-quality human control. In future technology we postulate the integration of force feedback in telemanipulating surgical systems, not only for support the surgeon, but also to augment the variety of indications and surgical techniques in heart surgery. Currently the system is used to determine the degree of automation that can be included into surgical procedures.

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