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# Virtual interactive suturing for the Fundamentals of Laparoscopic Surgery (FLS)

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ABSTRACT

*Background:* Suturing with intracorporeal knot-tying is one of the five tasks of the Fundamentals of Laparoscopic Surgery (FLS), which is a pre-requisite for board certification in general surgery. This task involves placing a short suture through two marks in a penrose drain and then tying a double-throw knot followed by two single-throw knots using two needle graspers operated by both hands. A virtual basic laparoscopic skill trainer (VBLaST©) is being developed to represent the virtual versions of the FLS tasks, including automated, real time performance measurement and feedback. In this paper, we present the development of a VBLaST suturing simulator (VBLaST-SS©). Developing such a simulator involves solving multiple challenges associated with fast collision detection, response and force feedback.

*Methods:* In this paper, we present a novel projection-intersection based knot detection method, which can identify the validity of different types of knots at haptic update rates. A simple and robust edge-edge based collision detection algorithm is introduced to support interactive knot tying and needle insertion operations. A bimanual hardware interface integrates actual surgical instruments with haptic devices enabling not only interactive rendering of force feedback but also realistic sensation of needle grasping, which realizes an immersive surgical suturing environment.

*Results:* Experiments on performing the FLS intracorporeal suturing task show that the simulator is able to run on a standard personal computer at interactive rates.

*Conclusions:* VBLaST-SS© is a computer-based interactive virtual simulation system for FLS intracorporeal knot-tying suturing task that can provide real-time objective assessment for the user's performance.

## 1. Introduction

With reduced surgical invasion and faster recovery, minimally invasive surgery (MIS) has rapidly evolved over the past couple of decades as a technique of choice for an increasingly large number of surgical procedures. However, the complexity of MIS exceeds that of traditional open surgery as long slender surgical tools inserted through trocars into the abdominal cavity are used to perform the procedures with a two-dimensional field of view captured by a wide-angle camera. The complexity of the eye-hand coordination necessary in laparoscopic surgery and the occurrence of adverse events in the early days of its introduction have led to increased emphasis on psychomotor skill training using simulations and models outside the operating room (OR).

Virtual reality (VR) is of growing interest in medical training, especially in surgery [1,2]. With the advance of VR techniques, considerable effort has been dedicated to the development of VR-based surgical training simulators, which provides both visual and force feedbacks to users when they interact with virtual environment. VR-based simulators offer many advantages over the traditional training method by teaching surgical skills in a safe and controlled environment, ensuring repeatable conditions, offering automated assessment, and often without the need for supervision. The simulators provide a computer-generated realistic environment where surgeons can be trained with no risk to patients. The repeatability and reusability offered by VR-based simulators can improve surgical skills by allowing repetitive practice on different scenarios. In addition, these simulators can also provide objective evaluation of task performance and assessment of competency, and those may be unmeasurable via traditional means. For

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instance, a simulator has the potential to record the motion of virtual surgical instruments or detect whether a damaging contact with nearby anatomy has been made by the user. With rapid advances in hardware and software capabilities, VR-based simulators are also becoming increasingly affordable.

Laparoscopic suturing is one of the most commonly performed tasks in MIS, that requires significant practice to master as a curved needle is used to close a tissue defect with a knot that is neither too loose nor too tight. In open surgery, suturing is much less complicated as full articulation of the needle can be achieved. Using needle drivers in laparoscopic surgery deprives the surgeon of this natural wrist articulation, increasing the difficulty level of the procedure. A simple suturing task is included in the Fundamentals of Laparoscopic Surgery (FLS) [3], which is now a pre-requisite for board certification in general surgery. In the FLS intracorporeal suturing task, one needs to place a thread through two dots marked on either side of defect in a penrose drain using a surgical needle, and then tie a double-throw knot followed by two single-throw knots using two needle graspers operated by both hands. The task is designed to test multiple skills including hand-eye coordination, bimanual operation and precision. A proctor must be present to score the procedure and the system suffers from multiple other drawbacks of a physical simulator pointed out earlier. A virtual basic laparoscopic skill trainer (VBLaST) is being developed to represent the FLS tasks, including automated real-time performance measurement and feedback [4]. In this paper, we present the development of a VBLaST suturing simulator (VBLaST-SS©). A VR-based suturing simulator is expected to be able to simulate the deformation of thread and penrose drain, knot detection and tying, as well as interactions between needle, thread, penrose drain, surgical needle graspers and the environment, which require intensive computations for collision detection and dynamic response between the virtual tools and the models. As a high update rate of 1 kHz is necessary for the haptic servo loop to be stable, designing an interactive suturing simulator allowing for these features while providing force feedback in real time is a challenging task.

Virtual suturing techniques have been extensively explored by others. A thread is often modeled as a sequence of nodes connected by either rigid links or springs. For rigid links, a kinematic scheme such as “follow the leader” has been used while the force between adjacent nodes is not considered [5]. The use of elastic springs is more physically realistic [6–13]. Le Duc et al. [13] modeled the thread using a simple linear mass-spring system to achieve good computational performance. Jia and Pan [7] simulated interaction and deformation of the thread and tissue. However, these algorithms lack detection of self-collision and knot-tying, nor can they be used for more complex suturing tasks. Payandeh and Shi [8] presented a suturing platform to teach basic stitching on a pre-wound tissue with only one tool provided to perform suturing. Some recent work [9–11] explored the feasibility of utilizing a physics engine, NIVIDIA PhysX [32], to develop a suturing simulator that can take advantage of hardware acceleration. As the force data is not available from the PhysX engine, the computation of force feedback is not straightforward [9] for those methods. Furthermore, none of the above simulators integrate real surgical suturing instruments with haptic devices as hardware interfaces to improve the fidelity of suturing sensation which includes the feeling of picking up a rigid needle and orienting it appropriately to achieve the right bite angle. There are some commercial virtual surgical training systems have been developed, such as LAP Mentor [35], Lap-X [36], LapVR [37] and Lapsim [38]. These training systems are able to simulate basic suturing skills, such as stitching a pre-wound tissue, but they generally differ from the actual FLS intracorporeal suturing task. In addition, in order to operate all the training modules of the system, they all customize their own user interfaces which deviate from the tools specified by FLS.

Robust handling of self-collision is critical to prevent the thread from passing through itself. Early work on collision detection based on one instance of geometry [14] led to missed detection in high speed contact. Initial work on continuous collision detection (CCD) was based on formulating and solving a cubic equation with time-to-collision of edges [15] accounting for multiple time frames. Several enhancements on this approach for reducing missed collisions, false-negatives and improving performance have been developed. For instance, *ExactCCD* [16] involves analysis of the roots of the equations to achieve geometrically exact detection in cloth simulation. In *FastCCD* [17], analytical reformulation of the approach led to more efficient and robust detection. *SafeCCD* [18] improves safety through analysis of numerical and rounding errors while *TightCCD* [19] uses Bernstein sign classifications to significantly enhance performance and reduce false-negatives.

In these approaches, as the underlying initial computation is to find roots of a cubic equation, extensive arithmetic and choice-making (Boolean) operations are involved, leading to propagating floating point errors and performance degradation. In addition, failures to handle scenarios such as parallel segments and geometrically degenerate cases have been reported [16].

Methods to robustly handle self-collision of suture thread in real-time simulation environment is challenging [20,21]. In [22], collision is handled by resolving thread penetration considering the current geometry. An energy based approach for self-collision of tentacles in a squishy-ball is developed in [23]. In the work on collision detection of deforming cables, a sweep-and-prune [24] algorithm is employed for simulation of cable assembly operations. Most of the above approaches are developed for simulation of cloth or hair and are used for aesthetic appeal where missed collisions are not very critical, while in suturing simulation, missed self-collisions can lead to loss of the knot. The key here is to simulate simultaneous collision of thread segments accurately.

In this paper, we present an algorithm for robust handling of self-collision, which can be applied for general edge-edge collision, based on simple distance calculation between line segments. The method is conducive to early elimination of collision and the data from collision detection can be used to handle collision response. The time-to-collision can be easily derived. Furthermore, we extend the concept to triangle-point collision to handle the piercing (or puncturing) of the surgical needle through the penrose drain.

Knot tying is an essential component in suturing simulation [5,6,8–12]. Knot identification is useful to evaluate the quality of the suturing operation, for instance, double-throw knot (square knot) is often considered to be more secure than a single-throw knot. For some surgical suturing training programs [3], the skill of tying certain types of knots is usually required to be mastered. The user must be allowed to commit errors including incorrect knots or missed knots. Considering that collisions need to be updated at haptic rendering rates, the knot detection routine must be performed in real-time as well. Existing methods [5,25] identify a knot using the knot theory, where a knot needs to be tied up first and frozen for evaluation of its topology. In knot theory [26], a knot is topologically represented by projecting onto a plane and labeling the crossing order in the planar diagram. For the same knot, choosing different planes can lead to different planar diagrams, though those planar diagrams may be reached from one another based on a sequence of three manipulations known as the Reidemeister moves [27]. Moreover, incorrect result may be generated by this method in the case of multiple crossings projecting to the same point in the diagram [5].

In this work, we propose a novel projection-intersection based knot detection method, which can interactively evaluate the validity of a knot on the basis of **two criteria**: (1) *closed loop around the tool*; (2) *loop penetration*. Different types of knot (e.g., single-throw or double-throw) can be identified using the same criteria. During the knot tying process, these two criteria are checked respectively using simple projection and intersection tests, and a knot can be detected when both criteria are satisfied. The basic idea is as follows.

To identify if there exists a closed thread loop around the tool, the thread line segments are projected onto a plane that is perpendicular to

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