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A modular extreme learning machine with linguistic interpreter and accelerated chaotic distributor for evaluating the safety of robot maneuvers in laparoscopic surgery

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ABSTRACT

In this investigation, a systematic sequential intelligent system is proposed to provide the surgeon with an estimation of the state of the tool-tissue interaction force in laparoscopic surgery. To train the proposed intelligent system, a 3D model of an in vivo porcine liver was built for different probing tasks. To capture the required knowledge, three different geometric features, i.e. Y displacement of the nodes on the upper surface and slopes on the closest node to the deforming area of the upper edge in both X–Y and Z–Y planes, were extracted experimentally. The numerical simulations are conducted in three independent successive stages. At the first step, a well-known partition-based clustering technique called accelerated chaotic particle swarm optimization (ACPSO) is used to cluster the information of database into a number of partitions. Thereafter, a modular extreme learning machine (M-ELM) is used to model the characteristics of each cluster. Finally, the output of M-ELM is fed to a Mamdani fuzzy inference system (MFIS) to interpret the safety of robot maneuvers in laparoscopic surgery. The proposed intelligent framework is used for real-time applications so that the surgeon can adjust the movements of the robot to avoid operational hazards. Based on a rigor comparative study, it is indicated that not only the proposed intelligent technique can effectively handle the considered problem but also is a reliable alternative to physical sensors and measurement tools.

1. Introduction

In robotic laparoscopic surgery, robots are used to move the laparoscopic instruments that are inserted into the body through small incisions. The movements of robots are controlled with the aid of a camera [1]. The robotic system comprises a master robot, a slave robot and a communication channel. Generally, the master robot has two different obligations: (1) receiving the movements from surgeons hand and (2) simulating the tool-tissue interaction forces on the surgeon's hand. The latter characteristic of master robot enables the surgeon to feel the tool-tissue reactions over the surgery. The second robot, known as the slave robot transfers the surgeon's motions to the surgery instruments working inside the patient's body. As a master-slave system, these two independent robots are connected by a communication channel. Indeed, this communication hardware provides a link between the surgeon and the surgery tools. During the operation, surgeons observe the slave robot movements through a 2D or 3D video system, and discern the next motions of the robot. Fig. 1 depicts the block diagram of a robotic laparoscopic system.

Robotic laparoscopic surgery has several prominent advantages. The most salient assets of laparoscopic surgery are:

(1) The use of robot which in turn causes less damages and hazards by filtering the sudden movements as well as vibrations of the surgeon's hand.
(2) Fast recovery and low risk of complications such as infection.
(3) Using small incisions for surgery which in turn decreases the damages to the patient's body.
(4) Reducing the need for repeated surgery [2].

In spite of the abovementioned benefits, in most of the robotic laparoscopic surgery systems, the surgeon does not have any tactile perception, and thus cannot evaluate the tool-tissue force [3]. This is while it is crucial to surgeons to have a sense from tool-tissue interactions to verify the exerted forces on patient's tissues by the grasper. One way to address this problem is using sensorized tools to measure the forces directly which will be then recreated at the master robot using a force control scheme. However, due to the size

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0925-2312/

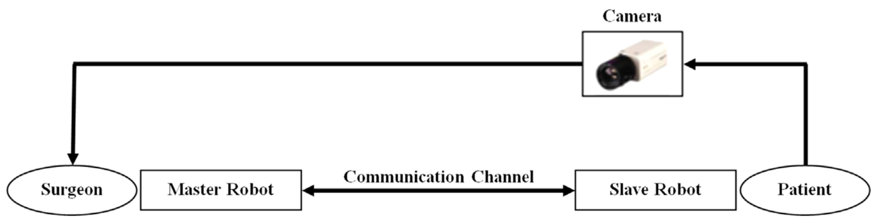

Fig. 1. The block-diagram of a robotic laparoscopic system.

and sterilizability requirements, design of such intricate sensors with high SNR is challenging [4].

The second way is to contrive proper algorithmic numerical methods to estimate/evaluate the tool-tissue forces based on visual data. In such frameworks, for instance, some geometric features are extracted from the real-time images taken from the surgery site. Those pieces of information are then used to develop numerical physic-based or soft models. Once the model is prepared, it can be used for estimating the tool-tissue interaction forces.

The physic-based nonlinear modeling of soft tissues and numerical methods such as boundary element and finite element (FE) are widely used to provide precise pragmatic estimators. Tirehdast et al. [2] used a nonlinear FE method to investigate the tissue deformation and sliding occurrence between a three-fingered grasper and human spleen. Basafa and Farahmand [5] simulated the nonlinear visco-elastic deformations of soft tissue for real-time applications. Miller [6] used FE approach to develop a model of brain tissue to be used in surgical procedure. The numerical results were compared with analytical solutions to ensure the validity of solutions obtained by FE. Nienhuys and Van Der Stappen [7] used an adaptive version of FE technique and quasi-static stick slip friction concept for simulating needle-tissue interactions over the surgery. By further exploration of archived literature, it can be easily seen that numerical modeling methods such as FE were widely used in medical robotic to model different types of tool-tissue interactions. However, although such models yield relatively precise results, their practical applications are still limited due to the expensive and time consuming computational requirements. In fact, such techniques cannot be used for real-time applications unless several simplifications are exerted on their structure which in turn reduce their precision [4,8].

The need for fast and inexpensive computational techniques persuaded the researchers of medical robotic society to take the advantages of computational intelligence (CI) and surrogate expert systems. Generally, intelligent approaches have the following advantages as compared to numerical approaches such as FE:

(1) Their training does not require any knowledge about the physics of the problem.
(2) They are really inexpensive computational approaches. There is neither a need for discretizing the solution domain nor solving a system of equations. Rather, they combine a set of soft computational units (rules in fuzzy systems and neurons in neural network) to model any nonlinear system.
(3) They are suited for real-time applications and incremental learning. This feature enables the experts to use the experimental feedbacks to retrain or refine the structure of such modeling approaches over time. This is while using adaptive FE methods significantly increases the algorithmic complexity and computational time.

Despite such prominent advantages, CI modeling techniques have not found their real reputation in medical robotic applications such as laparoscopic surgery. There are relatively few seminal researches in literature trying to confirm the applicability of CI techniques in laparoscopic surgery. Gholipour et al. [9] used artificial neural network (ANN) to identify the conversion of laparoscopic cholecystectomy to open surgery. Their experiments demonstrated that neural modeling can yield reliable predictive results based on the preoperative health characteristics of patients. Greminger and Nelson [10] used a neural network together with images of an elastic rubber torus deformed under compressive load to estimate the applied force over the laparoscopic surgery. After experiments, they observed that the soft modeling tool can effectively identify the tool-tissue force. Becker et al. [11] fused the fuzzy and neural computational principles to develop a mapping scheme suitable for evaluating pneumoperitoneum in laparoscopic surgery. Their findings endorse the better performance of neuro-fuzzy modeling tool as compared to statistical methods. Estebanez et al. [12] used ANN and hidden Markov models to recognize the movements of two-arm-surgical robotic system for laparoscopic surgery. The simulation results revealed that the developed intelligent model is capable of correctly recognizing and distinguishing certain standard surgical maneuvers. Kohani et al. [4] utilized a feed forward neural network and geometrical features obtain from 2D images to estimate the tool-tissue force in laparoscopic surgery. Mozaffari et al. [13] proposed two hybrid neuro-evolutionary fuzzy systems and a synchronous self-learning hyper level supervisor to identify the tool-tissue force in laparoscopic surgery.

In spite of novelty and practical innovations in all abovementioned proposals, CI techniques have not been used for automate decision making over the procedure. To be more to the point, identification of interactions between surgery instruments and patient issues may not always be interpretable for surgeon. To tackle the problem, it is really essential to use a consequent linguistic inference soft method which helps the surgeon to conveniently evaluate the quality of operation. However, to the best knowledge of the authors, such requirement was not clearly fulfilled. In a preliminary research by Huang et al. [14], the potential of fuzzy classifier for evaluating the possibility of classifying skill levels was examined. To do so, some scoring metrics such as the number of errors made and the economy of movement were taken into account. Different operators, i.e. laparoscopic surgeons, surgical assistance and non-surgical staffs were assigned to perform certain operations by robots. The results were not so promising. Based on experiments, the authors reported that their effort for developing an expert system capable of providing a qualitative feedback from the operation did not yield reliable and conclusive results. They stated a number of reasons, and outlined some areas for future works to augment the reliability of their expert system. In a seminal research, Feng et al. [15] developed a fuzzy based decision making expert system to help the surgeon to assess the success of operation. However, on that research, micro sensors were used to provide information for fuzzy inference system (FIS). Therefore, the methodology proposed by Feng et al. [16] may not be a deliberate strategy for all types of minimum invasive surgery. In this investigation, instead of using physical micro sensors, an efficient neural modeling technique (as a data-driven soft sensor) is taken into account.

The proposed expert system in this paper has two main obligations, i.e. tool-tissue force estimation and linguistic interpretation. Although the first objective, i.e. soft modeling, was addressed before, there is no effort for increasing the training speed of the existing soft techniques. This is while contriving fast and reliable