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A Novel Modeling Approach for Collision Avoidance in Robotic Surgery

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Abstract: We present a new system that can be used in combination with an array of ultrasonic piezoelectric sensors and has application in surgical navigation procedures. Using the proposed assembly, the maneuverability of the surgical tools can be enhanced and the incidence of potentially damaging contact with non-target tissue can be reduced. The emphasis of our work was based on controlling the motion of the surgical tools so that they can readily move around a biological tissue. According to the results of the simulation performed, the direction of the tool can be monitored and controlled continuously and hence the outcome of the surgery can be improved. Another important parameter that incorporated in the simulation was the distance between the tool and the tissue. The simulation results show that the proper control of the tool movement can keep the distance between the two at a certain predetermined value while the tool passing by the tissue. In the collision avoidance scheme, the transducers located on the lateral side of the surgical tool mainly act as the distance detector to keep the distance between the lateral surface of the tool and the tissue surface at a constant value of 5 mm.

Keywords: Navigation, Ultrasonic Transducers, Minimally Invasive Surgery, Robotics

INTRODUCTION

Minimally invasive surgery (MIS) is now being widely used as one of the most preferred choices for various types of operations[1, 2, 3, 4, 5]. In MIS, any inhibitions on the surgeon's sensory abilities might lead to undesirable results[6, 7, 8, 9]. MIS has many advantages; however, it decreases the sensory perception of the surgeon and the surgeon might accidentally cut or incur damage to some of the tissues[10, 11, 12, 13]. This effect is more pronounced when the surgeon approaches a target tissue while moving past other healthy tissues. This could happen during grasping or manipulation of biological tissues such as veins, arteries, bones, etc.[14, 15, 16, 17]. Therefore, tracking of instruments during a surgical operation is being used more and more frequently to increase precision, reduce the risk of injury, plan optimal access routes preoperatively, find and follow the instruments intraoperatively, and finally, to increase the quality of interventional procedures [18, 19]. In certain areas of MIS, such as neurosurgery, the procedure is already well established, whereas in other procedures, such as laparoscopy or other endoscopic surgeries, the research activities are very limited[20, 21, 22, 23].

In navigation protocols, because the precision required is extremely high, the costs of such systems are too high and restrictive for broad use[24, 25, 26, 27]. In MIS, both the tactile sensing and the visual capabilities of the operators are very restricted. Accidental cutting of tissues while maneuvering in human body is a common unfortunate outcome during minimally access surgical procedures[28, 29]. One solution to this problem is to use robotic arms to perform the tasks that required precision and repeatability[30, 31, 32, 33]. However, even by incorporating surgical tools on these artificial arms, we encounter some serious problems. Among these are the lack of ability to avoid the obstacles and accidental damaging of the biological tissues while moving towards the aimed tissues, which are both major impediments.

In order to make various MIS procedures safer, the maneuverability of the surgical tools should be enhanced. In this regard, controlling the motion of the

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surgical tools so that they can readily move around a biological tissue is of great importance. Both the speed of the tool and its direction can be monitored in this way. Another parameter is the distance between the tool and the tissue that is not the target tissue but is located in the way and acts as an obstacle. Proper control of the movement can keep the distance between the two at a certain predetermined value while the tool is passing by the non-target tissue. The combined effects of these two maneuver capabilities can greatly improve the outcome of the surgeries.

The sensitive structures of the lateral skull base demand for robotic procedures since a higher precision than provided by standard navigation systems is required. A report has been published in which a multisensor approach was used to improve accuracy in the use of ultrasound for local navigation[34]. In this study, they compared two different ultrasound techniques to measure human skull bone in vitro: a classic echo technique and a combination of coded excitation and matched filter.

Conventional imaging and navigation during intravascular intervention employ fluoroscopic positioning of intracoronary devices[35]. It may also include intravascular ultrasound, allowing two-dimensional slice visualization of blood vessels for enhanced imaging, diagnosis, and stent placement. In this work, the focus is on the use of an innovative 3D imaging system, as well as stent placement using a new non-fluoroscopic, intra-coronary positioning system. They used a miniaturized sensor that might be assembled on tips of various catheters (such as stent delivery system) and provides accurate real-time position and orientation, enabling real-time tracking of a catheter tip in 3D space. The designed system allows accurate computer-assisted stent navigation and deployment. Their system is a promising new method that can be used to improve ease and accuracy of stent/device placement during intravascular interventions.

Advances in the basic scientific research within the field of computer assisted oral and maxillofacial surgery have enabled scientists to introduce features of these techniques into routine clinical practice[36]. During these types of surgeries, instrument navigation tools offer the surgeon interactive support through operation guidance and control of potential dangers. In this report, potential intraoperative assistance systems are discussed. They predict that in the near future, it is the surgical robots which will execute specific steps completely autonomously.

The goal of another study was to adapt an augmented reality system to work next to a MR scanner and to test its use as a navigation tool for MRI-guided needle biopsies[37]. A tracking camera measures the viewer's position and orientation in relation to a set of optical markers on the MRI table. The needle depth was within the target phantoms in 11 biopsies and 9 biopsies showed a slight deviation with a mean distance to the edge of the target slice of 1.5 mm.

Computer-aided surgical navigation technology is also commonly used in craniomaxillofacial surgery[38]. It offers substantial improvement regarding esthetic and functional aspects in a range of surgical procedures. In augmented reality principles, where the real operative site is merged with computer generated graphic information, computer-aided navigation systems are employed, among other procedures. The applications are reported to be in dental implantology, arthroscopy of the temporomandibular joint, osteotomies, distraction osteogenesis, image guided biopsies, and removals of foreign bodies.

Tracking down the tools is equally important in the field of virtual reality and haptics (force-feedback) for medical applications[39]. In this research, visualization techniques have been developed for medical images from various sources together with a high-performance haptic interface. Here, they presented a technique that combines visualization with haptic rendering to provide real-time assistance to medical gestures. In fact, they have developed a system that provides haptic feedback to the surgeon using patient specific data. During the biopsy, haptic feedback is used to first help the surgeon to find the target and to define the optimal trajectory, then to physically guide the surgical gesture along the chosen path.

Based on the above facts, we propose the use of an array of ultrasonic piezoelectric sensors mounted on a surgical tool in biomedical navigation procedures. As this tool approaches a biological tissue, it can manipulate the movement of the tool in the vicinity of the biological tissue, using a tailored-made control system.

MATERIALS AND METHODS

The whole procedure of the navigation is schematically shown in Fig. 1. At first, the transducer detects a biological tissue (or an obstacle of some sort) within a distance of about 10 mm. Following this, the surgical tool that is incorporated into a robotic arm can vary its speed, and change direction until the right (or left) transducer detects the tissue. Then, it goes straight for one step while measuring the distance on a continuous basis. If the distance is on the verge of increasing, then in the next step, the tool will move on with a little change in direction. That is, it turns left when the distance becomes shorter or turns right when the distance becomes longer. When the signal of the lateral transducer disappears, the tool stops and adjusts its direction only until the signal appears again.

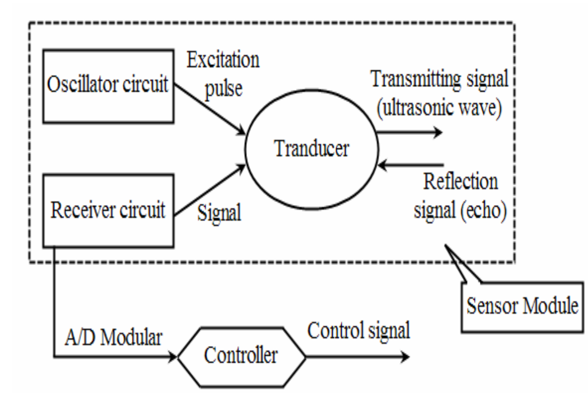

Fig. 1: Schematic representation of the navigation process.

During the above maneuver, a microprocessor records and computes the changes of the position of the tool. When the accumulated changes are coincident with the direction of the original path, the surgical tool will move around the tissue (if necessary) and will resume its normal route.

Different types of sensors were considered for this application, including PZT-5A, PVDF, and quartz. It is known that PZT-5A has a very large value for d3n, however, these kinds of ceramic transducers are fragile and it is very difficult to produce them in large sizes. Further, these piezoelectric materials have relatively high acoustic impedance. This means that they would require complex damping and matching techniques to induce broadband signals. PVDF-based piezoelectric sensors also have a relatively large value of piezoelectric coefficient and stress coefficient. Consequently, considering the economic factors and the suitability of PVDF-based sensors for biomedical applications, we selected PVDF as the material of the transducer. The relevant properties of the PVDF used are summarized in Table 1. Based on the data presented in Table 1, the performance characteristic equation of the transducer can be presented by $\Delta t = d_{33} \times V$, where Δt is the displacement of the PVDF transducer in the thickness direction, d_{33} is the strain coefficient of the PVDF, and V is the applied voltage to the oscillator circuit. The transducer configuration is shown in Fig. 2.

Table 1: Material specifications of PVDF.

Piezoelectric Coefficients				**Young's Modulus (GPa)**	
d-form (pC/N)		g-form (Vm/N)		E_x	2.25
d_{31}	20	g_{31}	0.15		
d_{32}	2	g_{32}	0.015	E_y	2.20
d_{33}	-20	g_{33}	-0.15		

To reach a practical value for Δt, a high voltage is required. In our design, the transducer is built from a number of thin individual elements, electrically connected in parallel. As a result of this, operating voltages around 100~200 V can be attained. The transducer is made up of five stacks of PVDF films, which are connected with electrodes. We have $\Delta t_{max} = 5\times d_{33}\times V_{max} = 3.3\times10^{-8}$ m. Here, the excitation voltage amplitude is $V_{max} = 200$ V.

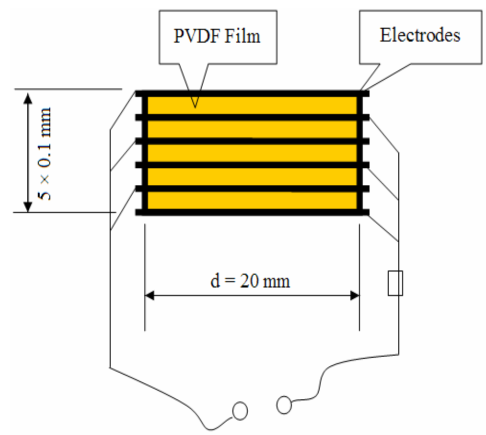

Fig. 2: Transducer configuration.

The performance of the sensor assembly has been previously reported by the authors elsewhere and proven to be effective in other similar applications[5]. For a typical surgical tool, such as a grasper used in endoscopic surgery, our calculations show that an assembly of five separate sensors would suffice for the purpose of this task. Our suggested method is presented in Fig. 3. The middle three transducers are used for detecting tissue in front of the grasper. After the transducers receive the echo signal, the tool changes direction to move around the obstacle's surface. Here, the surgical tool can be connected to a robotic arm by which the movement of it (both speed and direction) can be readily controlled.

During the collision avoidance (see Fig. 3), the lateral transducers work as the distance detector to keep the distance between the lateral surface of the tool and the transducer surface at 5 mm.

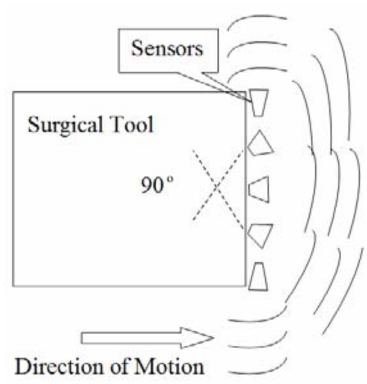

Fig. 3: Proposed sensor assembly on the surgical tool.

Based on the afore-mentioned assumptions, a thorough computer simulation was conducted using MATLAB (version 7.0) as the modeling tool and the feasibility of the proposed approach was tested. We defined a cycle time that is the interval time during which the transducer operates as a transmitter and as an echo receiver. It is composed of two periods: receiving time T_r and waiting time T_w. The measurement rate of the transducer is 10 Hz, hence, the cycle time is calculated to be 100 ms. The block diagram of the signal processing system is shown in Fig. 4 whereas the signal processing circuits and its composition are represented in Fig. 5.

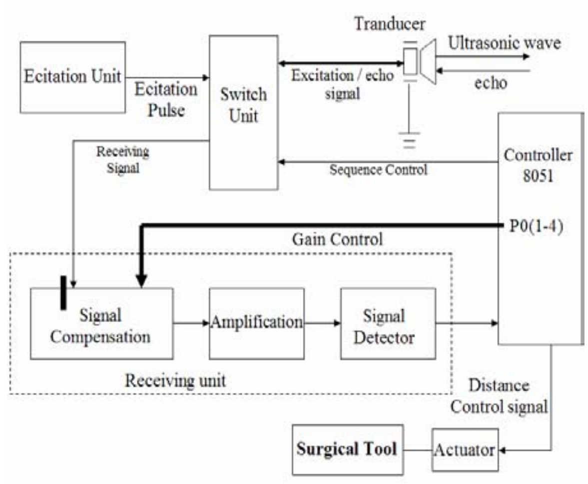

Fig. 4: Block diagram of the signal processing system.

The first main part of the circuit is the switch circuit. Because the transducers were used as both transmitters and receivers, we needed to switch the sensor to the excitation and signal amplifier, respectively. To achieve this, a transistor controlled by one of the I/O of 8051, drives a relay.

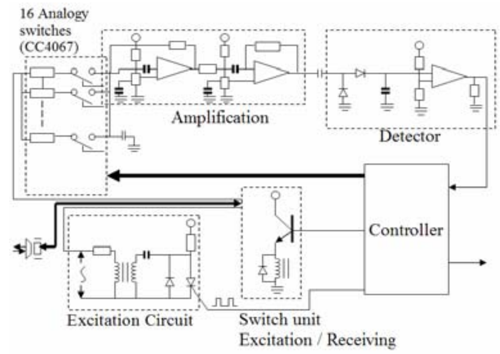

Fig. 5: Various circuits of the signal processing system.

The circuit processes both the ultrasonic wave and echo signals. The second part is the excitation pulse circuit. This circuit provides about 200 Vp-p 40 kHz pulse. One of the I/O of microprocessor 8051 was used as the source of 40 kHz signal pulse. Because we had designed the sensor with 200 Vp-p excitation pulse, the pulse generated by 8051 needed to be enhanced in both amplitude and power. Here, a pulse transformer is used and the capacitor is discharged into the primary winding of a transformer. From the secondary, the high voltage is drawn. The third main part of the circuit is the signal amplification circuits. Due to the energy loss during the sound wave propagation, we had to design a unit in the receiving circuit in order to compensate for this phenomenon. Energy loss was considered by taking into account the frequency and the reflection rates from different media. To accomplish this, we designed a dynamic compensation circuit (a gain-adjustable amplifier) to compensate for the energy loss during signal processing. The last main part of the circuit is the detector circuit. This circuit detects the received ultrasonic signal and is a half-wave rectification circuit with Schottky barrier diodes. The DC voltage, according to the level of the detection signal, is the output to the capacitor behind the diode. In the designed system, the 80C51 micro-controller software is used to complete the following functions: control the switch for transducer/receiver switching; provide a 40 kHz ultrasonic excitation pulse; provide the control sequence for the gain-adjustable amplifier; record the time of the ultrasonic traveling and compute the distance; record the coordinate position change of the surgical tool; and give the command for the tool movement.

RESULTS AND DISCUSSION

Using MATLAB software package (version 7.0), the dynamic simulation of the collision avoidance was conducted. The results of this simulation, which incorporated all the details presented in Fig. 5, are depicted in Fig. 6 in a chronological order.

To perform the simulation, a 2-dimensional environment was constructed and the movement of the surgical tool (shown by a rectangular block) towards the obstacle or tissue (shown by an arbitrary shape) is analyzed. The obstacle is initially located at an approximate coordinate of (X = 70 mm, Y = 20 mm). During the whole process, the obstacle remains stationary. The initial position of the surgical tool is (X = 20 mm, Y = 20 mm). As the simulation commences, the tool moves on a straight line towards the left-hand-side surface of the non-target obstacle or tissue. This path is represented by the dash line in Fig. 6. When the surgical tool is within a distance of 10 mm from the left surface of the obstacle, the array of ultrasonic sensors detects the presence of the obstacle. As a result of this, the tool slightly changes its direction to start performing the collision avoidance protocol. As shown in Fig. 6a, the surgical tool approaches the target and if it needs to avoid it or turn around it, our designed system can readily perform this task. When the surgical tool is within a 10 mm distance from the target tissue, the sensors located on the tool will detect the echo signal (Fig. 6b). Consequently, the surgical tool is moved to the left side of the biological tissue that is located in the way of the tool and should not be contacted with. The rest of the maneuver takes place while the tool is moved around the tissue (Fig. 6c to 6e). This occurs while the lateral transducer measures the distance between the lateral surface of the tissue and the tool. By performing this task, the distance between the tool and the tissue is kept at a constant value of 5 mm. As shown in Figure 6f, the surgical tool is returned to its original path immediately after it has passed the tissue. In our simulation, the preset distances can be changed according to the requirements of the particular maneuver.

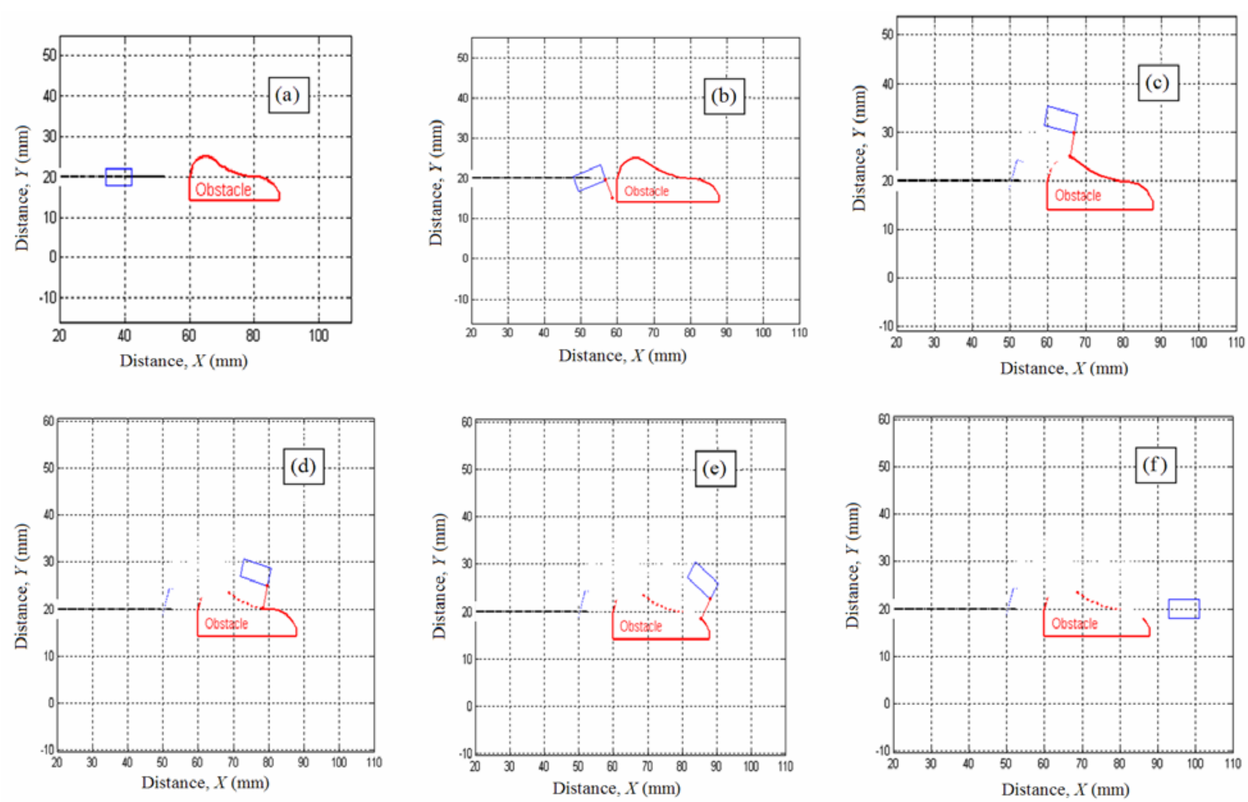

Fig. 6: Computer simulation results of the navigation process. (a) Surgical tool approaching the operating site (obstacle or biological tissue). (b) At a distance of 10 mm, the sensors detect the signal of the echo and the tool makes left turn. (c) to (e) Surgical tool is moving around the surface of the tissue, while the lateral transducer measures the distance between the lateral surface of the tissue and the tool and keeping the distance at 5 mm. (f) Surgical tool returns to its original path after avoiding the obstacle.

In order to improve the collision avoidance protocol, a 3-dimesional analysis can be performed with incorporating more details on various features of both the tool and the non-target biological tissue. Work is currently underway in our labs to address this particular issue.

CONCLUSION

It can be concluded that the designed system can be used in combination with an array of ultrasonic piezoelectric sensors in surgical navigation procedures. By doing this, the maneuverability of the surgical tools can be enhanced and the incidence of potentially damaging contact with non-target tissue can be reduced. The proper control of the tool movement can keep the distance between the two at a certain predetermined value while the tool is passing by the tissue.

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