ABSTRACT

This paper describes the design, analysis, and experimental validation of a novel minimally invasive instrument for lung tumor localization. The instrument end effector is a two-degree of freedom lung tissue palpator. It allows for optimal tissue palpation to increase useful sensor feedback by ensuring sensor contact, and prevents tissue damage by uniformly distributing pressure on the tissue. Finite element analysis was used to guide the design process, resulting in a final design that could achieve a factor of safety of 4 for a 20 N force acting on the end effector—the approximate weight of a human lung. Validation experiments were conducted on a prototype instrument to assess its articulation and load carrying capacity. The end effector design allows for the inclusion of ultrasound, tactile, and kinesthetic sensors. It is expected that this device will form the basis for robotics-assisted palpation and increase the likelihood of positive tumor localization.

INTRODUCTION

In traditional open thoracic surgery for lung cancer treatment, the surgeon feels the target tissue with a gloved hand. This approach allows the surgeon to characterize tissue by palpation—sensing the tactile and kinesthetic attributes of the target tissue with his or her fingers. An underlying tumor is identified by feeling a spheroid lump within the tissue, because tumors typically exhibit a higher stiffness than the surrounding healthy tissue.

Although avoiding open thoracic surgery offers numerous benefits to the patient, minimally invasive surgery (MIS) forces palpation to be done with instruments that are inherently difficult to use due to reversed instrument movement, a lack of direct vision, impaired kinesthetic force perception resulting from friction and elastic effects of the tissue at the trocar (entry port), and the complete loss of tactile perception [1].

A commonly used minimally invasive technique is to palpate the lung with a standard Babcock grasper in a jaws closed
position. With this instrument, the surgeon attempts to determine tissue stiffness by feeling the force exerted on the instrument handle, or by visually inspecting the characteristics of the tissue as seen through an endoscopic camera. In current robotics-assisted procedures the surgeon must rely on visual information alone since the master–slave system does not relate any haptic feedback. Experiments have shown that with limited feedback available, excessive palpation forces are often applied [2] and permanent tissue damage may result.

This paper presents a tissue palpation device designed with the goal of eliminating tissue damage and optimizing sensor feedback such that tumor localization accuracy and sensitivity approaches, and possibly outperforms, direct finger palpation. The design and a first prototype of this device are presented herein. The instrument has been designed similar to a Babcock grasper; however, it is not limited to handheld manipulation. By mounting the palpation device onto a surgical robot, many of the challenges of robotics-assisted MIS tumor localization may be addressed.

PRIOR WORK

To prevent damage to the target tissue, to decrease the time spent during an MIS procedure, and to help reliably localize a lung tumor, the most commonly used intraoperative technologies are kinesthetic feedback, tactile feedback, or ultrasound imaging.

If only kinesthetic, or bulk force, feedback is available, the number of injuries caused during palpation is reduced [3]. Examples of kinesthetic techniques include the use of force sensing resistors, strain gauges, force/torque sensors or measurement of the current drawn from a motor that controls the palpatating jaws of a grasper [4–7].

Tactile information relates to information about the surface and underlying structure of objects, as felt by our fingertips. This includes localized pressures, forces, and textures. In MIS applications, tactile feedback often pertains to a topographical pressure map of a localized region. The benefit of this technique is that more information can be extracted about the tissue that the sensor is in contact with, and any nonlinearities caused by indirect force measurement are eliminated [8]. Tactile feedback remains an area of active research. Many researchers have attempted to make tactile sensors for tumor localization in MIS that make use of piezoelectric sensors, resistive sensors, current sensors, optical sensors, and thin film sensors [9–12], while others rely on a variety of capacitive sensors produced by Pressure Profile Systems Inc. (PPS) [13–15].

Ultrasound imaging is an excellent way to detect the presence of a tumor, but a radiologist is required in the operating room to properly assess the ultrasound images. The use of ultrasound on a lung also requires the lung to be fully collapsed to prevent artifacts in the ultrasound signal.

Devices that fuse information from different sources include one made by Miller et al. [14]. It uses a PPS capacitive sensor that can slide over the surface of a target tissue and overlay the pressure distribution on the operating video feed. A limitation of their study is that the experiments were performed with tissue on a rigid surface, which is dissimilar to the soft tissues that exist in a human body. Their device does not have the ability to grasp tissue.

Methil et al. constructed a device for teleoperated breast examinations [16]. The device included two sensing modalities, tactile and ultrasound, and also provided haptic feedback. They claim that the mechatronics-assisted palpations may actually outperform a physician’s own hand. Although not suitable for MIS, the increased modalities are an attractive option to pursue, due to the possible increase of tumor detection performance.

Tholey et al. developed an automatic palpation function for instrument validation experiments to eliminate variability in the results [17]. Their experiments used equally-sized tissue phantoms that were palpated for exactly 10 seconds in the same physical manner each time.

These state-of-the-art designs for lung tumor localization devices have intrinsic limitations in their use for tumor localization in MIS. This paper presents a novel device that addresses these shortcomings.

INSTRUMENT DESIGN

A handheld laparoscopic minimally invasive tumor localization device designed to accommodate multiple sensing modalities is presented in this section. The goal of the device is to accurately locate tumors through a process of data fusion, combining tactile, kinesthetic and ultrasound information in a manner that is easily understandable, reduces the chance of false positive or false negative results, and strives to eliminate the necessity of a radiologist on site through intuitive sensor feedback display.

Requirements

The main requirements for the instrument include: a maximum outer diameter of 12 mm, being capable of manipulating and palpating a lung of varying cross sections and shapes up to 50 mm thick, facilitating the use of multiple sensing modalities (kinesthetic, tactile, and ultrasound), allowing for adjustment of the end effector angle with respect to the handle, and intuitive operation. To achieve these requirements, a grasper-type instrument was envisioned, with an ultrasound transducer on one jaw, and a tactile sensor on the other. The dimensions of the end effector and total instrument length were modeled after an Ethicon Echelon Flex 60 articulating linear cutter following a recommendation from an expert in the field of minimally invasive thoracoscopic surgery. As such, in addition to fitting through a 12 mm diameter trocar, the shaft length was specified to be 400 mm and the instrument jaws were designed to be 90 mm long.

The design was required to support a human lung, which can exert a force of approximately 20 N when maneuvered in sections, as is standard practice. Dynamic load cases were not considered because the device would be used in a quasi-static manner.
Sensing
The inclusion of multiple sensing modalities can increase the likelihood of tumor detection. Previous tumor localization experiments using a tactile sensor from PPS have demonstrated that tumor localization accuracy can be increased by systematically applying constant force across the tissue [18]. Ultrasound, which is currently used for intraoperative tumor localization, was chosen as a sensing means to be coupled with tactile sensing, along with force sensing using strain gauges on the jaw linkages. The purpose of the strain gauges is to determine a more accurate bulk force measurement that can be measured by the tactile sensor. When compared to using the sensing modalities separately, it is hypothesized that the simultaneous use of these complementary sensors should be able to provide a better understanding of the palpated tissue. As discussed in the next section, the instrument jaws must be designed to accommodate the selected sensors: a custom capacitive-array based tactile sensor from PPS, strain gauges, and a custom ultrasound transducer from Blatek, Inc.

Mechanical Design
The focus of the design was primarily on the end effector. For the best sensor readings from both tactile and ultrasound sensors, the sensors should be in contact with the tissue over as much of the sensing surface as possible. Since different lungs are of different shapes, the device must be able to adapt to different contact profiles. A two degree of freedom (DOF) design was developed adhering to the restrictions stated previously, allowing the jaws to adapt to a variety of tissue geometries, while remaining compact. The design uses coupled scissor-like jaws that can palpate both varying thickness, and varying inline angle (Fig. 1). Coupling minimizes the number of actuating mechanisms and saves space to make room for sensor cabling. The use of a grasper design guarantees that the tactile sensor always palpates tissue that is supported by a rigid backing. This increases the repeatability of measurements.

DC servo gear motors from Maxon Precision Motors Inc., model 283856, coupled with EPOS controllers using a proportional integral derivative (PID) control scheme, were selected to actuate the instrument jaws. Cables were used for actuation of the end effector, allowing the motor and drive components to be located in the instrument handle. The cables were attached to sliding mechanisms (Joints 1 and 6, sliding along the x-axis in Fig. 2), and were routed such that the sliders could be moved both forward and backward.

In general, all joints form triangles, and the symbol convention used for angles is $\theta$, with subscripts indicating the joints on the opposite side of the triangle. Thus, for the triangle defined by Joints 1, 2, and 3, the angle formed at the corner of Joint 1 is labeled $\theta_{23}$. The only exception to this rule is $\theta_6$, which is measured from the x-axis to the linkage joining Joints 5 and 6. Lengths are defined between two joints, and use the symbol $l$. Since each linkage is used as a vector, the subscripts indicate where the vector starts and ends. For example, the length vector defined between Joints 4 and 6 is labeled $\vec{l}_{46}$. The triangle formed by Joints 2, 3, and 4 is one solid linkage with three joints. All other linkages have only two joints, with the exception of linkage 5–7–8, where Joint 7 is immovable, and the unlabelled $\theta_{58}$ is a constant 90 degrees.

Minimizing the overall end effector size forced the load bearing areas to be supported by small components, which subsequently increased the material stresses. All moving parts were designed to fold around each other to minimize frontal cross section and high manufacturing tolerances for the parts ensured maximum stiffness of the assembly.

A number of properties were considered in material selection, including corrosion resistance and the ability to be sterilized. Following a review of existing instruments, stainless steel
was selected. Since the grasper should not permanently deform, the material stresses should not surpass the material yield strength [19]. Initial simulations of the end effector were carried out to determine stresses in the linkages and jaws, and to find the resultant forces on the pin joints. SolidWorks Simulation 2010 was used for all finite element analysis (FEA) cases. Fig. 3 shows the general load cases studied in one particular end effector position. Various positions were studied to determine material stresses under the worst-case load configurations.

Both jaws were designed differently to include custom-made tactile and ultrasound sensors. As such, the jaws were designed to route all electrical cabling from the end effector sensors to the proximal end of the device. This forced material thickness down, and because the jaws are the primary load-carrying component, they are prone to the highest material stresses. Under the presented load cases, the material had a Factor of Safety (FOS) of 1, with a yield strength of 448 MPa (Fig. 4). Heat treatments were carried out on the selected 440C alloy and proved that an FOS of 4 was attainable with an experimentally-achieved yield strength of 1650 MPa. The developed device is shown in Fig. 5. On the proximal end is the instrument handle, which includes the actuating motors for end effector movement, motor control electronics, and a mechanism to twist the end effector relative to the handle. On the distal end is the closed 2 DOF end effector, comprised of two articulating jaws. The instrument shaft is 400 mm long and 12 mm in diameter, similar to a laparoscopic stapler. While the custom sensors are under development, a demonstrative control system was implemented to prove the utility of the 2 DOF grasper and that an automatic palpation method is possible.

**INSTRUMENT CONTROL**

Due to symmetry, the control system only models half of the designed end effector. Symmetric movement was deemed appropriate because of the compliance of the tissue, which can deform to the jaw faces in varying configurations. With 2 DOF, the desired grasper position is based on the thickness of palpation, $t_d$, measured from the axis of the cylindrical instrument shaft perpendicularly to the mid-point of the jaw length, and the angle of palpation, $\theta_d$, measured from the axis of the cylindrical instrument shaft to the surface of either palpation jaw (Fig. 2).

In operation, it is desirable to have the palpation thickness, $t_d$, and palpation angle, $\theta_d$, move linearly from current to desired values. The approach used was a continuous point-to-point motion. Though kinematically coupled, the thickness and angle were treated separately in the presented approach. Between the current thickness and angle of palpation, and the desired thickness and angle, the path was broken down into multiple linear segments to reduce the computational burden as compared to solving the linear movement of the end effector and subsequent motion profiles of the actuating sliding linkages driven by motors in the proximal end of the instrument.

In order to set a desired value for the jaw position, it is required that, in the case that a position is not kinematically possible, the jaw should move to the closest possible position. This is a necessity when used with sensor feedback. If the implemented control system were to provide a position that is impossible to
reach due to the jaw geometry, the program running the system could freeze, or the grasper might experience lock-up or failure.

Using inverse kinematics equations, shown in Eqns. (1) and (2), the workspace of different possible thicknesses and angles was determined and mapped to a two-dimensional binary image: colored white where the end effector position is possible, and black where the position is not possible (Fig. 6). Input variables $t_d$ and $\theta_d$ are included within angles $\theta_{64}$ and $\theta_6$, respectively, the basic trigonometric proof for which is not shown. The variables in Eqns. (1) through (4) refer to those shown in Fig. 2. Variables $\vec{l}_{31}$ and $\vec{l}_{36}$ physically refer to sliding mechanisms that actuate the end effectors jaw movement. Forward kinematics equations (3) and (4) were used to determine the end effectors actual motion profile versus its desired motion profile when simulating the proposed continuous point-to-point scheme using Matlab and examining the effects of path discretization.

\[
\vec{l}_{31}^* = \frac{|\vec{l}_{12}| \sin(\theta_{13})}{\sin(\pi - \theta_{34} - \theta_{64})} \tag{1}
\]

\[
|\vec{l}_{36}| = |\vec{l}_{34}| \cos(\theta_{64}) + |\vec{l}_{45}| \cos(\theta_6) - |\vec{l}_{65}| \cos(\theta_6) \tag{2}
\]

\[
\theta_d = \tan^{-1} \left( \frac{|\vec{l}_{65}| \sin(\theta_6) - |\vec{l}_{34}| \sin(\theta_{64})}{|\vec{l}_{36}| + |\vec{l}_{65}| \cos(\theta_6) - |\vec{l}_{34}| \cos(\theta_{64})} \right) \tag{3}
\]

\[
t_d = |\vec{l}_{65}| \cos(\theta_6) + |\vec{l}_{57}| \sin\left(\theta_d - \frac{\pi}{2}\right) - |\vec{l}_{78}| \sin(\theta_d) \tag{4}
\]

By providing the desired thickness and angle and then converting them into their associated pixel values, the image is used essentially as a lookup table of kinematically possible positions. If the desired location is within the workspace, then the chosen location is selected as the one with the smallest pixel distance to the desired location, as shown in a general workspace, Fig. 7.

To demonstrate the proposed control system, two force sensing resistors (FSR) mounted to one of the end effector jaws were used to obtain data related to the total force of palpation and the angle of palpation. This served as a temporary solution to approximate the feedback from a tactile sensor, while still proving the usability of the design.

The control scheme consisted of two independent proportional controllers (P controllers): one for palpation thickness control, and one for palpation angle control. Two FSRs were required in order to interpret the angle of palpation. The thickness controller’s reading was calculated by averaging both FSR values. The result was then scaled and interpreted as a required change in palpation thickness. The angle controller’s reading was determined by calculating the difference between the two FSR readings. The result was scaled and interpreted as a required change in palpation angle. By combining the two P controllers simultaneously, the palpator jaw was able to conform to approximately flat surfaces.

To demonstrate the designed automatic palpation process, a flexible plastic beam was used to palpate against. The manner of the beam’s deformation shows that the system is robust and can work around changing object geometries. Similarly, lung tissue has some flexibility. During testing, the palpator jaw with the mounted sensors moved such that it was always flat against the beam, whether the beam pushed hard against the jaw, increasing the palpation force above the desired value, or was completely removed, forcing the jaw to slowly close until it made contact once again with the beam. Fig. 8 shows this process—from top to bottom, the plastic beam is inserted between the jaws until the beam position changes and only touches one of the FSRs, the jaw
pose changes once again such that both FSRs touch the beam. It is also noted that it was impossible to back-drive the motors by pushing or pulling on the jaw. All movement was completely sensor driven.

VALIDATION

A number of experiments were performed to validate the workspace of the mechanism and test its load carrying capacity in comparison to the FEA results. The first design assessment considered the general motion of the device and the comparison of the real workspace to the workspace as modeled in SolidWorks 2010. It was observed that the instrument was able to reach all theoretical limits. Since the grasper was designed to separate its jaws wider than necessary, an extensive workspace evaluation was not performed.

To validate the grasper’s load carrying capacity, an experiment was set up to move the jaws through a number of different positions with a varying applied load. The test setup is shown in Fig. 9. The force against the jaws was increased in 1 N increments. Although the instrument was designed for loads up to 20 N, applied forces were limited to 10 N because the presented prototype was not heat treated. In addition to the configuration shown in Fig. 9, the capability to hold a 10 N load side to side was also tested. Although no permanent deformation occurred in this configuration, it is noted that due to the deformation of the loaded jaws and linkages, it was not possible to open and close the jaws (Fig. 10).
DISCUSSION AND CONCLUSIONS

This project describes the design and development of a novel minimally invasive lung tumor localization device. Its purpose is to surpass the performance of present laparoscopic devices and approach the capabilities of the human finger without the need for open surgery. To do so, the device is designed to incorporate the use of multiple sensing modalities, and uses a novel mechanical linkage for optimal tissue palpation. Also presented is a proof-of-concept for a control scheme to improve palpation over surgeon-controlled palpation.

The use of multiple sensors in a minimally invasive lung tumor palpation device is an idea that has not yet been fully tested. The design is made to include an ultrasound transducer and a tactile sensor. Combining these two technologies increases the available information on the tissue and underlying features. Considering the two orthogonal imaging planes, it is reasonable to assume that a three dimensional model of the subsurface tissue can be created using data fusion techniques. In addition to the aforementioned sensors, the device may also make use of kinesthetic force feedback sensors mounted on linkages of the grasper mechanism. These sensors would be intended for more accurate bulk force measurement over the palpated region than can be achieved with the tactile sensor alone. Relatedly, the device can make use of robotics-assisted palpation with the mounted sensors for increased tumor localization results and decreased tissue damage. A proof of concept control system using two force sensing resistors shows the practicality of such an idea by automatically conforming to approximately flat surfaces in varying orientations.

In traditional grasper-based minimally invasive palpating designs, only one degree of freedom is used. This severely limits the palpable regions of tissue. The 2 DOF design presented herein allows for varying geometries of tissue to be palpated, presenting two benefits. The first is that a large portion of the imaging sensor surfaces can be used since they have the ability to align themselves tangentially to the tissue. The second is that uniform pressure can be applied to the tissue, improving imaging and preventing damage. Furthermore, being made from a stainless steel alloy, the design is completely sterilizable, it meets the physical design parameters, can manoeuvre loads of 10 N, and can achieve a FOS of 4 to yield if heat treated. To increase the usefulness of the overall device, a redesigned instrument handle could benefit from including haptic feedback based on the sensor readings of the end effector. This could give the surgeon an idea of the feel of the palpated tissue which could further increase tumor localization likelihood.

Future work involves the integration of custom designed tactile and ultrasound sensors into the instrument jaws. A position-tracking sensor built into the device will allow individual palpation events (tactile sensor maps and ultrasound images) to be registered with others, enabling accurate models of large tissue volumes to be created. The control system and operator interface will be refined to enhance the ease and robustness of automated tissue palpation.

ACKNOWLEDGMENT

This research was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under grants 312383-05 and 312383-2010, the MITACS Accelerate Program, and by infrastructure grants from the Canada Foundation for Innovation awarded to the London Health Sciences Centre (Canadian Surgical Technologies & Advanced Robotics (CSTAR)) and to The University of Western Ontario. Financial support for Ms. Trejos has been provided by NSERC through an Alexander Graham Bell Canada Graduate Scholarship.

The assistance of Kevin Barker at University Machine Services is gratefully acknowledged, as well as advice from Dr. Shaun Salisbury, Dr. Jeff Wood, and Dr. Pawel Kurowski from the University of Western Ontario.

REFERENCES


