Issues and Design Concepts in Endoscopic Extenders

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Abstract. Endoscopic surgery as a less invasive method of surgery, is more difficult to perform. The associated problems are visual issues, hand/tool's movement, and force/tactile sensing. To overcome some of these difficulties, in this paper new design concepts are reviewed and proposed such as tools with flexible stem, suturing device, positioning stand, and robotic endeffectors for master-slave systems.

Key Words. Master-slave systems, Endoscopy, Endoscopic tools/equipments, Flexible stem graspers, Suturing/sewing devices.

1. Introduction

Endoscopic surgery has been used widely in the past decade as an alternative to conventional open surgery and it is also gaining more grounds for other applications. This is due to many advantages such as:
– Shorter recovery time
– Decreased risk of infection
– Less pain/ trauma for the patient
– Reduction in hospital stay/cost
Generally, endoscopic surgery is a less invasive method of surgery which is performed by long surgical tools and endoscopes that are inserted through small hole incisions for reaching the surgical site. The main draw-backs of the current designs are that they are not able to *extend* all of the movements and sensory capabilities of the hand of the surgeon to the surgical site. Inherently, this method of surgery introduces many new problems when compared to the conventional open surgery. For example, some of these problems are:
– Indirect vision through endoscope and monitor, that is usually two dimensional without depth perception.
– Limited degrees of freedom of tools movement at the surgical site compared to open surgery.
– Very limited force/tactile sensing.
There have been many developments of new endoscopic extenders, vision systems, and a few robotic assisting devices (Nagy,*et al.*,1994; Rininsland,1993; Mitchell,*et al.*,1993). However there still remain a great deal of demand for research and development to answer some of the basic needs of the surgeon, such as flexible stem graspers, suturing devices, positioning stands, and robotic systems. In this paper, the main attempt is to examine issues related to endoscopic surgery and systematically specify the main problems. Then solutions and design concepts are proposed that facilitates the surgeon in performing his tasks.
In the following sections of this paper, first the issues and problems related to endoscopic surgery are discussed, then some of the design variations and concepts are provided as possible solutions for them.

2. Endoscopic issues and problems

There are basically three categories of endoscopic issues and problems: visual issues, hand/tool's movement, and force/tactile sensing, that are described in the following sections:

2.1. *Visual Issues*

Endoscopes are basically a video camera where the visual information is obtained through a long tube (about 10 mm in diameter and 300 mm in length). Two types of camera systems of direct and indirect designs can be used. In the direct type the CCD array is located at the tip of the tube and signals are transmitted through the tube, while in indirect system, the image is transmitted through the fiber optic or lenses to the other end of endoscope where the CCD camera is located. Both systems provide a clear field of view of $0-60°$, but still some problems remain

to be addressed such as:
– *Lack of stereoscopic view* (in the case of usual 2D vision systems): Even for simple positioning tasks with endoscopic tools, it takes almost twice the time to perform under direct monocular vision comparing to direct binocular vision, and it is even longer (almost 3 times) under endoscopic viewing condition (Tendick,*et al.*,1993).
– *Limited field of view :* Due to the size limitation of the monitor, as well as endoscopes field of view, the vision does not give the natural 120° field of view of human eyes. Therefore the vision is not perceived naturally and does not provide a natural control environment for the surgeon.
– *Limited resolution :* Visual resolution could be increased by decreasing field of view of endoscope as a trade off. But even in this case the final viewing resolution is determined by the resolution of monitor, which is much lower than resolution of human eyes viewing from a distance.
– *Limited contrast and color fidelity.*

There have been some technological advancement in the application of 3D vision systems in endoscopic surgery. 3D stereo endoscopes available on the market, from quite a few different manufacturers, have improved the depth perception and consequently performance (Mitchell,*et al.*,1993). On the other hand, there are some practical considerations that if taken into account can improve the performance greatly, such as:
– *Position of the monitor:* The distance of monitor from the surgeon should be arranged so that the angle of view of monitor is the same as the endoscopes field of view.
– *Position of the endoscope:* It is important to adjust the axial position of the endoscope for optimum resolution/magnification. On the other hand it is even more important to select the proper incision points for endoscope to give the natural viewing angle of the surgical site and surgical tools. If the angle between the endoscope and tools is more than 45°, then the performance of surgeon drops significantly (Tendick,*et al.*,1993). The best incision location for the endoscope can be in the region between the left and right surgical tools.
– *Angular orientation of the endoscope:* In order to have proper viewing orientation on the monitor, the endoscope should be rotated around its central axis, so that the general orientation of the vision on the monitor can be adjusted to be the same as the vertical orientation of surgeon.

2.2. *Movement of Hand/Tool*

In endoscopic surgery the main requirement is based on the performing the operation through small holes (of trocars on each incision point).

Fig. 1. Movements of the endoscopic tool/hand.

This introduces limitations to the required surgical movements as well as the available degrees of freedom. Basically the incision point and trocar act as a spherical joint on the abdominal wall that allows 3 rotational and one axial movement at the joint location. The inherent problems associated with this spherical configuration of movements are:
-*The sensitivity* of tool's movement (ΔT) with respect to the hand movement (ΔH) which is determined by the distance of incision point to the surgical site (or L1 the length of tool inside the body, Fig.1) over the outside length of the tool (L2).

$$\frac{\Delta T}{\Delta H} = \frac{L1}{L2} \tag{1}$$

Since the total length of tool is fixed ($L1 + L2$), when the incision point is far from surgical sight the sensitivity of movement is high ($L1/L2 > 1$) and positioning control is more difficult to achieve. On the other hand when the surgical sight is close to the incision point ($L1/L2 < 1$) most of the tool is outside and sensitivity is low. But the positioning control is usually difficult in this case as well, since the surgeons hand is in a high awkward position that is tiring and difficult to control. The optimum case could be when $L1$ is almost equal to$L2(L1/L2 = 1)$, this can give equal hand/tool movement and provides more normal hand posture for the surgeon. Therefore whenever possible it is better to select the location of the incision points with respect to the surgical site in such a way that the distance is about half the tools length. However, due to other practical reasons this might not be possible all the time and create difficulties in hand control of the tool.
- *Reverse Motion:* The pivoting joint effect like

movement of the tool around the incision point gives the reverse effect at the handle. This means for example when tools tip should move to the right, the surgeon must move his hand to the left. It is a matter of long training and practice to get used to this unnatural way of position control. What makes it even more difficult is the fact that usually the vision systems provide images that are mirror image along the vertical axis of monitor (i.e. a tool on the left hand side on the monitor is actually in the right hand of the surgeon).

- *Fix Orientation:* For proper manipulation of tissue and suturing needle, 3 degrees of rotational movement is required at the surgical site. With current design of rigid stem tools, only one rotational movements around the axis of stem is possible. Specially in the case of complicated tasks the importance of tools orientation at the surgical site is prominent. For example, in suturing, the completion time with endoscopic tools is twice as much as with ordinary surgical hand tools that have the advantage of orientational flexibility (Tendick, *et al.*, 1993).

2.3. *Force/tactile Sensing*

Force sensing at the tip of surgical tool is important for better and safer performance of tasks such as: cutting, suturing, moving, and testing tissues. Due to the endoscopic tools length, forces are transmitted very poorly to the hand. Also the lever effect of tool around the incision point changes the magnitude and direction of these forces ($F2/F1 = L1/L2$)Fig.1.

Also tactile sensing is an important sensory to control grasping force, evaluate surface texture, and to detect small movements such as artery pulse. In endoscopic tools all of these informations are lost and only the grasping force of the tool can be sensed to some extend by the surgeon. Of course even in this case its magnitude and stiffness is altered by all the intermediate mechanical linkages.

3. Solutions and Design Concepts

By improving surgical procedures, training, and more practice, it is possible to reduce completion time per task and increase level of skill. But there is a limit based on learning curve for each task, procedure, and set of tools being used. Any dramatical change usually comes by introduction of new tools or systems that in turn bring totally new procedures and new skills. In endoscopic surgery, there are many new tools and systems needed that can improve performance in many ways. Their success generally depends on their effectiveness, ease of use and natural interface with surgeons hands. In the rest of this paper some of new design concepts are reviewed and proposed which are subject of further research and development. They span from basic mechanical components such as flexible stem to master-slave robotic systems.

Fig. 2. Different designs of flexible stems

3.1. *Flexible Stem*

As mentioned earlier, the present rigid stem (or cannula) endoscopic tools have 4 degrees of freedom and lack 2 rotational movements at the surgical site. The challenge and difficulty lies in creation of these rotational motion on a stem diameter of only about 10 mm which is deep inside the body. The design still should provide some room for the linkages and connectors to pass through the joint(s) to the other moving elements and sensors at the end of the stem. Basically there are three types of designs to provide the required angular movement: Single joint, Multi-joints, and Continuous stem, that are described in following sections.

a) *Single joint:* In this design all the rotational movement is performed by one pin joint that is actuated by linkage mechanism, or pneumatic actuators from outside (Fig.2a). The advantages of single joint mechanism are its relative simplicity, and low space requirements for its movement inside the body. The disadvantages are that it does not provide much room for other linkages to pass through, having a very sharp bending angle, and it only provides one degree of rotation.

b) *Multi-joints:* In this design the rotational movement is distributed among a number of joints with limited range (Fig.2b). These joints could be pin joints (with relative 1 DOF) or spherical joints (with 2 DOF). The control and actuation is usually performed by tendons on the periphery of the stem. In the case of spherical joints there are

usually 4 wires while through their axial displacements and the amount of tension, it is possible to bend the stem to the desired angle and lock it in that orientation. The advantages of this design are in its wide rotational range, allowing large passage for other linkages to pass through the joint, and its capability to create gradual bend. The disadvantages are larger space requirements inside the body to bend to a desired orientation, and more complex control of wires axial movement/tension.
c) *Continuous Stem:* Due to recent Results in research and development Shape Memory Alloys(SMA), there is a new prospect of developing joint-less flexible stem (or multi-joint stem) that could be bent by heating the SMA part of the stem (Fig.2c). Although more research is needed to evaluate its potentials, but at this stage, it can be mentioned that its advantages and disadvantages are very similar to the previous multi-joint design. Except for the fact that main issues here are the control of SMA stem and its mechanical performance under dynamic conditions.

3.2. *Suturing Device*

One of the most difficult tasks in endoscopic surgery is suturing. It needs a lot of training and practice to perform the simplest sewing and knotting techniques inside the body. Basically it is performed by using two endoscopic graspers(which are called needle drivers). As mentioned earlier, problems of vision, tools movement, and force sensing in endoscopic surgery are most tangible and acute in suturing task due to the complex tools/needle movements. In this regard there have been some attempts to develop miniature suturing devices that facilitate sewing by eliminating manipulation of needle (Nagy,*et al.*,1994; Rininsland,1993; Neisius,*et al.*,1994, Melzer,*et al.*,1993). The main idea behind most of these designs (Fig.3a and 3b) are to transfer a needle between two jaws by a reciprocating motion and intermittent locking of the needle by one of the jaws each time (Melzer,*et al.*,1993). The needle has a central cross bore for the thread that is carried through tissues being sutured. The advantage of this design is its compactness and few moving parts.
There is another design under investigation and development that the needle is a circular arc shape(about 240°), that is moved in a circular path(Fig.4). The movement is provided by continuous motion of one finger, and the surgeon has total control of needle both in terms of position and direction of the needles movement.

Fig. 3. Suturing devices with reciprocating motion design.

Fig. 4. The suturing device with circular motion design.

3.3. *Positioning Stand*

In the endoscopic surgery, positioning of the tool and keeping it fix in that position is a routine task that is carried out frequently. This is usually done by an assistant surgeon, that beside crowding the operating area, it is costly. An alternative could be the usage of a stand similar to the configuration of SCARA robot (Fig.5) with additional end-joints that can give the tools two rotational degrees of freedom about X and Y axis. Since the stand is naturally balanced, the surgeon can move the tools freely with minimal opposing frictional forces, and lock them at any position and orientation. Even in the unlock state of the stand, the surgeon does not have to carry the total weight of the tools. On the other hand, dexterity can be improved by locking the two joints at the base of the arm (i.e. joints A and B, Fig.5) when the tools are already inside the body through abdominal incision points. This provides a resting frame for the surgeon as well as a rigid base for the end-joints(i.e. joints C and D, Fig.5) to be moved in a much more controlled manner.
The positioning stand can be upgraded to a computer aided surgical system by adding measuring sensors to joints of the arms. Through the kinematic model of the mechanisms, one can monitor and approximate the position vector and the ori-

Fig. 5. The positioning stand with three arms.

entation vector of the end-point. Also by having a database of the abdominal cavity and internal organs, It is possible to provide graphical map of the body and the relative position of surgical tools with respect to them.
Specially this could be used for training purposes by developing interactive softwares tools to aid students with graphical, video, and text, that provide them step by step complementary information about each procedure.
By adding actuators (in a closed loop control) to the above passive system, it is possible to obtain full robotic capabilities for automatic positioning of tools.
This is possible without sacrificing other capabilities mentioned earlier. Here the surgeon is still able to move the arms manually with ease while performing the operation with tools attached to the arms. To achieve this, the arms not only must be light and frictionless, but also their engagement with motors should not interfere with manual handling of the arms by the surgeon.

3.4. *Robotic Endeffectors and Telesurgery*

This could be implemented in two stages:
a) *Hand-tool endeffectors:* Initially, it is possible to incorporate some of the more advanced mechanisms and sensors into endoscopic hand-tools to provide more dexterity for the surgeon. Such improvements can be:
- The implementation of flexible stem in the hand-tool that is actuated by the surgeon for obtaining the proper orientation at the surgical site. This extra actuation mechanism can be used in conjunction with the surgeon's own hand movements to accomplish a proper orientation. Though the surgical movements are totally generated by direct hand movement of the surgeon.
- The application of force sensors in the hand-tool to provide the surgeon with better force/tactile sensing.
b) *Master-slave endeffectors:* The main difficulty in endoscopic surgery is the usage of very long tools through fix small incision points. No matter how much the design of tool (both in terms of degrees of freedom and optimum interface with the surgeon's hand) is improved, still direct physical hand control of the tool is unnatural, remote,and physically demanding. Only with a lot of training and practice, it is possible for the surgeon to obtain a fraction of skill and dexterity level of open surgery. Therefore to obtain much higher dexterity, direct hand control of endoscopic tools can not be the solution. Further improvement lies in the development of robotic endeffectors (to replace the hand tool) which are indirectly controlled by the surgeon. This is actually a master-slave robotic system that surgical movements of the robotic endeffector inside the body is generated and controlled by hand movements of the surgeon on a telesurgical workstation.
The success of such a system not only depends on the general control characteristics of the master-slave system (such as accuracy, fast response, and force reflection), but also its ease of usage and being natural to control the slave. For example to control the endeffector by means of a "joystick" is not a natural interface for the surgeon, since all the endeffectors movements should be translated to movements of the joystick by logical step by step reasoning, instead of subconscious control. In order to achieve an easy to control master-slave system, which does not require substantial training, the mechanical movements (or DOF) of the endeffector should be similar to natural movements of human hand. In other words the master and slave should be kinematically similar. For example, the graspers jaws movement to be directly controlled by angular movement of the thumb with respect to other fingers, or the orientation of the grasper could be directly controlled by angular movements of the wrist.
Force reflection is an important sensing and safety issue that could be incorporated into the master-slave system. It gives force sensing to the surgeon during operation by friction control of the axes of master arm.
- *Slave Configuration:*
Based on previous discussion, there could be different design variations of master/slave configurations. The following is based on one such design that is subject to research and future development.
The slave endeffector (Fig.6) is mounted on the arm of a positioning stand similar to the one described in section 3.3. The positioning stand in this case is a passive mechanism that holds the endeffector in the proper position and orientation with respect to the incision point. The slave en-

Fig. 6. The slave endeffector.

Fig. 7. The master arm controller.

deffector provides 3 positioning axes (R, α, β), 2 orientational axes (θ, ϕ), and one grasping action (G). This configuration provides a very compact robotic system which is essential for endoscopic surgery since in a normal operation at least 2 endeffectors are required in a limited space.

- *Master configuration:*

The master arm has a polar configuration (Fig.7) that hand's position is sensed by axes (R', α', β'), the wrist orientation by (θ', ϕ'), and the angle of thumb/finger for grasping by (G').

Since the master and slave are kinematically similar, not only it is easy to use, it is much less difficult to implement the system in terms of sensing, actuation, and control issues. Though the challenge lies in design and manufacturing of such miniatured endeffector with 5 degrees of freedom that is accurate and dynamically controllable by hand's movements.

4. Conclusion

Endoscopic surgery is prefered mostly over open surgery due to many advantages it has for the patient.Though special problems that surgeons are facing in endoscopic surgery , should be studied and analyzed in order to provide better visual information, easier movement of hand/tool, and better force/tactile feedback sensing. Surgical tools with flexible stem provides better access to the surgical site. The suturing device is a special tool for the difficult task of suturing and knotting that increases speed substantially. The positioning stand can be used for positioning tools, a resting frame for the surgeon, as well as a computer-based information system. Robotic technology can be used in endoscopic endeffectors and telesurgical manipulators. Master-slave systems of similar kinematics are suitable mostly, due to the ease of usage, and ease of implementation.

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