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Analysis of the Surgery Task for the Force Feedback Amplification in the Minimally Invasive Surgical System

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Abstract **– This paper presents a new method of amplifying the small reaction force in the minimally invasive surgical system according to the surgeon's intended action. For this purpose, the analysis of the laparoscopic cholecystectomy procedure is first studied. The procedure is broken down and analyzed for the necessary forceps actions based on the degrees of freedom of the surgical tool and the task to be performed. For this system, there are seven necessary forceps actions. Then the concept of the force feedback augmentation has been proposed. It amplifies the small reaction force in specific directions according to the surgeon's intended action. Each action determines how the reaction force should be amplified.**

Index Terms – Surgery Task Analysis, Minimally Invasive Surgical System, Force Feedback Augmentation

I. INTRODUCTION

Laparoscopic minimal invasive surgery (MIS) is the surgical operation done through small incisions (ports) with the help of specialized instruments and endoscopes. Patients benefit much from the laparoscopic MIS technique such as reduction in trauma and faster recovery time. On the other hand, surgeons lose important senses commonly accessible in the conventional open surgery. It takes time for the surgeons to get acquainted to the technique, yet the risk in surgical accident still remains.

Researchers have developed many assistive technologies and systems to solve these difficulties. As a few successful examples related to robotic system, [1] developed the AESOP® robot to position and hold the endoscope in respond to voice commands. The commercialized da Vinci® surgical system [2] is well known for the excellent user interface, vision system, and smooth motion of the cable driven slave manipulator and instruments. Recently, [3] developed the "Microhand" slave manipulator which is controlled by the PHANToM® as the master manipulator for open micro surgery. Moreover, the assistive system can extend the surgeon's dexterity and performance. Motion scaling [2, 4] allows centimeters of motion by the surgeon to be translated to millimeters of motion at the surgical tool, thus increasing his effective motion resolution along with the magnified visual scene. Hand tremor was canceled using the sensed force information, exerted by the surgeon on the tool and by the tool on the environment, in the robots' controllers [5]. As a result, precision and accuracy in surgery had been dramatically improved [6]. Laparoscopic MIS tele-surgical experiments with animal subjects have been reported, including the earlier works of [7] and [8].

There are extensive researches about force feedback in the assistive surgical systems. As a few examples, [9] fabricated a miniature force sensor to measure contact fore at the tip of the instrument using the MEMS technique. [10] developed and evaluated the high-fidelity force controlled teleoperated endoscopic grasper. PI force control was applied in [11] to regulate the reaction force of the microgripper. Many works warranted the virtue of force feedback. For example, it was concluded from a knot experiment in [12] that the repeatability in applied force is improved with the force feedback function enabled.

Section II describes and analyzes the laparoscopic cholecystectomy procedure for the necessary forceps actions. From this classification, the concept of the force feedback augmentation and the calculation of the augmented reaction force are explained in section III. Results from the preliminary experiments are presented in section IV and the conclusions are given in section V.

II. PROCEDURES AND FORCEPS ACTIONS IN THE LAPAROSCOPIC CHOLECYSTECTOMY

Laparoscopic cholecystectomy is the surgical procedure of removing the gallbladder that has cystoliths. It basically consists of the detachment, separation, and ligature processes. The procedure can be broken down into six main steps [13], which are

1. position and expose the gallbladder
2. peel off the gallbladder from the liver
3. position and expose the cystic duct/artery
4. clip and cut off the cystic duct/artery
5. tear off and pull out the gallbladder from the liver
6. remove the gallbladder out of the abdomen

Each step is further analyzed for the primitive *action*s it used. Primitive actions are the necessary and sufficient basic *actions*, based on the *force* and *motion* context, such that the manipulation of the forceps can be described by the interpolation of these primitive actions. The decomposition

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depends on the degrees of freedom of the specific kind of tool and on the task to be performed.

Prior work in [14] classified the tool/tissue interaction of two laparoscopic surgical tasks and used Markov modeling technique to model and evaluate the surgical skills of experienced and apprenticed surgeons. [15] also discussed the task and motion analysis for the subtasks and primitive motions from the captured video.

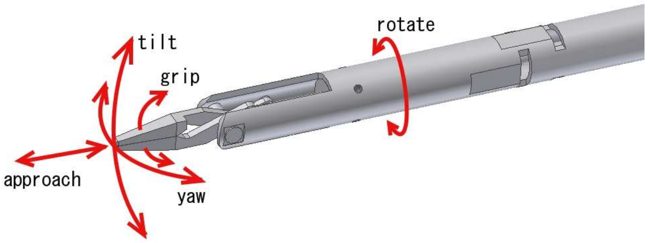

Fig. 1: Five d.o.f.s of the straight-typed forceps

For this system, the straight-typed forceps is used. Its end tip possesses five degrees of freedom when mounted onto the slave manipulator arm: the approach, yaw, tilt, rotate, and grip motions. Figure 1 shows their directions. However, by analyzing the primitive actions of the remote laparoscopic cholecystectomy procedure, the active forceps controlled by the surgeon does really perform only small set but important skillful operations. The auxiliary tasks such as pulling/pushing the neighboring organs aside the working area are done by the assisting passive forceps at the patient's side. This is partly due to the arrangement of the ports position where it is rather cumbersome for the active forceps inserted into the abdomen from the middle ports to move much in the yawing direction. Also, the suture task, which involves plenty of the forceps tip rotational movement, is rarely performed in the laparoscopic cholecystectomy. The procedure removes the gallbladder out of the abdomen and it is more convenient and efficient to apply the clipper to the cut cystic duct /artery than to suture them.

Table 1: Necessary actions of the forceps for the laparoscopic cholecystectomy procedure

Action no.	Direction of force amplification
1. grasping / spreading	grasping direction
2. pushing / pulling	z direction
3. lifting up / tapping	x-z plane
4. grasping & pushing / grasping & pulling	grasping & z direction
5. grasping & lifting / grasping & tapping	grasping & x-z plane
6. grasping & lifting & pulling / grasping & probing	grasping & x-y-z direction
7. lifting & pulling / probing	x-y-z direction

With this consideration, the forceps actions along the yawing and rotating directions are not treated as the primitive actions. For this system, there are seven necessary primitive actions, which are grasping, spreading, lifting up, tapping, pushing (pressing), pulling, and probing. In practice, several primitive actions may be executed simultaneously at an instant, such as grasping while lifting up the covering organ. In this case, it is appropriate to amplify the reaction force components related to both grasping and lifting action. Logically, it is convenient (for calculating the augmented reaction force) to consider the possible combinations of the primitive actions and treat them as new actions. Ultimately, seven distinct actions, listed in Table 1, have been defined. It also serves as the list for the corresponding force and motion signal pattern. Specific directions of the force amplification for each action are listed alongside according to the forceps coordinate frame in Fig. 2.

III. FORCE FEEDBACK AUGMENTATION

Remote environment of the forceps in MIS is mainly the unstructured terrain of compliant tissues, of which their properties have been studied extensively [16]. Highly nonlinear and time-varying compliant characteristics of the tissues yield the small reaction force amplitude, which is difficult to perceive. Unpredictable varying contact geometry of the forceps tool tip with the tissue prevents the practical use of the assumed priori model. Their effects result in the complexity of the interaction force during the operation. The essence of the simple but significant reaction force of the intended action is concealed.

Amplification of the reaction force by simply multiplying it with the gain values may disorient the intended operation because the unimportant and complex force components are also magnified; it does not distinguish the significant reaction force components resulted from the current forceps action. However, the surgeon needs to concentrate on the reaction force in specific directions, in accordance with his intended action. Force components in some directions, which account for the complexity of the resultant force, may not be so important. Besides, large loop gain threatens the stability of the delayed system.

To solve the stated problems, i.e. small and unnecessary complex reaction force, the feedback force should be amplified effectively before displaying to the surgeon. It should be amplified according to the forceps action. In particular, the force components along the ideal reaction force directions resulted from the forceps action will be amplified (see Table 1) while those in other directions will be sent and displayed as they are. As a result, the relative magnitude of the irrelevant force components, constituting the complex behaviour of the reaction force, is attenuated. The amplified reaction force gets closer to the corresponding ideal reaction force. Only the simple but significant reaction force components are emphasized.

Calculation of the augmented reaction force will be now presented. Note that this method will be valid only if the unrelated complex force portion is not too significant. Gripping force can be easily amplified by direct multiplication with the appropriate gain. For the translational force, the gain represents the magnification of the translational force amplitude, which simplifies the calculation and the gross stability analysis. Let $\{x_o, y_o, z_o\}^T$ and $\{x_n, y_n, z_n\}^T$ be the translational force vector before and after a specific amplification. Also let the amplitude of the amplified translational force be n times of the original one, that is,

$$\sqrt{x_n^2 + y_n^2 + z_n^2} = n\sqrt{x_o^2 + y_o^2 + z_o^2}\ . \tag{1}$$

For the action involving pushing or pulling, the force component in z-direction is to be amplified which means the other two will be unchanged;

$$x_n = x_o,\ \ y_n = y_o\ . \tag{2}$$

Substituting (2) into (1), the amplified z component is

$$z_n = \operatorname{sgn}(z_o)\sqrt{(n^2-1)x_o^2 + (n^2-1)y_o^2 + n^2 z_o^2}\ . \tag{3}$$

For the action involving lifting or tapping, the force components in the x-z plane are amplified while that of y-component remains unchanged;

$$y_n = y_o\ . \tag{4}$$

Currently there is only one equation but two unknowns to be solved. The assumption that the complex and insignificant force components are limited implies the principal direction of the projected vector onto the x-z plane is corrected and therefore unchanged;

$$\frac{x_n}{z_n} = \frac{x_o}{z_o}\ . \tag{5}$$

Substituting z_n and x_n from (5) into (1) to solve for the amplified x and z component respectively;

$$x_n = x_o\sqrt{\frac{n^2x_o^2 + n^2z_o^2 + (n^2-1)y_o^2}{x_o^2 + z_o^2}} \tag{6}$$

$$z_n = z_o\sqrt{\frac{n^2x_o^2 + n^2z_o^2 + (n^2-1)y_o^2}{x_o^2 + z_o^2}}\ . \tag{7}$$

Finally, if all three components are significant and there are only small amount of the insignificant force components, each new amplified component is just simply

$$x_n = nx_o,\ \ y_n = ny_o,\ \ z_n = nz_o\ . \tag{8}$$

Fig. 2 gives the visualization for the augmented reaction force. Original reaction force vector shown in blue tends to be along the z-direction due to the intended pulling action. By amplifying the force according to the ideal pulling action with the amplitude being doubled, the resultant augmented reaction force vector (red) almost coincides with the z-axis. The pulling action is emphasized.

Another example illustrating the lifting up of the tissue is depicted in Fig. 3. Reaction force vector should lie vertically in the x-z plane. However, complicated contact geometry and imprecise manipulation make the reaction force off the plane. After amplifying the force according to the ideal lifting up action with the amplitude being doubled, the augmented reaction force vector is pulled closer to the x-z plane and more vertically downward. The resultant augmented force will be dispatched as the reference command to the local PI gain scheduling force feedback controller at the master side. Built on top of this concept, the action determination algorithm has been developed to automate the force feedback augmentation process [17]. The identified forceps action is used to select the appropriate calculation of the augmented reaction force.

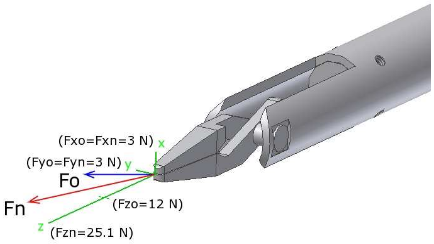

Fig. 2: Augmented reaction force for the pulling action

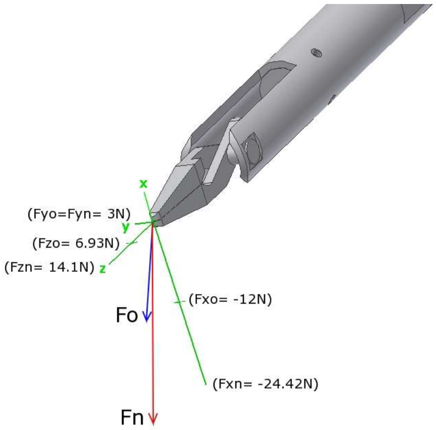

Fig. 3: Augmented reaction force for the lifting up action

IV. PRELIMINARY EXPERIMENTS AND EVALUATION

A sponge fixedly placed on a steel block was used as the environment. A series of subtasks, selected to represent the common action accounted in the real operation, was performed successively. It was composed of grasping, grasping & pushing, grasping & pulling, grasping & lifting, and grasping & probing subtasks. Each was performed for a specified time. This same operation was done twice with and without the force feedback augmentation. More experiments about the force feedback augmentation were reported in [18].

The average magnitude of the translational interaction force,

$$\overline{|F|} = \frac{1}{T}\int_{T} |F|\, dt \,, \qquad (9),$$

was increased from 1.35 to 2.77 N when the force feedback augmentation was disabled. Plot of the magnitude of the interaction force is shown in Fig. 4. Average magnitudes of the applied translational forces at the master manipulator, however, were comparable: 1.22 and 1.32 N with and without the force feedback augmentation. Therefore reaction force perceived by the operator is not deteriorated for the beneficial decrease in the actual interaction force.

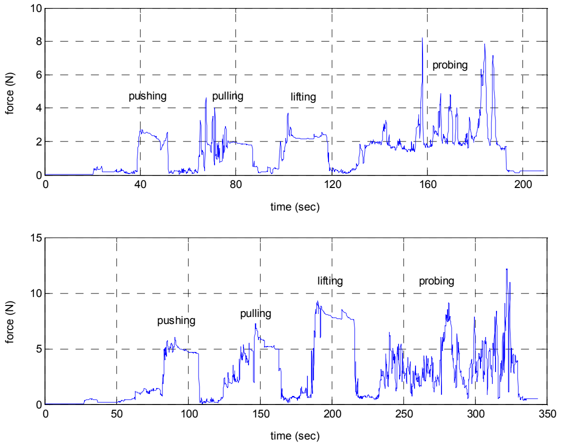

Fig. 4: Magnitude of the interaction force with force feedback augmentation enabled (top) and disabled (bottom)

V. CONCLUSIONS

The forceps actions for the laparoscopic cholecystectomy procedure have been analyzed. For this system, there are seven necessary forceps action. Force feedback augmentation method, by considering the tasks and tissue mechanical properties, has been proposed to enhance the force perception of the surgeon during the operation. In brevity, force is amplified in specific directions according to the forceps action. Force feedback augmentation implicitly makes the tissue feel stiffer which effectively signals the surgeon of initial contact. The magnitude of the interaction force with the tissue is then reduced while the feedback force felt by the surgeon remains unchanged. Smaller interaction force implies less chance of accidental damage on the organ. Also, since the relative magnitude of the irrelevant force components for the action is attenuated, the feedback of the intended action is emphasized and the surgeon is better able to focus on his action.

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REFERENCES

[1] J. M. Sackier and Y. Wang, "Robotically assisted laparoscopic surgery. From concept to development," *Surgical Endoscopy*, Vol. 8, pp. 63-66, 1994.
[2] G. S. Guthart and J. K. Salisbury, "The intuitive telesurgery system: Overview and application," *Proc. ICRA*, pp. 618-621, Apr. 2000.
[3] S. Wang, et al., "A robotic system with force feedback for micro-surgery," *Proc. ICRA*, pp. 200-205, Apr. 2005.
[4] S. Prasad, et al., "Surgical robotics: Impact of motion scaling on task performance," *J. Am. Coll. Surgeons*, Vol. 199, pp. 863-868, 2004.
[5] R. Taylor, et al., "A steady-hand robotic system for microsurgical augmentation," *Int. J. Robotics Research*, Vol. 18, pp. 1201-1210, Dec. 1999.
[6] Intuitive Surgical, Inc. http://www.intutitivesurgical.com
[7] M. Ghodoussi, S. E. Butner, and Y. Wang, "Robotics surgery – the transatlantic case," *Proc. ICRA*, pp. 1882-1888, May 2002.
[8] M. Mitsuishi, et al., "Development of a remote minimally invasive surgical system with operational environment transmission capability," *Proc. ICRA*, pp. 2663-2670, Sep. 2003.
[9] P. J. Berkelman, et al., "A miniature instrument tip force sensor for robot/human cooperative microsurgical manipulation with enhanced force feedback," *MICCAI*, pp. 897-906, 2000.
[10] J. Rosen, et al., "Force controlled and teleoperated endoscopic grasper for minimal invasive surgery – experimental performance evaluation," *IEEE Trans. Biomedical Eng.*, Vol. 46, No. 10, pp. 1212-1221, Oct. 1999.
[11] A. Eisinberg, et al., "PI force control of a microgripper for assembling biomedical microdevices," *IEE Proc. Circuits Devices Syst.*, Vol. 148, No. 6, pp. 348-352, 2001.
[12] M. Kitagawa, et al., "Analysis of suture manipulation forces for teleoperation with force feedback," *MICCAI*, pp. 155-162, 2002.
[13] I. Brune, ed., *Laparo-Endoscopic Surgery*, 2nd ed., Blackwell Science, 1996.
[14] J. Rosen, et al., "Markov modeling of minimally invasive surgery based on tool/tissue interaction and force/torque signatures for evaluating surgical skills," *IEEE Trans. Biomedical Eng.*, Vol. 48, No. 5, pp. 579-591, May 2001.
[15] C. G. L. Cao, et al., "Task and motion analyses in endoscopic surgery," *Proceedings of the ASME/IMECE*, pp. 583-590, 1996.
[16] Y. Fung, *Biomechanics: Mechanical properties of living tissues*, 2nd ed., Springer Verlag, 1993.
[17] P. Pitakwatchara, et al., "Automatic determination of the actions and force feedback augmentation in the minimal invasive surgical system," *ISER 2006*.
[18] P. Pitakwatchara, et al., "Force feedback augmentation method for the minimally invasive surgical system," *to appear in Proc. IROS*, 2006.