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Development of a Micro Mobile robot in the Abdominal Cavity

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Abstract— **Recently, NOTES (Natural Orifice Translumenal Endoscopic Surgery) has attracted attention as a new approach in laparoscopic surgery. This approach achieves extremely less invasive surgery, however, manipulation of forceps is very difficult in NOTES, which brings more burdens on the surgeons. Under these situations, the aim of this study is to develop a micro mobile robot that could move in the abdominal cavity, loaded with a camera and/or forceps. In order to achieve stable movements and surgery support actions, we proposed using peritoneum (abdominal wall) as the surface for moving in the abdominal cavity. Moreover, we devised a robot system that relies on two suckers to attach to the peritoneum, and a cable driven mechanism to realize the relative movement of the two suckers, by which 3 D.O.F. (Degree Of Freedom) movements, i.e., moving forward/backward, turning left/right, and moving up/down could be realized. After examining the suction availability of suckers employed, we built a prototype robot system. We verified that, hanging upside down on the surface of vinyl wall, the robot could accomplish the designated movements with a certain load, which showed potential of using the robot system as the surgery support for NOTES.**

I. INTRODUCTION

The number of laparoscopic surgery has increased with the development of endscopical instruments in these days. NOTES, in which, forceps are put through a natural orifice, such as mouth, anus, and vagina, and a hole was cut at the site to reach intra-abdominal cavity, so that it enables extremely less invasive surgery, thus greatly improves QOL (Quality Of Life) of patients [1], [2]. Although, this approach may hold tremendous potential, however, several issues should be addressed before this technique is introduced into the clinical care. One of the important issues is that since the pathway from the surgeon's fingertip to the targeted site is generally longer than that of usual laparoscopic operations, manipulation of forceps is much more difficult, which brings more burdens on the surgeons.

On the other hand, most surgery support robotic systems developed so far for laparoscopic surgery are forceps manipulators [3], [4]. Main purpose of few in vivo robots is to take pictures in the digestive tract for diagnosis, and very few robots could load and guide forceps [5]. Under this situation, the aim of this study is to develop a micro mobile robot that could move in the abdominal cavity, loaded with a camera and/or forceps, enhancing the visibility and performing treatment if necessary.

II. BASIC CONSIDERATIONS AND SPECIFICATION OF THE ROBOT

To devise a system working in abdominal cavity for surgery support, the following issues should be taken into consideration.

● Stable movement and surgery support

Since the surface of the intraperitoneal organs, such as the large intestine and the stomach, is unstable due to peristalsis and other factors, in order to achieve stable movements and surgery support actions, we had to consider the other possibility. In this study, we proposed using peritoneum (the smooth serous membrane which lines the abdominal cavity) as the surface for moving in the abdominal cavity.

● Less damage to the internal environment and fewer electrical devices

The effort to give less damage to the internal environment (according to the issue just discussed, the peritoneum) and use fewer electrical devices is insignificant important considering the robot's medical application. In this study, we employed vacuum suction as the means to attach to the peritoneum, and devised a cable driven mechanism to realize the relative movements of the two vacuum suckers.

● D.O.F. necessary for mobility and surgery support

In order to move on the peritoneum and guide forceps to the targeted site, 3 D.O.F. (Degree Of Freedom) movements, i.e., moving forward/backward, turning left/right, and moving up/down should be realized. The moving up/down is necessary because the peritoneum is not a flat plane, especially after filled with gas during usual laparoscopic operations, the peritoneum turns to be a dome-like 3D surface. Also, the robot should be able to clear the ramp, when moving from overtube to abdominal cavity.

Also, another D.O.F. is needed for the lock and release of the forceps.

● Size and weight constraints

Although, functions discussed above should be realized, there are design constraints that should be met, i.e., the robot should be small and light enough. Constraints come from the size of overtube for endoscopic operation, and robot's weight loading ability that depends on the sucking force, robot's own weight and camera and forceps. For our first prototype implementation, the outer diameter was set as 30mm, which is the maximal inner diameter we could assume for overtubes for

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NOTES usage.

III. DESIGN OF THE ROBOT

A. Key parts design

The constraints mentioned in the section Ⅱ should always be considered while designing the robot. The parts for the robot turn to be not so straightforward. One particular example is the design of air joints.

In order to provide independent control for two suckers, two air supply ducts should be contained in the robot housing, and connected to suckers through two air joints. As shown in Fig. 1, although the sucker could be aligned along the axial direction, the air ducts should be aligned on the different sides of the centerline, to downsize the robot housing. Thus, two air joints should have a bent head for air supply duct, as illustrated by the dotted line in Fig. 1, and Fig. 2 (a).

Due to their weight or size, commercially available air joints could not used. Fig. 2 (b) shows a designed prototype joint and a commercial joint. The prototype joint is made of acrylic, weights 0.6g compared to commercial available joint's 16.2g. For the other key parts, the similar design policy was applied. The weight of the robot is 9.5g, but the wires and guide-tubes were not counted.

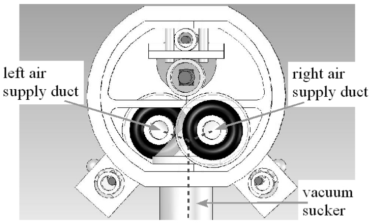
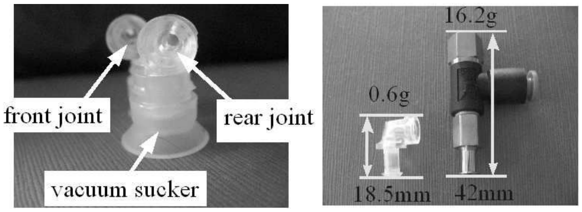


Fig. 1. The configuration of two joints



(a) rear and front joints (b) designed joint (left) and a commercialized joint (right)

Fig. 2. Design of air joints

B. Architecture of the robot

Fig. 3 shows a picture of the first prototype robot (a), (b), and its illustration (c). Three pairs of wire/guide-tube were equipped to realize relative movement of two suckers, thus achieve the 3 D.O.F. movements for the robot. The three pairs of wire/guide-tube, together with two air supply ducts were contained in two housings (front and rear housings). Wires were fixed to the front housing and guide-tubes were fixed to the rear housing. In the front housing, there is a hole for loading and guiding forceps.

The maximum dimension of the first prototype was 35mm, bigger than the specified size, however, the second prototype will clear this problem.

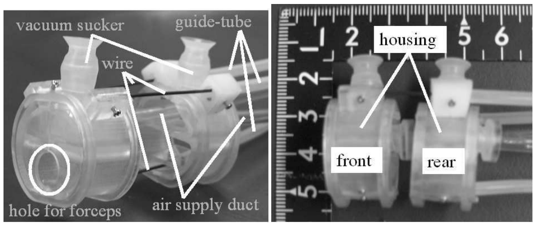
IV. MANIPULATION OF THE ROBOT

A. Control system

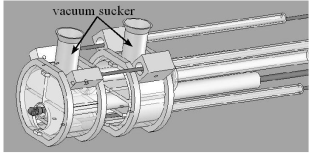
The components of the robot control system are shown in Fig. 4. A block diagram of the control system is shown in Fig. 5. It is clear that, two aspects of the robot should be controlled, the suction control, which decides the adsorption and release of the sucker, and the relative movement control which changes the relative position of two suckers.

The suction control was achieved by using a digital solenoid valve for the vacuum pressure generated by a compressor. The valve can switch between the adsorption and release of the suckers according to the command sent to it from output ports of a personal computer. Note that there is a pressures sensor in the valve, which outputs 0v for adsorption, and 12v for sucker released. This sensing ability could enable automatic manipulation of the robot in future.

In the relative movement control, it is the length of part of wire stretching out from the guide-tube that needs adjusting. Different stretching-out length for three pairs of wire/guide-tube, different robot motions could be realized.



(a) construction of the robot (b) the size of the robot



(c) 3D illustration of the robot

Fig. 3. The overall robot

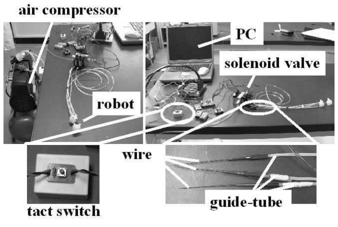


Fig. 4. Hardware for control system

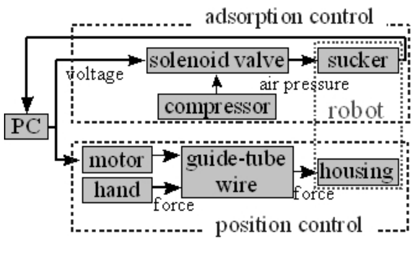


Fig. 5. Block diagram

Note that, the system components other than the robot are installed outside of human body.

B. Phase diagrams for different movements

1) Moving forward/backward

The phase diagram of moving forward is shown in Fig. 6, where a hatched circle means an adsorbed sucker, whereas an open circle means a released one.

It is obvious that, the motion could be divided into 5 phases, starting from an initial phase 0 (both suckers absorb), releasing one sucker and pushing forward (shown by an arrow marked with F) the wires (for moving the front sucker) or the guide-tubes (for moving the rear sucker), sequentially and repeatedly.

Also the phase diagram of moving backward could be acquired by simply reversing the direction of force (arrows).

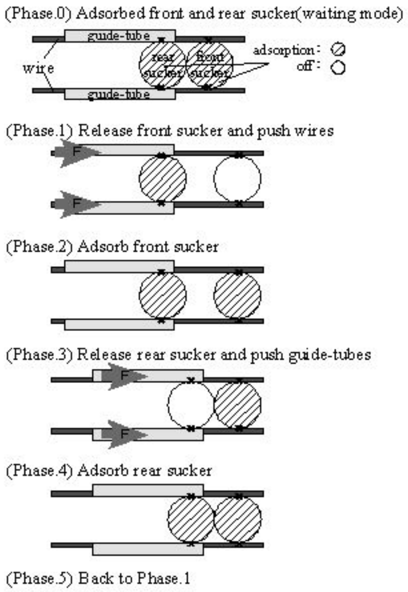


Fig. 6. Phase diagram of moving forward

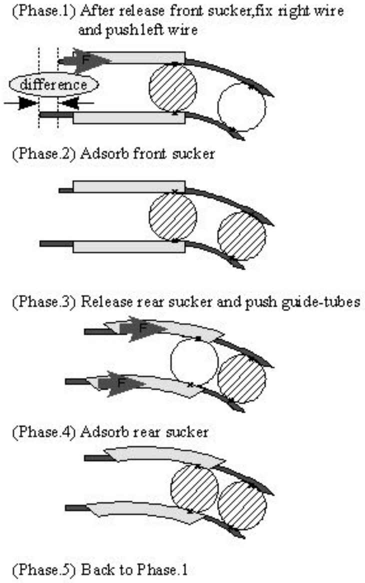


Fig. 7. Phase diagram of turning right

2) Turning left/right

Turning motion is realized by making difference between the stretching-out length of left and right wires. The phase diagram of turning right is shown in Fig. 7.

Different with moving forward motion, in phase 1, in order to move the front housing right, the left wire was pushed out, while fixing the right wire length, thus, the left wire will bend towards right, and the front housing will turn right. Turning left could be achieved by making stretching-out length of right wire longer during phase 1.

Except this making difference between the left and right stretching-out wire length, the suction control of turning motion is basically the same as that of moving forward.

3) Moving up/down

Vertical movement is also possible by making difference between the stretching-out length of upper wires (those two wires close to suckers) and lower wire (one single wire).

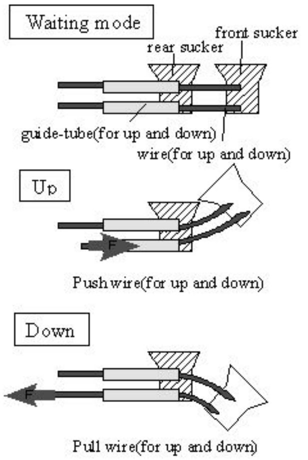


Fig. 8. Vertical motion

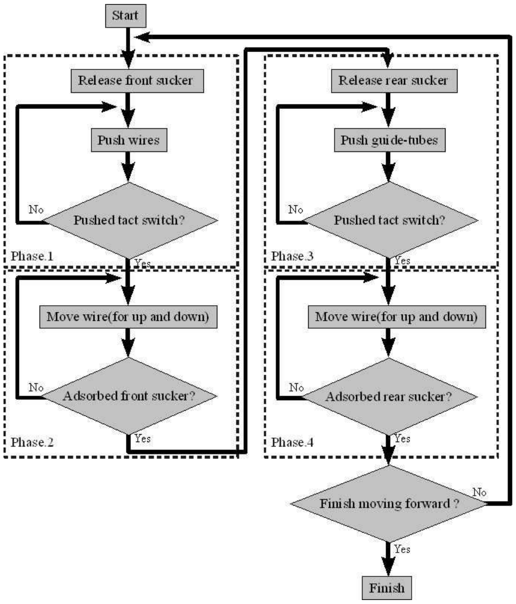


Fig. 9. Control program for moving forward

C. *Control programs of robot motions*

A set of control programs were assembled for realizing the phase diagrams. Fig. 9 shows the control program for moving forward.

In Fig. 9, the program for each phase was enclosed by dashed line. Since in the current stage, the prototype robot was manually operated, a tact switch was installed to reflect the end of the phase 1 and phase 3. That is, an operator pushes the wires or guide-tubes to move forward the front housing or rear housing, respectively. After deciding that the stretching-out length is enough, he pushes the tact switch to denote the end of the phase to the control program implemented in a personal computer.

Similarly, the sensor signals in the valve were used to check the end of phase 2 and 4. However, since moving the suckers near to the adsorption surface could not guarantee adsorption to the surface, the operator should fine adjust the sucker's posture by changing minutely the three wire/guide-tube pairs, until the output of sensor in solenoid value down to 0v, which means a successful adsorption.

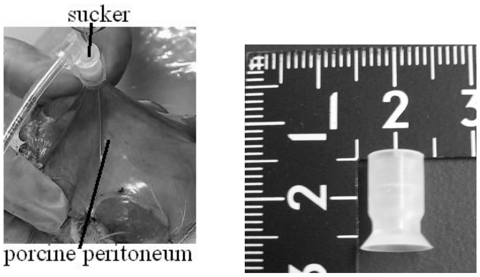
The control program for the other motions could be made similarly.

V. EXPERIMENT RESULTS

A. *Measurement of sucker adsorption force*

Although various types of robots employing suction cups as part of actuation have been developed [6]-[8], there are few reports about the effect of the sucker adsorption to a living body. Besides, although the adsorption effect to the avian liver [9] and that the sucker were used for the adsorption and movement to the heart (epicardium) [10] were reported, there is hardly any result of using suction cups for realizing the movements in the intraperitoneal environment. Hence, verification is required. An adsorption experiment was conducted using the peritoneum of a porcine. Fig. 10 shows the peritoneum and suction cup used. Adsorptivity was measured as follows: the sucker was adsorbed to the peritoneum and attached to a spring balance. The spring balance was gradually lifted until the sucker went off from the peritoneum.

As a result, the maximum adsorptive force was 150g. Since, the weight of the robot is around 10g, and the forceps supposed to load is 1g/cm, moreover, the micro camera is around 20-30g, thus it is evidential to declare that, the vacuum suction force is enough for the weight loading for the surgery support task.



(a) porcine peritoneum used (b) sucker used

Fig. 10. adsorption experiment

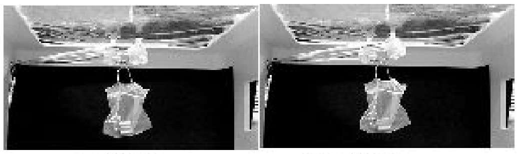
One problem rose from the experiment was that the peritoneum extended to the tension from suckers, due to its high elasticity. This may make the operation of the robot difficult, thus should be taken notice of during the development.

B. *Moving forward with weight load*

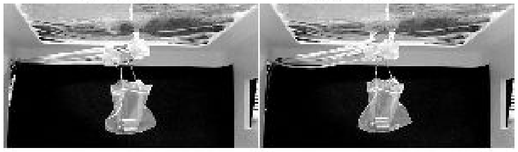
Using the control program described in section Ⅳ and the prototype robot system developed, a weight loading experiment was conducted. A 50g weight was hung on the robot, and moving forward motion was carried out. An endoscopic surgery simulation unit (Fig. 11), with a vinyl sheet as the adsorption surface was used. The control signals of the experiment, i.e., output of solenoid valve and tact switch were given in Fig. 12. As shown in Fig. 12, front and rear pressure sensor valves give a clear distinction for 4 phases.

Phase 1: front voltage=6v, rear voltage=0v
Phase 2: front voltage=6v, rear voltage=0v
Phase 3: front voltage=0v, rear voltage=6v
Phase 4: front voltage=0v, rear voltage=6v

Although output voltage of solenoid valve was 12V, it was adjusted to 6V to meet the A/D voltage range.



(a)Phase.1 (b)Phase.2



(c)Phase.3 (d)Phase.4

Fig. 11. Phase views of moving forward motion with a 50g weight

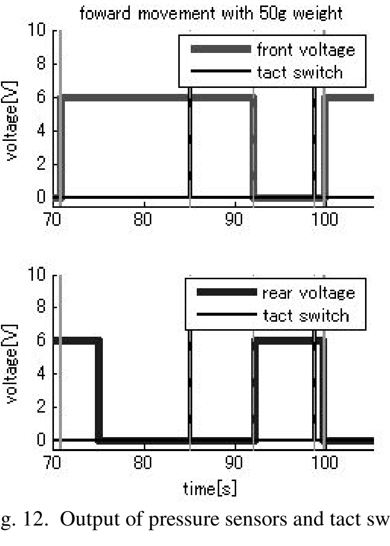


Fig. 12. Output of pressure sensors and tact switch

The phase transition occurred when the output of tact switch and pressure sensor changed.

Again, it is evidential to declare that the weight loading is enough for a forceps and a micro camera. However, the graph (Fig. 12) showed that, it took around 25 seconds for one cycle of movement. This required further investigation and effort.

C. *Moving forward on a slope*

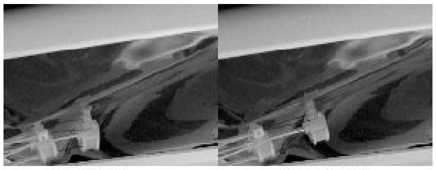
As described in section Ⅴ-A, the peritoneum extended to the tension from suckers, due to its high elasticity. Moreover, the peritoneum is a dome-like 3D surface, rather than a plane. To determine whether the robot could respond to the situation, an experiment on moving forward on a 10-degree slope was conducted. Some phase views were shown in Fig. 13. The output of pressure sensors and tact switch were shown in Fig. 14.

The result showed that the robot was able to move forward on the slope, so that could adapt to the environment. However, the operations were even more difficult, which was reflected by the longer cycle time in Fig. 14.

The shape of suckers, and the way to fine tune posture of the suckers, should be further investigated.

D. *The other motions*

By a series of experiment, the other motions, such as moving backward, turning right/left, moving up/down were tested. As expected, the robot system could successfully achieve the motions.


(a)Phase.1 (b)Phase.2

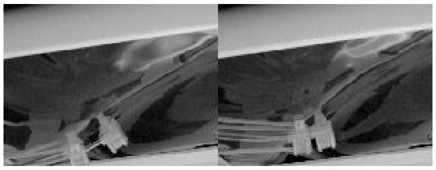

(c)Phase.3 (d)Phase.4

Fig. 13. Phase views of moving forward motion on a 10-degree slope

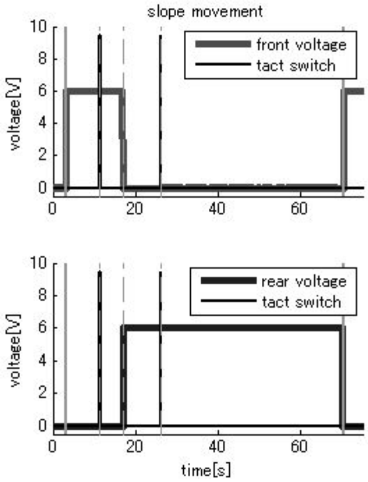


Fig. 14. Output of pressure sensors and tact switch

VI. CONCLUSION

We proposed a robot system that could move in various directions, while hanging upside down on the peritoneum. The robot system was designed to realize the necessary functions, while considering weight and size constraints.

A prototype robot system was made. Using the prototype system, adsorption force experiment showed the vacuum suction could facilitate stable motion and support.

Weight loading experiment showed that, the robot system could provide surgery support for NOTES by guiding and holding forceps and loading a camera for visibility.

In near future, in order to improve the efficiency of the surgery support, the shape of suction cups, and the way of fine-tuning sucker posture, should be further investigated. Moreover, the control of wires and guide-tubes should be automated by building a computer-based motor control system. Furthermore, biocompatible material and design should be paid more attention, and animal experiment is necessary before clinical trial.

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