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Design and Control of a Compact Laparoscope Manipulator: A Biologically Inspired Approach

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1. Introduction

Laparoscopic surgery is a technique where surgical tools and a laparoscope are inserted into the patient's body through small holes in the abdomen, and the surgeon carries out the surgery while viewing the images from the laparoscope on a TV monitor (see Fig. 1(left)). Laparoscopic surgery has grown rapidly in popularity in recent years, not only because it is less invasive and produces less visible scarring, but also because of its benefits in terms of healthcare economy, such as shorter patient stays. The most important characteristic of this technique is that the surgeon performs the operation while watching the video image from the laparoscope on a monitor instead of looking directly at the site of the operation. Thus, an important factor affecting the safety and smoothness of the operation is the way in which the video images are presented in a field of view suitable for the surgical operation. Manipulation of the laparoscope is not only needed for orienting the laparoscope towards the parts requiring surgery, but also for making fine adjustments to ensure that the field of view, viewing distance and so on are suitable for the surgical operation being performed. A camera assistant operates the laparoscope according to the surgeon's instructions, but must also make independent decisions on how to operate the laparoscope in line with the surgeon's intentions as the surgery progresses. Consequently even the camera assistant that operates the laparoscope must have the same level of experience in laparoscopic surgery as the surgeon. However, not many surgeons are skilled in the special techniques of laparoscopic surgery. It is therefore not uncommon for camera assistants to be inexperienced and unable to maintain a suitable field of view, thus hindering the progress of the operation. To address this problem, laparoscope manipulating robots are expected as a substitute for the human camera assistant and have already been made commercially available (see Fig. 1(right)). However, there are several problems to be solved:

1. **Hardware problems**: A large apparatus sometimes interferes with the surgeon. The setting and repositioning is awkward. Furthermore, the initial and maintenance costs are expensive.

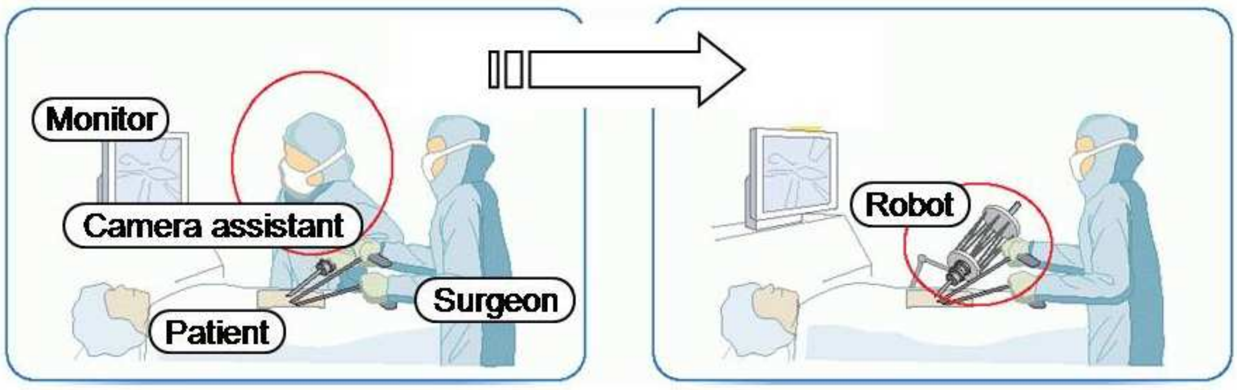

Fig. 1. Laparoscopic surgery. (left) Conventional laparoscopic surgery where the laparoscope is operated by a human camera assistant. (right) Robot-assisted surgery where the laparoscope is operated by a laparoscope manipulator.

2. **Software problems**: It is difficult to build and implement the accurate laparoscope manipulating model and consequently the conventional systems may not always offer the optimal view that the surgeon wants.

In this chapter, we will introduce a biologically inspired approach to the development of a new laparoscope manipulating robot to overcome those problems.

2. Related works

Laparoscope manipulators have been developed in the last fifteen years and there are at least 27 kinds of laparoscope controlling robots which are commercialized or published in refereed articles as of September 2009 (Taniguchi et al. (2010)). Some of them have already been made commercially available and are in widespread use. These include AESOP made in the US by Computer Motion Inc. (now known as Intuitive Surgical Inc.) (Sackier & Wang (1994)), EndoAssist made in the UK by Armstrong Healthcare Ltd. (now known as Prosurgics Inc.) (Aiono et al. (2002)), LapMan made in Belgium by Medsys s.a. (Polet & Donnez (2004)), and Naviot made in Japan by Hitachi Co.,Ltd. (Tanoue et al. (2006)). Although these commercialized manipulators have various merits such as stable view and reduction of need for medical staff, several problems have been noted. First, the bulky manipulator and the supporting arm often interfere with the surgical procedures. Second, the setting and detaching of the robot is frequently awkward, causing an extension of the time required for the operation. Furthermore, the initial and maintenance costs are expensive. In addition to such hardware problems, they usually must be controlled by the operating surgeon himself/herself using a human-machine interface such as an instrument-mounted joystick, foot pedal, voice controller, or head/face motion-activated system. This is an additional task that distracts the surgeon’s attention from the main region of interest and may result in frustration and longer surgery time.

To free the surgeon from the task of controlling the view and to automatically offer an optimal and stable view during laparoscopic surgery, several automatic camera positioning systems have been devised (Casals et al. (1996), Wei et al. (1997), Wang et al. (1998), Nishikawa et al. (2003), Ko & Kwon (2004), Nishikawa et al. (2006)). These systems visually extract the shape and/or position of the surgical instrument from the laparoscopic images in real time, and automatically manipulate the laparoscope to always center the tip of the instrument in the displayed image. Such systems are based on the simple idea that the projected position of the distal end of the surgical tool corresponds to the surgeon's region of interest in a laparoscopic image. Besides centering on the most interesting area, there is an additional and important factor that defines a good image of the surgical scene—*zooming ratio* (Nishikawa et al. (2008)) — that corresponds to the depth of insertion of the laparoscope along its longitudinal axis. The pioneering studies of fully automatic camera positioning systems defined the zooming ratio as a "uniform" function of the estimated distance between the tip of the tool and the laparoscope (Wei et al. (1997)) or the area ratio between the visible tool and the whole image (Casals et al. (1996)). Although these approaches may completely remove the surgeon's camera control burden, they may not provide the specific view that the surgeon wants, because the most appropriate zooming ratio varies widely during surgery. The best zooming ratio depends on both the surgical procedure/phase and the habits/preferences of the operating surgeon. For this reason, most of the instrument tracking systems recently developed (Wang et al. (1998), Nishikawa et al. (2003), Ko & Kwon (2004), Nishikawa et al. (2006)) have abandoned the idea of systematic control of zooming parameters; instead, the surgeon is required to define the parameters preoperatively or adjust them intraoperatively through conventional human-machine interfaces, which again means an extra control burden for the surgeon.

3. Hardware design: analogy to human muscular structure

We developed a compact and lightweight robot manipulator, named P-arm (Sekimoto et al. (2009)), in collaboration with Daiken Medical Co., Ltd., Japan.

3.1 Parallel mechanism

There are several parallel robots (Kobayashi et al. (1999), Tanoue et al. (2006), Pisla et al. (2008)), which operates a laparoscope through the incision point on the abdominal wall of the patient. These systems have "less than 4" DOF and set up the laparoscope "outside" the parallel mechanism. Unlike the previous systems, the proposed manipulator is composed of a Stewart-Gough platform equipped with "six" linear actuators arranged in parallel "around" the laparoscope (see Fig. 2). This novel mechanism has an analogy to human muscular structure in which many extensors and flexors interact with each other; the rigid laparoscope corresponds to a bone of the human body and the linear actuators correspond to the muscles attached to the bone. This bio-inspired structure enables both the manipulator itself and the space necessary for operating the manipulator to be simple and small. The size of the P-arm is 120 mm in maximum diameter and 297.5 mm in length. Consequently, the manipulator can avoid interference with the surgeon's work during surgery. The Stewart-Gough platform has 6 DOF, whereas laparoscope movements are kinematically restricted to 4 DOF, due to the constraints imposed by operating through the incision point. In our case, even when two of the six actuators stop and are dislocated, the manipulator works safely because the system uses the remaining four actuators to produce constrained 4 DOF motion. Thus, our laparoscope manipulating robot based on the use of Stewart-Gough platform architecture provides both flexibility and accuracy while maintaining safety.

(a) (b)

Fig. 2. Compact and lightweight laparoscope manipulator, named P-arm. (a) The P-arm is composed of a Stewart-Gough platform equipped with six linear hydraulic actuators. (b) The P-arm can hold a general laparoscope and can be supported by the conventional instrument holder.

3.2 Hydraulic actuators

The “artificial” muscles of the manipulator, that is, the linear actuators, are driven by hydraulic pressure transmitted via tubes connecting to the water cylinders in the controller unit. The actuator, tube, and the cylinder containing water were assembled en bloc and packaged in sterilized condition for clinical use. Also, the materials that were as inexpensive as possible were selected for all the parts of the manipulator including the actuators among those suitable for medical use and sterilization. All of the previously developed robots had to be wrapped in a sterilized plastic bag preoperatively, because the robot itself was not suitable for sterilization. The proposed manipulator was designed to be disposable and to be provided in a sterilized condition to make the preparation for the operation easy and quick and lessen the maintenance cost of the robot. Furthermore, materials in the manipulator were also selected in consideration of their weight. The actuator, which was mainly made of polycarbonate, weighed only 30 g. In total, the manipulator weighed only 580 g. The light weight allows that the manipulator to be fixed to the operating table with a conventional slim instrument holder. This makes the setting and repositioning of the manipulator easier and quicker. Also, the operating table can be tilted without repositioning the manipulator.

The actuators are attached to the manipulator using a permanent magnet. Therefore, when excess force is applied to the manipulator, the actuator is readily dislocated so it does not injure the patient. In addition, even when two of the six actuators are dislocated, the manipulator works safely as discussed above. The dislocated actuators can be easily reattached to the manipulator. Furthermore, in the case of an emergency, the robot can be stopped promptly by the emergency stop system, which is controlled by a circuit independent of the operating system.

3.3 Results

The robot was evaluated by performing the following three types of operations using a living swine: a laparoscopic cholecystectomy, a laparoscopic anterior resection of the rectum, a laparoscopic distal gastrectomy (Sekimoto et al. (2009)). As a result, it worked steadily for all the operations, without interfering with the surgeon's work (see Fig. 3). Also,

Fig. 3. View of an *in vivo* experiment (laparoscopic cholecystectomy) using a living swine. The P-arm and its supporting arm were so small that they did not interfere with the surgeon's work.

it contributed to shortening the setting and detaching time. The setting times were 66, 93, 104 seconds and the detaching times were 24 and 17 seconds, respectively. Wagner reported the setting time of 2 minutes for AESOP and 5.3 minutes for EndoAssist (Wagner et al. (2006)). Compared with these results, the P-arm was considered to be superior. The facility of the system is essential for the robot to be accepted by surgeons.

4. Software design: Use of biological fluctuation

Recent studies revealed that biological systems did not require the precise environmental model but rather made use of "fluctuation" in order to adapt to the environment. This adaptation mechanism can be represented by the following equation (Kashiwagi et al. (2006)):

$$\frac{d\vec{x}}{dt} = \vec{f}(\vec{x}) \times activity + \vec{\eta} \tag{1}$$

where $\vec{x}$ and $\vec{f}(\vec{x})$ are the state and the dynamics of the system, and $\vec{\eta}$ indicates noise (fluctuation). A scalar variable *activity* indicates the fitness of the state $\vec{x}$ to the environment and controls the behavior of the system. The term $\vec{f}(\vec{x})$ × *activity* becomes dominant in the above equation when the variable *activity* is large, and the state transition becomes deterministic. On the other hand, the noise $\vec{\eta}$ becomes dominant when *activity* is small, and the state transition becomes probabilistic. If the function $\vec{f}(\vec{x})$ has several attractors, the state of the system $\vec{x}$ is entrained into one attractor when *activity* is large, while the behavior of the system becomes like a random walk when *activity* is small. The variable *activity* is designed to be large (small) when the state $\vec{x}$ is suited (not suited) to the environment. The function $\vec{f}(\vec{x})$ is designed to have several attractors and updated in real-time based on the present *activity* information such that the state $\vec{x}$ may efficiently become suited to the environment. As a result, the state of the system is entrained into an attractor that is suited to the environment and *activity* becomes large. Otherwise *activity* remains small and the system searches for a suitable attractor by a random walk.
By letting the state $\vec{x}$ be the desired position of the tip of the right-hand surgical instrument in terms of laparoscopic camera coordinates, we developed a novel laparoscope positioning system that did not require any precise camera manipulating models (Nishikawa et al. (2009a)).

4.1 Design of activity

In order to find the *activity*–the most important factor for offering the specific view that the surgeon wants during laparoscopic surgery, a number of *in-vitro* laparoscopic cholecystectomy tests were performed. For each test, a swine liver with a gallbladder was placed in a training box and the gallbladder was removed by an operating surgeon with the use of the laparoscope robot P-arm controlled through a joystick interface by a camera assistant (another surgeon). In order to gather the positional relationship between the right and left surgical instruments and the laparoscope during surgery, a 3D tracking system (Polaris Accedo, NDI Corporation) was used. As a result, it was found that the velocity of the tip of the left-hand instrument and the velocity of the tip of the laparoscope had a high correlation (the cross correlation coefficient between the two was +0.765, (Nishikawa et al. (2009b))). We hypothesized that, at least in case of laparoscopic cholecystectomy, the camera assistant changed the field of view when the magnitude of the acceleration of the tip of the left-hand instrument was large, and employed the following equation as the activity:

$$activity = \frac{1}{N}\sum_{n=0}^{N-1} activity_{i-n} \tag{2}$$

$$activity_i = \frac{1}{N}\sum_{n=0}^{N-1} p_{i-n} \tag{3}$$

$$p_i = \begin{cases} 0 & \text{if } \left|v_i - v_{i-1}\right| > K \\ 1 & \text{if } \left|v_i - v_{i-1}\right| \le K \end{cases} \tag{4}$$

where i means time, N indicates the positive number for calculating the moving average. v_i indicates the magnitude of the velocity of the tip of the left-hand instrument at time i, and $K(>0)$ is a threshold value.

4.2 Design of attractors

In Eq. 1, $\vec{f}(\vec{x})$ must have several attractors. Fukuyori et al. (2008) pointed out that the attractor should be adaptively allocated where the activity becomes large. Based on this concept of "adaptive attractors", we regard the position of the tip of the right-hand instrument at time j as the center of the j-th attractor with the magnitude of $C^{i-j} \times activity_j$ at time $i(\ge j)$, and employ the following equation to design attractors:

$$\vec{f}(\vec{x}) = \sum_{j \le i, C^{i-j} \times activity_j > M} \left[C^{i-j} \times activity_j \times \frac{B}{\left\|\vec{r}_j - \vec{x}\right\|^2 + A} \right] \cdot \frac{\vec{r}_j - \vec{x}}{\left\|\vec{r}_j - \vec{x}\right\|} \tag{5}$$

$$\vec{x}(t)\big|_{t=0} = \frac{1}{N}\sum_{n=0}^{N-1} \vec{r}_{i-n} \tag{6}$$

where i means the present time, N indicates the positive number for calculating the moving average. The vector $\vec{r}_j$ represents the position of the tip of the right-hand instrument at time j. A, B, and C are all the positive constants: the parameters A and B respectively set the range and power of attractors, and the parameter $C(<1)$ indicates a forgetting factor. $M(>0)$ is a threshold for ignoring weak attractors. The term $\frac{B}{\left\|\vec{r}_j - \vec{x}\right\|^2 + A}$ acts like the Gaussian function whose center is $\vec{r}_j$.

4.3 Results

We implemented this bio-inspired method on our robotic laparoscope positioner described in section 3. Fig. 4 shows the overview of our automatic laparoscope positioning system. The position/pose of the three tools: the right and left instruments and the laparoscope can be obtained simultaneously by the commercial 3D tracking system, Polaris Accedo (NDI Corporation) (See Blasinski et al. (2007) and Nishikawa et al. (2008) for the details). Then

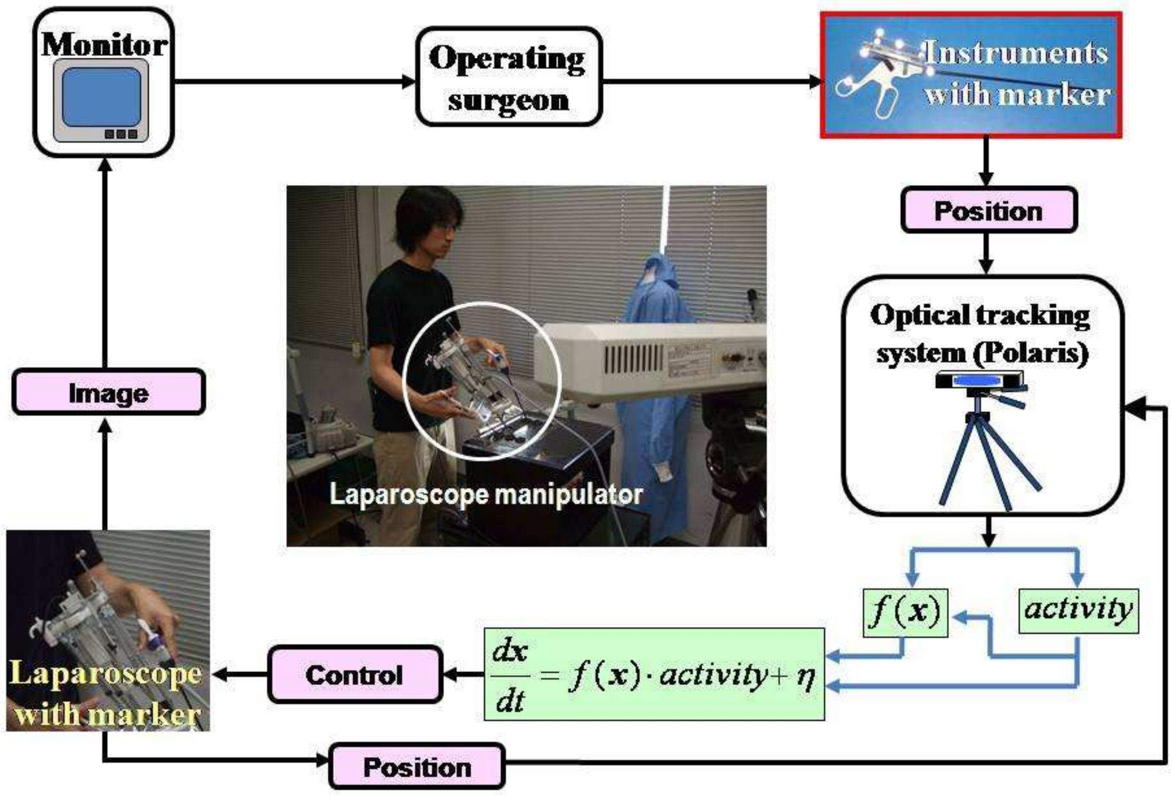

Fig. 4. Overview of automatic laparoscope positioning system. The proposed system uses "fluctuation" to determine and update in real-time the desired position of the tip of the righthand instrument, $\vec{x}$, during surgery.

both $\vec{r}_i$ (the position of the tip of the right-hand instrument) and $\vec{v}_i$ (the velocity of the tip of the left-hand instrument) are estimated in terms of laparoscopic camera coordinates, and *activity* and $\vec{f}(\vec{x})$ are calculated from Eqs. 2 and 5 respectively. As a result, we can determine and update also in real-time the desired position of the tip of the right-hand instrument, $\vec{x}$, during surgery, by substituting the resulting values: *activity* and $\vec{f}(\vec{x})$ into Eq. 1 and solving the Eq. 1 numerically (e.g., by the Runge-Kutta method) under the initial condition given by Eq. 6.
To validate the proposed system, a number of *in-vitro* laparoscopic cholecystectomy tests were performed. For each test, a swine liver with a gallbladder was placed in the training box and the gallbladder was removed by an operating surgeon with the support of the laparoscope robot P-arm controlled by Eq. 1. As a result, our system successfully and automatically controlled the position of a laparoscope during all the operations (Figs. 5–10).

5. Concluding remarks

A compact and lightweight laparoscope manipulator was developed. Also, a novel method for controlling the position of a laparoscope was inspired by biological systems dynamics. Our approach opens potential applications to skill transfer and adaptive behavior in medicine.

Fig. 5. View of an *in vitro* experiment (laparoscopic cholecystectomy) using a swine liver with a gallbladder (1/6). (left) a surgeon and the laparoscope robot P-arm, (mid) image from the laparoscope, (right) visualization of attractors as the contour map on the image plane.

Fig. 6. View of an *in vitro* experiment (laparoscopic cholecystectomy) using a swine liver with a gallbladder (2/6). (left) a surgeon and the laparoscope robot P-arm, (mid) image from the laparoscope, (right) visualization of attractors as the contour map on the image plane.

Fig. 7. View of an *in vitro* experiment (laparoscopic cholecystectomy) using a swine liver with a gallbladder (3/6). (left) a surgeon and the laparoscope robot P-arm, (mid) image from the laparoscope, (right) visualization of attractors as the contour map on the image plane.

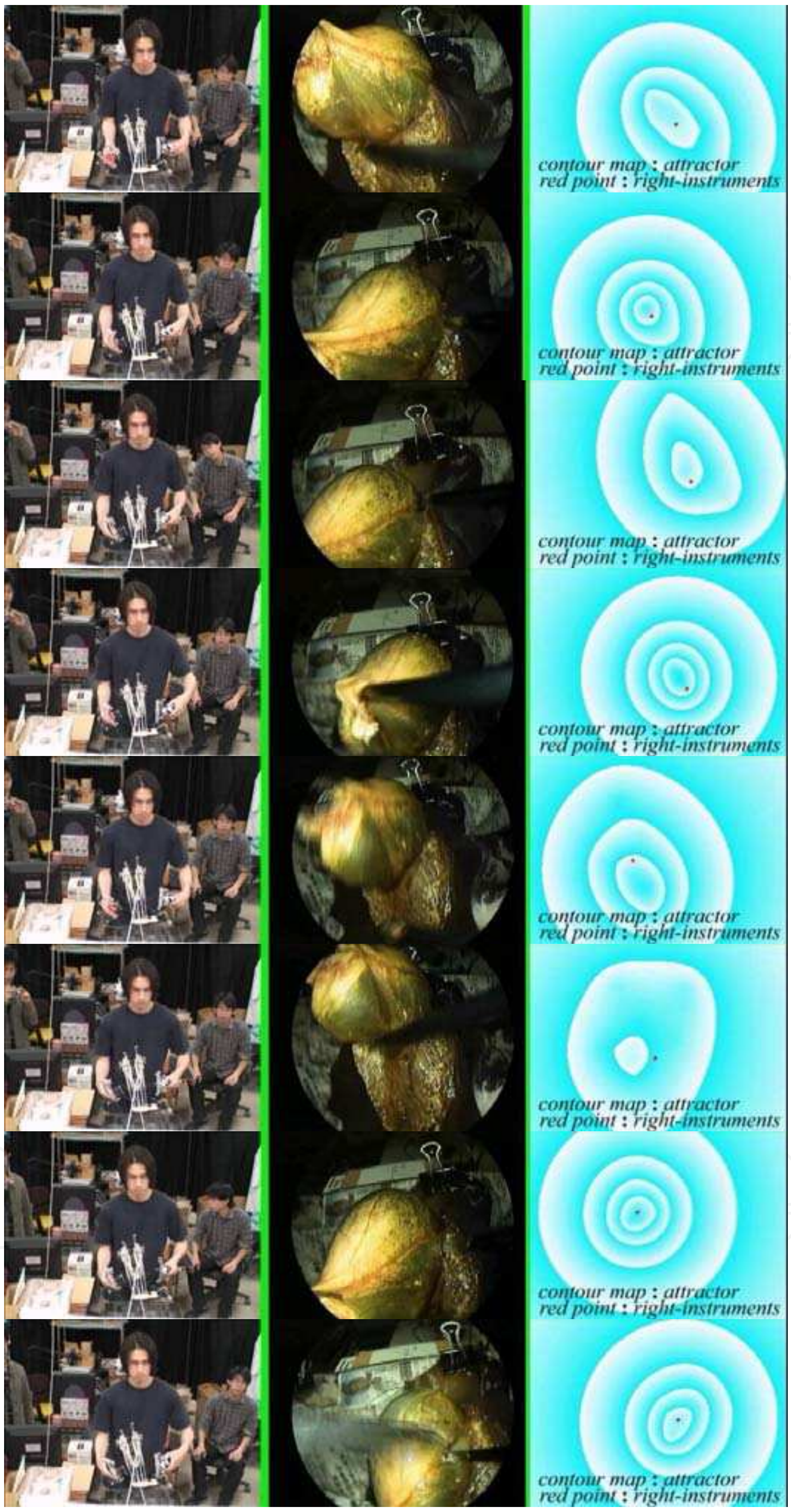

Fig. 8. View of an *in vitro* experiment (laparoscopic cholecystectomy) using a swine liver with a gallbladder (4/6). (left) a surgeon and the laparoscope robot P-arm, (mid) image from the laparoscope, (right) visualization of attractors as the contour map on the image plane.

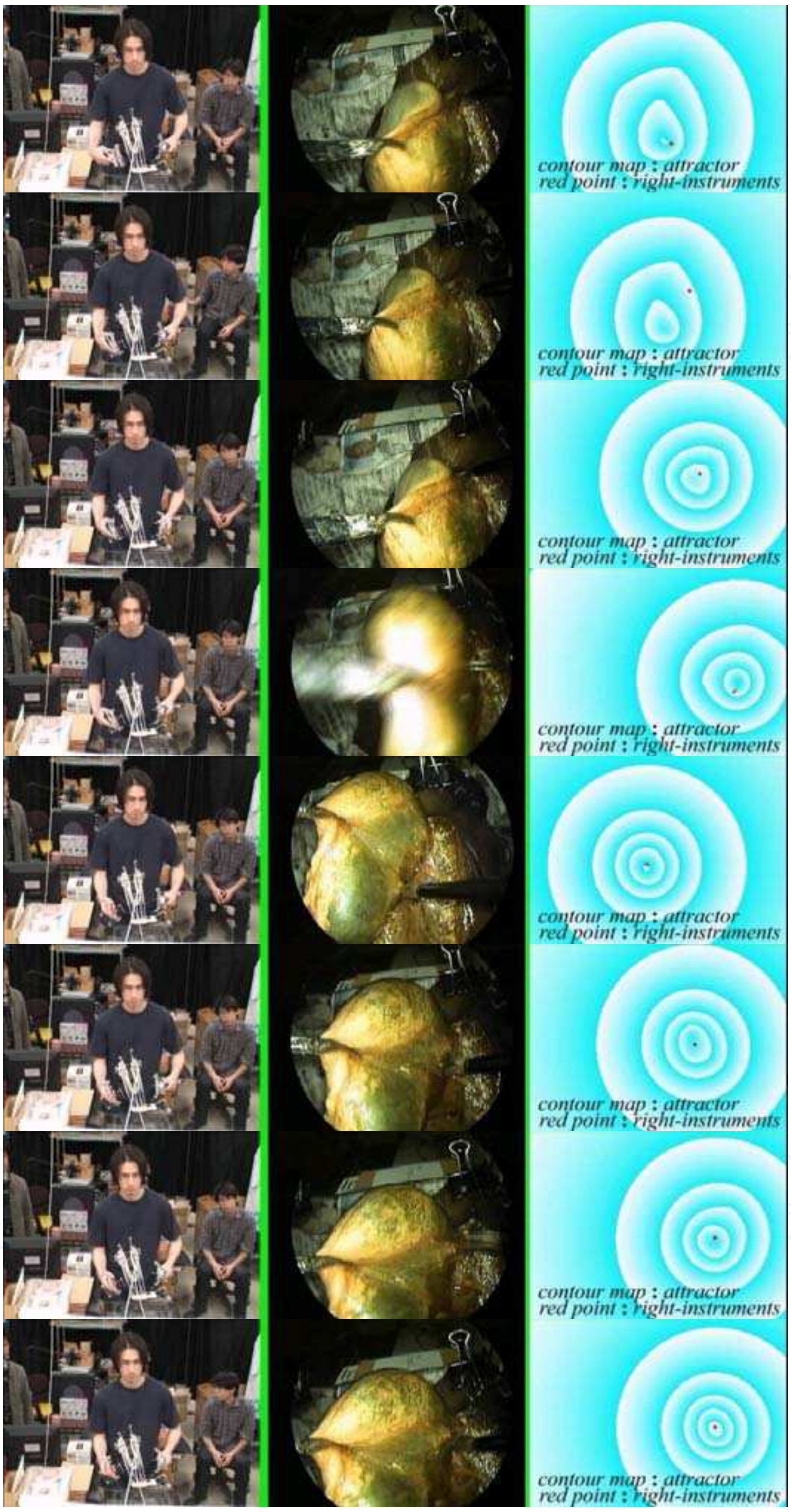

Fig. 9. View of an *in vitro* experiment (laparoscopic cholecystectomy) using a swine liver with a gallbladder (5/6). (left) a surgeon and the laparoscope robot P-arm, (mid) image from the laparoscope, (right) visualization of attractors as the contour map on the image plane.

Fig. 10. View of an *in vitro* experiment (laparoscopic cholecystectomy) using a swine liver with a gallbladder (6/6). (left) a surgeon and the laparoscope robot P-arm, (mid) image from the laparoscope, (right) visualization of attractors as the contour map on the image plane.

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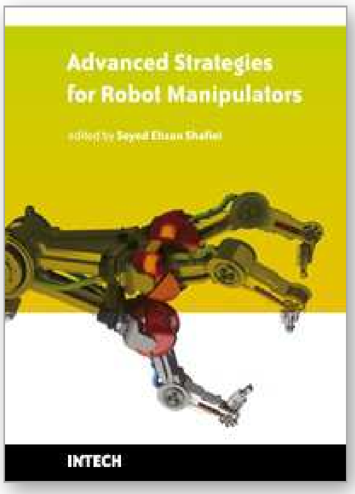

Advanced Strategies for Robot Manipulators
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Amongst the robotic systems, robot manipulators have proven themselves to be of increasing importance and are widely adopted to substitute for human in repetitive and/or hazardous tasks. Modern manipulators are designed complicatedly and need to do more precise, crucial and critical tasks. So, the simple traditional control methods cannot be efficient, and advanced control strategies with considering special constraints are needed to establish. In spite of the fact that groundbreaking researches have been carried out in this realm until now, there are still many novel aspects which have to be explored.