Published in final edited form as:
Rep U S. 2009 October 15; 2009: 2783–2788. doi:10.1109/IROS.2009.5354704.

Perceptually Docked Control Environment for Multiple Microbots: Application to the Gastric Wall Biopsy

Ka Wai Kwok,
Institute of Biomedical Engineering, Imperial College London, UK, Tel: +44 (0) 20 7594 8358; fax: +44 (0) 20 7581 8024; k.kwok07@imperial.ac.uk

Loi Wah Sun,
Institute of Biomedical Engineering, Imperial College London, UK

Valentina Vitiello,
Institute of Biomedical Engineering, Imperial College London, UK

David R. C. James,
Institute of Biomedical Engineering, Imperial College London, UK

George P. Mylonas,
Institute of Biomedical Engineering, Imperial College London, UK

Ara Darzi, and
Department of Surgical Oncology and Technology, Imperial College London, UK, a.darzi@imperial.ac.uk

Guang-Zhong Yang
Institute of Biomedical Engineering, Imperial College London, UK

Abstract

This paper presents a human-robot interface with perceptual docking to allow for the control of multiple microbots. The aim is to demonstrate that real-time eye tracking can be used for empowering robots with human vision by using knowledge acquired *in situ*. Several micro-robots can be directly controlled through a combination of manual and eye control. The novel control environment is demonstrated on a virtual biopsy of gastric lesion through an endoluminal approach. Twenty-one subjects were recruited to test the control environment. Statistical analysis was conducted on the completion time of the task using the keyboard control and the proposed eye tracking framework. System integration with the concept of perceptual docking framework demonstrated statistically significant improvement of task execution.

I. INTRODUCTION

Recent advances in robotics have elevated Minimally Invasive Surgery (MIS) to a new level allowing enhanced vision and improved motor control. Previous work on human-robot interaction beyond manual control has been mainly focused on voice and visual data. The Automated Endoscopic System for Optimal Positioning (AESOP), for example, is a surgical robot capable of maneuvering and positioning a laparoscope in response to a surgeon's verbal commands [1]. The use of voice-control obviates the need for an assistant holding the camera and can increase the stability of the image. The main drawbacks of the voice controlled system are the time-consuming voice-training required for each individual surgeon before the operation and the distraction to other surgical staff due to continuous vocal adjustments of the system during surgery. The human visual line-of-sight, on the other hand, is based on the pose of the head and the orientation of the eyes. Since these are deeply correlated with user intention and attention, such information can be detected to build natural and intuitive interfaces. The feasibility of using a visual tracking technique to identify eyes, nostrils and lip corners has been demonstrated previously [2]. Early techniques were based on intrusive approaches such as measuring the electric potential of the skin around the eyes or applying special contact lenses that facilitate eye gaze tracking [3]. Unsurprisingly, this caused serious problems of user acceptance. A non-intrusive facial feature tracker [4] has been developed to track the eyes at a rate of 15 Hz using a remote camera without any other special accessories. However, gaze tracking systems are limited by the fact that only local information is used for estimating the user's gaze. Consequently, these systems rely on a relatively stable position of the user's head with respect to the camera. In fact, the problem of finding a user's focus of attention using only gaze information is ill-posed. Involuntary eye movements should also be addressed to develop a high level model. Recently, binocular camera tracking has been developed. Perception and control have been integrated on a stereo camera system capable of tracking objects of different shapes and motions in real-time, thus strongly improving its robustness for visual servoing tasks [5]. Recent research work has demonstrated the use of gaze contingent motor channeling by effectively linking haptics with visual tracking, thus further extending its practical value [6]. With the emergence of microbots (micro-robotic devices), the control of these systems becomes a difficult task. Although it is technically attractive to pursue a fully autonomous approach for microbots deployed *in vivo*, the regulatory, ethical and legal barriers would prohibit their practical clinical application. In this regard, the use of perceptual docking for highly integrated human-robot control represents an attractive way forward.

In this paper, the concept of perceptual docking is demonstrated on a multiple microbot control task for performing gastric wall biopsy. Perceptual docking allows the *in situ* extraction of the surgeon's attention always keeping the robot under the firm control of the operator. This study demonstrates that real-time 2D eye tracking can be used for empowering robots with innate human sensing and judgment. The overall setup of the framework is shown in Fig. 1. The feasibility of the proposed control environment has been evaluated and the results are discussed.

II. The concept of perceptual docking

The concept of perceptual docking has recently been introduced in the field of robotic control [7]. It is defined as a novel method of knowledge acquisition for robotic systems that utilizes *in situ* learning of operator specific motor and perceptual/cognitive behaviour, such as gaze direction. By tracking the binocular eye movement, the information from both eyes is used to determine the fixation point by averaging each eye's fixation position projected on the screen. It is also one of the strongest cues available to humans through binocular vision. Through 2D eye tracking, gaze-contingent motor channeling for augmenting the surgeon's motor abilities has also been proposed to control the surgical instruments with the aid of human vision [6]. In particular, gaze-contingent instrument guidance and attention selection enable the eyes to act as an additional human robot interface modality.

III. Methodology

The overall aim of this study is to develop a versatile simulator for practicing control of multiple microbots. Initially, a 3D stomach model is reconstructed by segmentation of preoperative CT scan images. The reconstruction is to transform volumetric data into vertex data upon which the triangular mesh defining the stomach structure is produced and implemented in the simulation environment using OpenGL. A realistic surface texture from high resolution mucosal and submucosal images is attached. The model serves as the basis for the animation and visual rendering. Subsequently, the kinematics of the microbots is modeled to provide effective manipulation capabilities. Collision detection is also incorporated to enhance the realism of the simulation environment.

A. Kinematics and Workspace of the Microbots

The microbots simulated in the control environment represent abstract devices with mechanical structure and workspace specifically designed in order to be able to perform the simulated surgical procedure. The simulated microbots feature two arms with identical mechanical structure, each equipped with a micro-forceps. They are constituted of two links connected by universal joints giving two degrees-of-freedom (DoFs) each and are attached to the base with a 1 DoF rotational joint, giving a total of 3 DoFs for each robotic arm. The base carries the camera and microcontroller. Both forward and inverse kinematics of the robotic arms are determined. Particularly, the kinematic chain model of the robot is shown in Fig. 2. The base reference frame of each two-link arm is centered in correspondence to the revolute joint connecting the base of the robot with the arm. Thus, the homogeneous transformation between base and end-effector coordinate systems is the same for both arms and is given by:

$$ {}^{0}T_{3} = {}^{0}T_{1}\,{}^{1}T_{2}\,{}^{2}T_{3}, \quad \text{where} \quad {}^{i-1}T_{i} = \begin{bmatrix} {}^{i-1}R_{i} & {}^{i-1}d_{i} \\ 0_{1\times 3} & 1 \end{bmatrix} \qquad (1) $$

with the rotation matrix ${}^{i-1}R_i$ and the translation vector ${}^{i-1}d_i$ denoting respectively the orientation and the position of frame i relative to frame i-1. The transformation matrix is determined and expressed in terms of the joint angles and the lengths of the links.

The forward kinematics of the arms describing the position of the end-effector in the base coordinate frame is given by the translation vector ${}^{0}d_3$. Since the number of DoFs is small, a closed form solution of the inverse kinematic equations can be computed and the up-elbow and down-elbow solutions are assigned respectively to the right and to the left arm of the robot in order to get specular motion. The kinematic configuration of the phantom tool device is different from the one of the corresponding microbot's robotic arm. Since the PHANToM Omni is used to provide the position of the microbot's end-effector, an appropriate mapping must be defined to have a correspondence between the actual motion of the phantom device and the virtual movement of the microbot's arm. The region of space that can be reached by the instrument tip attached on the robotic arms is “doughnut” shaped as shown in Fig. 3. The mapping between such complicated structure and the simple Cartesian workspace of the phantom device represents a challenging task because no standard procedure can be followed and the potential computational demand is high. The parametric representation of the toroid can be written as:

$$\begin{cases} x(\theta,\varphi)=[R+r\,cos(\varphi)]\,cos(\theta) \\ y(\theta,\varphi)=[R+r\,cos(\varphi)]\,sin(\theta) \\ z(\varphi)=r\,sin(\varphi) \end{cases} \quad (2)$$

where θ is the angle about the z axis, φ is the angle about the axis of the tube, R is the distance between the origin of the reference frame and the axis of the tube and r is the radius of the tube. The range of the θ angle is limited in order to restrict the manipulation within the field of vision of the operator, while the φ angle varies in the interval $[0,2\pi]$. In order to map each point of the Cartesian workspace of the phantom device to the constrained workspace of the robotic arm, the variation of the angular parameters of the toroid has to be determined in function of the corresponding variation of the normalized Cartesian parameters (x_c, y_c, z_c) of the phantom device workspace. Referring to Fig. 4, the θ angle can be mapped to the x_c axis as:

$$\theta=-(\theta_{max}-\theta_{min})\,x_c+\theta_{max} \quad (3)$$

while the φ angle depends on the y_c axis because:

$$z=(-2y_c+1)\,r \quad (4)$$

so that the corresponding extreme values of φ are:

$$\varphi_{min}=arcsin\left(\frac{z}{r}\right), \quad \varphi_{max}=\pi-\varphi_{min} \quad (5)$$

In order to span between these two values, the relation between the variation of φ and the z_c axis must finally be exploited:

$$\varphi=-(\varphi_{max}-\varphi_{min})\,z_c+\varphi_{max} \quad (6)$$

Once the position of the end-effector is mapped from the motion of the phantom device, the values of the joint angles of the robotic arm can be computed using the inverse kinematics and its motion can be simulated.

B. System Integration

Eye tracking is performed using the commercially available stand-alone Tobii X50 eye tracker with an measurement accuracy of 0.7° visual angle. It is an unobtrusive infrared video-based remote eye tracking system used to record fixation points on a screen at 50 Hz. An API interface is designed to calibrate the eye tracker and subject-specific calibration is conducted to learn individual user’s eye characteristics. Two phantom tool devices, (SensAble PHANToM Omni), are also embedded in the control environment to manipulate the micro-forceps of the microbots. They allow the operator to easily grasp the tissue, taking full advantage of the versatility of the arm. The buttons on the stylus control the opening/closing of the instrument micro-forceps within the simulation framework. Finally, the fully functional environment for the simulation of gastric wall biopsy is provided by a virtual reality system library developed in C++ and built with OpenGL API. All the objects belong to one of 3 different models: a geometric model used for rendering, a mechanical model for animation, and a collision detection model to evaluate the interaction with the environment.

C. Collision detection

Collision detection is the process of detecting pairs of objects that are intersecting or are within a given proximity. It is implemented in the simulator in 3D space according to the *GJK* algorithm [8]:

$$d\left(A,B\right)=min\left\{\parallel x\parallel :x\in A-B\right\} \quad (7)$$

$$p\left(A,B\right)=inf\left\{\parallel x\parallel :x\notin A-B\right\} \quad (8)$$

where the length of the shortest vector *d* between *A* and *B* and the penetration depth vector (contact normal) *p* are variables to be determined. The advantage of our collision detection is the capability of maintaining multiple scenes. Each scene tracks the changes of position and deformations of its objects, and updates its cached data accordingly. For complex scenarios involving multiple organ interaction, it can effectively parallelize pair-wise collision checks without going through an intermediate graphics API.

IV. Surgical scenario

For the surgical scenario used for evaluation, we assume that the patient is placed in the supine position under general anesthesia. Initially, a flexible access device is introduced into the patient to reach the gastro-esophageal junction and deliver the microbots in the gastric cavity. The operative field is created by inducing pneumogastrum using CO_2 insufflation [9]. A duodenal occlusive balloon is used in order to prevent insufflated gas escaping into the intestinal tract. We assume that intraluminal gastric lesions have been detected on the stomach wall and exteriorized by endoscopic ultrasonography or computed tomography during pre-operative examination [10]. The simulation control environment features two control interfaces. The operator can use either the arrow keys on keyboard (Fig. 1) as an input device or the integrated 2D eye tracker. Pressing those two keyboard buttons is evaluated as the easiest direct access method that does not involve as much planar hand movement has required by other manually controlled input devices, such as a mouse and a touch screen, which would severely distract the motor memory of the operator while manoeuvring the main instruments.

Different imaging modalities such as pre-operative confocal/Raman images of the gastric wall and intraoperative images from different on-board cameras attached on the robots are provided to the operator by the system during the procedure. The system should have different windows to handle the information. The operator mainly concentrates on the operating site (displayed on the main window) but can also switch between different robot views or imaging modalities and view them on the main window using the proposed framework. Perceptual docking is introduced so that the operator specific perceptual behaviour derived *in situ* can be used to control an array of microbots. The operating console embedding the gaze-contingent simulator, displays a main operative screen with multiple sub-windows. The operator mainly concentrates on the operating site and also can alternate different robot views or imaging modalities and view them on the main window. Since the fixation tolerance is as large as a sub-window that occupies 1/12 of the area of the entire screen (Fig. 1), the effect of gaze errors induced by human factor and system configuration is relatively insignificant under 0.7° measurement accuracy, thus can be neglected. Operator’s eye movement is used to determine the scene while “eye-over” highlighting and a foot pedal allows the operator to trigger the corresponding screen.

The testing scenario for the surgical procedure is incorporated into the simulation framework. The user performs the task in the following stages:

1. Selection of the site for the gastrotomy (target).
2. Selection and introduction of an optic robot to illuminate the target.
3. Triggering of the operative robot to navigate to the target.
4. Grasping the tissue to be elevated (the tissue changes color when touched – detected from collision checking). The tissue is elevated and the sample is extracted (Fig. 4).
5. Mobilization of the assistive robot to the target.
6. Positioning of the robotic arms of the operative robot.
7. Manipulation of the robotic arms of the assistive robot. Passing of the tissue sample from the operative robot to the assistive robot. If the user cannot grasp it properly due to misalignment of the gripper’s position or orientation, step (6) has to be repeated until grasping is successful.
8. Repeat steps (1) to (7) for each of the four lesions.

V. Experimental setup and subjects

Twenty-one subjects were recruited for this study and nineteen were engineers and two were surgeons. Written consent was obtained and the study was covered by local research ethics approval. Each subject practiced a minimum of 5 minutes with the system using both keyboard and eye-tracker before performing the actual task. The task was performed by each subject using the system with and without eye tracking, in a random order. Four variables were recorded:

1. Task completion time;
2. Time spent on the main window (Fixation duration);
3. Number of out-of-screen fixations (denoted by failure of tracking the eyes for durations of more than 1 second indicating that the subject diverts his/her attention to the phantom devices, keyboard or foot pedal);

4. Number of fixations recorded on the main window.

A questionnaire was designed to assess user satisfaction when using the eye tracker. It consisted of 6 statements and participants were asked to rate on a continuous scale from 1 (strongly disagree) to 5 (strongly agree) several aspects of the perceptually docked control environment compared with the use of the keyboard. The Statistical Package for Social Sciences, SPSS (version 17.0, US) was employed for statistical analysis in this study. *Paired t-tests* (confident level was set at 95%, $\alpha = 0.05$): statistical data analysis was conducted between two systems among the 4 parameters. *Correlation:* pearson's product correlation coefficient was determined to assess the degree of association. The p-value was used to examine the relationship between the 4 parameters.

VI. Results and discussion

Virtual biopsy of the gastric wall was successfully performed a total of four times by each participant with each of the control modalities. No misalignment was reported. The analysis was simplified by only considering fixations inside or outside the main window. However, the data were recorded on both the main window and peripheral windows. Fig. 5 shows a reduction of 26% and 34% respectively of the time spent on gazing at the main operative window and the time needed to complete the task. Table 1 summarizes the mean and standard deviation values of the 4 recorded parameters for the two systems. Table 2 presents the paired differences defined as the difference of the system using the keyboard minus the system using the eye tracker. Based on the same task, users spent less time looking at the main window (24.9s in average) as well as the peripheral windows (60.3 - 24.9 = 35.4s in average). The first result can be explained considering that without eye-tracking the subject was still gazing at the main window while switching from the keyboard to the haptic manipulators and vice versa. Together with the second result, this demonstrates improved performance on the control task when perceptual docking is enabled, with shorter completion time, shorter time spent on the main window and fewer out-of-screen fixations. Table 3 shows that the correlation between the overall completion time, the time spent on main window and the number of fixations on main window were very high with r values ranging from 0.710 to 0.884. However, r is low (0.228) for the number of out-of-screen fixations. This clearly demonstrates that the completion time primarily depends on the time spent and the number of fixations on the main window, rather than to the number of out-of-screen fixations. Similar results are achieved by the ICC reliability test. From the statistical results, we conclude that the system using the eye tracker demonstrates statistically significant ($p < 0.05$) improvement for the execution time and the number of fixations on the main window.

Jacob *et al* [11] proved that fixation duration is inversely correlated to the efficiency of task execution. Therefore, the system with eye tracker proved to be more efficient and effective. For the subjective evaluation of the task, we have collected and summarized opinions from the participants based on a questionnaire over 6 areas comparing the two systems (Fig. 6). More than 4 marks were scored in 5 areas signifying that all subjects strongly agreed on the superiority of the gaze-contingent implementation of the control interface. The question "Do you feel a time delay in the system response when using perceptual docking?" on the questionnaire yielded a low score implying that the participants were satisfied with the perceptually docked interface without sensing any excessive docking delay. For this aspect, the error of the study is subject-dependent. It is related partly to the composition of the scene and the procedure complexity, and partly to the observer’s abilities such as reaction time, hand-eye coordination and learning capabilities. In fact, human saccadic eye movements are very fast (30 - 120 ms) [3], it is no doubt that few participants partially felt that a time delay occurred. Using the keyboard arrow keys for robot selection tends to take the user’s attention away from the visual screen and this causes certain errors but not significant. Furthermore, users may lose their motor memory while they leave hold of the haptic device to push the key on keyboard. Depth perception was lost during the experiment due to an essential limitation of the control system which uses a 2D monitor as visualization system. The incorporation of perceptual docking into a control system with stereo display [12] is among the scopes of our future work. The main purpose of the simulated environment is to investigate the proposed perceptual docking control applied to multi-robot cooperation which is becoming one of the future areas in robotic MIS. To this end, a simple bimanual task has been simulated such as the gastric wall biopsy procedure, which involves elevating soft tissue and extracting the sample underneath the tissue. We endeavour to implement other more complicated and realistic surgical procedures such as suturing and create different models of the surgical site using real patient pre-op data acquired using different modalities. Overall, the system using perceptual docking has been met with enthusiasm by the participants. Minor comments were reported such as some difficulty with the foot pedal (too sensitive), or the desire to have some audible feedback during selection or window browsing. Also the need for a more ergonomic setup was reported. These suggestions will be taken into consideration in future setups. The relevant research works have been investigated to measure the binocular eye movement and ocular vergence. A 3D position of the surgeon’s fixation point and in turn 3D depth of the fixated tissue surface can be quantitatively extracted. It has been further demonstrated that eye movements and ocular vergence can be used to perform motion tracking and updating of active constraints in dynamic surgical scenes [12]. Furthermore, eye tracking with ocular vergence detection has been recently reported to perform soft tissue deformation tracking and motion stabilization [13]. For the future trend, eye tracking can potentially provide a whole new range of intuitive human-machine interfacing capabilities.

In this paper, we have described how 2D eye tracking was used to provide a more robust and flexible method for control which is less demanding than traditional mouse/keyboard for truly effective control applications. It can also be integrated in the operating room without obscuring the field of view of the surgeon and the need for intrusive headgear. Analysis of eye movement data provides a valuable methodology to evaluate multimodal human-robot interaction. It provides a moment-to-moment behavioral index of user’s human robot interactions, which serves to decrease the latency between the surgeon’s thoughts and the robot’s action. This approach may also improve acceptance of robotic systems, as the surgeon remains in control of the procedure. We believe that an array of such microbots among which the surgeon can select depending on the needs of the task to perform is far more feasible than a multi-functional robot. This allows the surgeon to supervise and control the robots, using innate human sensing and judgment.

VII. Conclusion

This study demonstrates that robust 2D eye tracking can be effectively used to perform attention selection and provide an efficient means to identify the region of interest for the surgeon. The performance of a control environment that enables endoluminal surgery where the surgeon can guide an array of microbots inside the gastric cavity of the patient is enhanced effectively. The study explores how perceptual docking can be actively used as part of a control interface for channeling selection of multiple microbots. Results have shown that integration with perceptual docking attracts statistically significant improvement in terms of execution time. It is efficient, effective, feasible and easy to operate. To our knowledge, this is the first study to examine the use of vision tracking for multiple microbot control.

Acknowledgments

The authors gratefully acknowledge Prof. Sir Alfred Cuschieri for his valuable comments on the surgical procedure and would also like to thank Dr. Danail Stoyanov for his support and fruitful discussions on the project. We also thank Prof. Paolo Dario and his research group at Scuola Superiore Sant'Anna for contribution to the study.

This research was supported by the Large-Scale Integrating Project (IP-ICT-2007-2#224565) which is entitled as "Array of Robots Augmenting the Kinematics of Endoluminal Surgery (ARAKNES)" and has received funding from the European Community's Seventh Framework Program.

References

[1]. Kunisaki C, Hatori S, Imada T, Akiyama H, Ono H, Otsuka Y, Matsuda G, Nomura M, Shimada H. Video-assisted thoracoscopic esophagectomy with a voice-controlled robot: the AESOP system. Surg Laparosc Endosc Percutan Tech. 2004; 14:323–7. [PubMed: 15599295]

[2]. Yang, J.; Stiefelhagen, R. Gaze tracking for multimodal human-computer interaction; Proc. of IEEE Int. Conf. on Acoustics, Speech and Signal Processing; 1997; p. 2617-20.

[3]. Glenstrup, AJ.; Engell-Nielsen, T. Eye controlled media: Present and future state. University of Copenhagen; 1995.

[4]. Stiefelhagen, R.; Yang, J.; Waibel, A. Tracking eyes and monitoring eye gaze; Proc. of the Workshop on Perceptual User Interfaces; 1997; p. 98-100.

[5]. Bernardion A, Santos-Victor J. Binocular tracking: integrating perception and control. IEEE Transactions on Robotics and Automation. 1999; 15:1080–94.

[6]. Mylonas, GP.; Kwok, KW.; Darzi, A.; Yang, G-Z. Gaze-contingent motor channelling and haptic constraints for minimally invasive robotic surgery; Proc. of Int. Conf. on Medical Image Computing and Computer-Assisted Intervention; 2008; p. 676-83.

[7]. Yang, G-Z.; Mylonas, GP.; Kwok, KW.; Chung, AJ. Perceptual docking for robotic control; Lecture Notes In Computer Science, Proc. of the 4th Int. workshop on Medical Imaging and Augmented Reality; 2008; p. 21-30.

[8]. Gilbert EG, Johnson DW, Keerthi SS. A fast procedure for computing the distance between complex objects in three-dimensinal space. IEEE J of Robotics and Automation. 1988; 4:192–203.

[9]. Chough, EK.; Andrus, CH. Physiology of pneumoperitoneum. Amsterdam: 1998.

[10]. Hyung WJ, Lim JS, Cheong JH, Kim J, Choi SH, Noh SH. Laparoscopic resection of a huge intraluminal gastric submucosal tumor located in the anterior wall: eversion method. J Surg Oncol. 2005; 89:95–8. [PubMed: 15660368]

[11]. Jacob, RJK.; Karn, KS. The mind's eye: cognitive and applied aspects of eye movement research. Elsevier Science; Amsterdam, The Netherlands: 2004. Eye tracking in human–computer interaction and usability research: ready to deliver the promises; p. 573-605.

[12]. Mylonas GP, Darzi A, Yang G-Z. Gaze-contingent soft tissue deformation tracking for minimally invasive robotic surgery. Computer Aided Surgery. 2006; 11:256–66. [PubMed: 17127651]

[13]. Mylonas GP, Darzi A, Yang G-Z. Gaze contingent depth recovery and motion stabilisation for Minimally Invasive Robotic Surgery. Medical Imaging and Augmented Reality. 2004:311–9.

Fig. 1.

Top: The overall setup of the control environment including two PHANToM Omni tool devices and a Tobii eye tracker. Bottom: A snapshot of the console display.

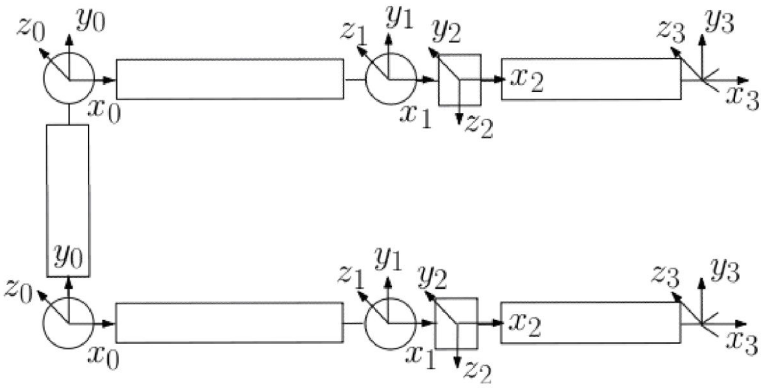

Fig. 2.

Kinematic model of the micro-robot.

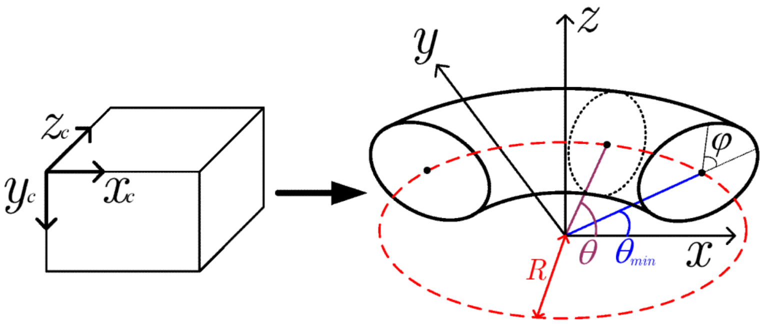

Fig. 3.

Mapping between the workspace of the input device (left) and the workspace of the robotic arm (right).

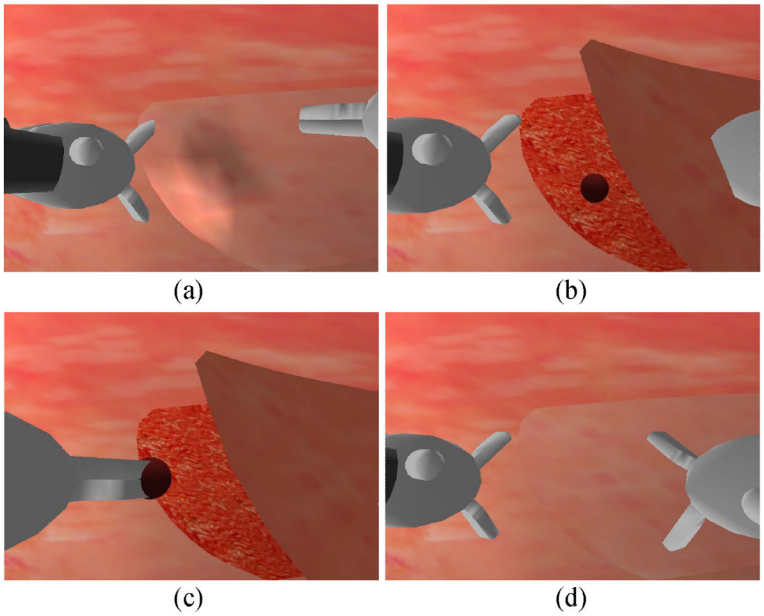

Fig. 4.

The gastric wall biopsy: a) before grasping, the lesion is located under the mucosal tissue; b) grasping and lifting up the layer of mucosal tissue; c) revealing the lesion; and d) the layer of mucosal tissue after sample removal.

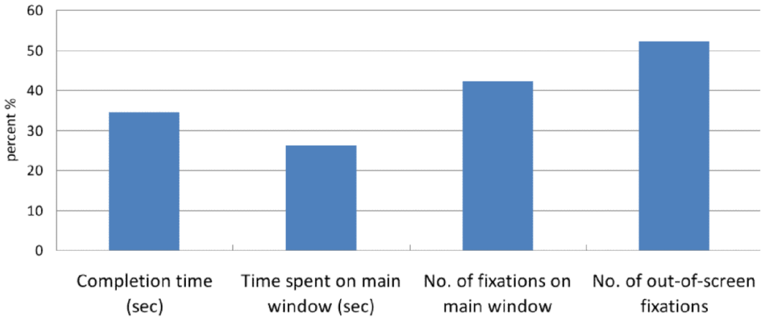

Fig. 5.

The percentage improvement of the four recorded parameters when using eye tracking.

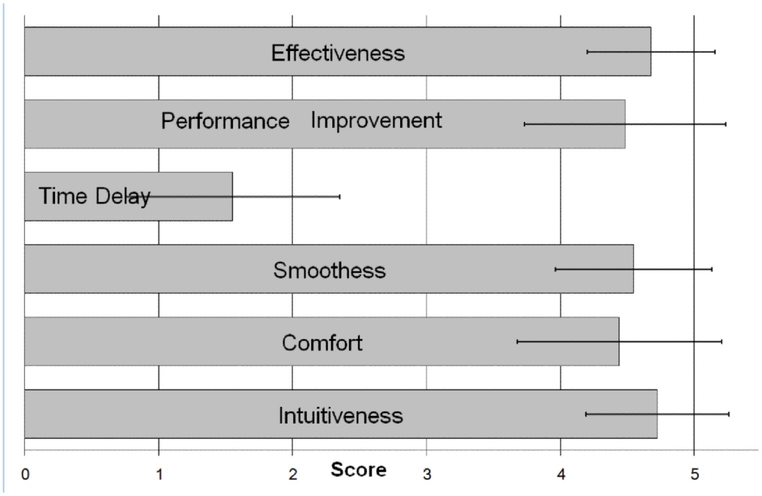

Fig. 6.

Summary of satisfaction in 6 areas when using the eye-tracker. Score mark between 1 (strongly disagree) and 5 (strongly agree)

Table 1

Summary of values of 4 parameters for the two systems

	Keyboard		Eye tracker	
	Mean	**SD**	**Mean**	**SD**
Completion time (sec)	175.2	40.4	114.9	23.5
Time spent on main window (sec)	91.3	32.4	67.4	15.0
No. of fixations on main window	59.3	25.8	34.3	10.4
No. of out-of-screen fixations	15.9	11.8	7.6	9.1

Table 2

Paired differences between the two systems

Paired differences	Mean	SD	95% confidence interval Lower	95% confidence interval Upper	*p*-value
Completion time (sec)	60.3	49.2	37.9	82.7	0.000[*]
Time spent on main window (sec)	24.9	38.1	7.6	42.3	0.007[*]
No. of fixations on main window	25.0	26.6	12.9	37.1	0.000[*]
No. of out-of-screen fixations	8.2	11.0	3.2	13.2	0.003[*]

Paired differences = difference of system using keyboard minus system using eye-tracker

[*] significant at $\alpha = 0.05$ (2-tailed)

Table 3

Correlations between four parameters

	Completion time	
Pearson Correlation, *r*	**Keyboard**	**Eye tracker**
Time spent on main window (sec)	0.724*	0.884*
No. of fixations on main window	0.658*	0.710*
No. of out-of-screen fixations	0.264	0.228