Combined Endo- and Exoscopic Semi-robotic Manipulator System for Image Guided Operations

Stefanos Serefoglou¹, Wolfgang Lauer¹, Axel Perneczky², Theodor Lutze³,
and Klaus Radermacher¹

¹ Helmholtz Institute for Biomedical Engineering of the RWTH Aachen University,
Pauwelsstrasse 20, 52074 Aachen, Germany

{serefoglou, lauer, radermacher}@hia.rwth-aachen.de
<http://www.meditec.hia.rwth-aachen.de/de/index.shtml>

² Neurosurgical Department of the Johannes Gutenberg-University of Mainz,
Langenbeckstrasse 1, 55101 Mainz, Germany

per@nc.klinik.uni-mainz.de
<http://www-klinik.uni-mainz.de/Neurochir/index.html>

³ Aesculap AG & CO. KG, Am Aesculap Platz, 78532 Tuttlingen, Germany
theodor.lutze@aesculap.de
<http://www.aesculap.de>

Abstract. This paper describes the development of a robotic assistance system for image guided operations. To minimize operation time, a multimodal user interface enables freehand robotic manipulation of an extracorporeal stereoscopic digital camera (exoscope) and an endoscope. The surgeon thereby wears a head-mounted unit with a binocular display, a head tracker, a microphone and earphones. Different view positioning and adjustment modes can be selected by voice and controlled by head rotation while pressing a miniature confirmation button with a finger. Initial studies focused on the evaluation and optimization of the intuitiveness, comfort and precision of different modes of operation, including a user test with neurosurgeons in a virtual reality simulation. The first labtype of the system was then implemented and demonstrated in the operating room on a phantom together with the clinical partners.

1 Introduction

Minimally invasive surgery is typically performed through several small incisions using slender instruments and a rigid endoscope. Compared to traditional open surgery, it reduces patient trauma and recovery time but also the surgeon's dexterity and sensibility. Visual assistance systems are necessary whenever the direct sight of the surgeon to the surgical field is difficult or impossible, and are useful to augment images with e.g. preoperatively segmented outlines or navigation data. Several systems utilize robotic manipulators and have already been proposed or used in surgery, as listed in [1, 2] and Table 1. However, some of these, especially retrofitted industrial robots, obstruct the workflow through large size and/or cumbersome handling, thus reducing their acceptance by the clinical staff.

Table 1. Representative robotic manipulators for intraoperative visual assistance

System	Institute/Company	Manipulation	Ref.
AESOP (ZEUS)	Computer Motion	endoscope (& instruments)	[3]
CLEM	TIMC/IMAG	endoscope	[4]
da Vinci	Intuitive Surgical	endoscope & instruments	[5]
EndoAssist	Armstrong Healthcare	endoscope	[6]
FIPS Endoarm	MIC, Tübingen Univ.	endoscope	[7]
KaLAR	KAIST	endoscope	[8]
LARS	IBM	endoscope	[9]
LER	TIMC/IMAG	endoscope	[10]
MKM	Carl Zeiss AG	microscope	[11]
SurgiScope	Elekta	microscope	[12, 13]

The MINOP 2 project included the development of a semi-robotic assistance system to control an extracorporeal digital camera (exoscope) and an endoscope during neurosurgical interventions [14]. To achieve optimal integration into the surgical workflow and space, the implemented user interface enables freehand manipulation of the scopes by the surgeon. The further sections describe the system design, followed by the results of user-centered evaluation with neurosurgeons.

2 Design

The system consists of a control unit, user interface and 2 semi-robotic manipulators, for the exoscope and the endoscope, as shown in Fig. 1-3.

Fig. 1. Labtype of the MINOP 2 system and its user interface

2.1 Control Unit

The control unit of the first labtype system, consisting of a PC, the controller hardware and a flatscreen monitor, is integrated in a trolley, as shown in Fig. 1. It interfaces all other system elements and can be used to transport them.

2.2 User Interface

A head-mounted unit is used by the surgeon during the operation, as shown in Fig. 1. It consists of a binocular display receiving the video image from the exoscope and/or endoscope, an orientation sensor for head tracking, as well as a microphone and earphones for voice control with acoustic feedback.

By using a miniature confirmation button mounted on a finger of the non-dominant hand of the surgeon, an unintentional motion of the manipulators is avoided. This button can alternatively be fixed on or integrated into an instrument such as the suction device. Optionally, the head tracking sensor can be used for manual control as a 3D joystick with integrated confirmation button. In contrast, foot switches were undesirable by the clinical partners, as these are already used for other devices.

Voice control is used to select an active scope and a mode for adjustment, as listed in Tables 2 and 3. Recognized commands are repeated for acknowledgement and performed while the confirmation button is pressed. Depending on the mode, adjustments are proportional to the following head rotation along the transversal, vertical and/or sagittal axis. The active scope is controlled with respect to its “eye” coordinate system, thus ensuring compatibility of view and motion. Releasing the button stops pending adjustments and the user may assume a more comfortable head orientation.

2.3 Exoscope Manipulator

The exoscope is a stereoscopic camera with motorized zoom and focus. It provides two composite video outputs. Illumination of the surgical field is provided by a cold light source through an optical fiber.

The exoscope is mounted on a semi-robotic manipulator, as shown in Fig. 2, utilizing a combination of manual coarse positioning and tele-manipulated robotic fine positioning. The manipulator is fixed on the operation table by a new type of multifunctional arch, as shown in Fig. 1. In case of emergency, the arch can be unlocked and swept aside within a few seconds to provide immediate access to the patient. After fixation, the system can be covered with sterile drape.

Coarse positioning comprises 3 translatory and 2 rotatory (pitch and yaw) degrees of freedom (DOF). The pitch axis is motorized, the other axes are passive and gravity balanced. The pitch and roll axes also possess electromagnetic brakes, which can be released before positioning by pressing a button on a grip. All axes for coarse positioning can be controlled simultaneously with one hand to bring the exoscope directly over the surgical field, typically at the beginning and the end of an intervention, thus allowing a robotic manipulator with compact design and kinematically restricted workspace for increased safety.

Especially during fine-visual preparation work, freehand manipulation of the exoscope is crucial, enabling the surgeon to adjust the system’s position in a more

restricted area, as well as zoom and focus. The robotic fine positioning of the exoscope features 2 translatory and 3 rotatory DOF. After appropriate coarse positioning of the exoscope manipulator, the exoscope's center can be moved on a plane parallel to the surgical field, at a distance currently defined by the neurosurgical partners as 300mm, depending on the length of the endoscopic instruments used. The intersection of the optical axis with that plane is defined as the viewed target.

Fig. 2. Robotic exoscope manipulator and its kinematic model

For the safety of the patient and the unobstructed use of endoscopic instruments, fine positioning comprises no DOF allowing translation perpendicular to the surgical field. This confinement is optically compensated by zooming. Also for safety reasons, non-backdrivable motors were used, ensuring instant standstill on power off, while the passive coarse positioning axes allow the manipulator to be swept aside anytime.

Table 2. Exoscope control modes with corresponding adjustments and head rotation

mode	adjustment	transversal	vertical	sagittal
turn	rotation about the exoscope center	pitch	yaw	roll
pivot	rotation about the viewed target	pitch	yaw	roll
lean	rotation about the optical axis			roll
shift	translation par. to the surgical field	up/down	left/right	
zoom	field of view	in/out		
focus	focal distance	in/out		
center	return to center position			
home	find home position and center			

2.4 Endoscope Manipulator

Similar to the exoscope, the endoscope is also mounted on a semi-robotic manipulator. A passive arm with pneumatic brakes is used for fixation on the operation table and coarse positioning.

As shown in Fig. 3, a robot mounted on the arm is used for fine positioning of the endoscope providing 5 DOF. The application specific kinematic design is optimized for minimal obstruction of the operator's view through the exoscope. A parallel kinematic design provides the proximal 4 DOF with high stiffness and low inertia, followed in series by an additional linear spindle drive parallel to the endoscope's optical axis for insertion and retraction. The 6th DOF, i.e. rotation about that axis, will be added in future.

Fig. 3. Robotic endoscope manipulator and its kinematic model

The trocar puncture site through the abdominal wall is defined by software as the remote center of motion. Non-backdrivable motors ensure standstill on an emergency power off. In order to avoid visual and mechanical obstruction by sterile drape, both the holding arm and the robot are autoclavable.

Table 3. Endoscope control modes with corresponding adjustments and head rotation

mode	adjustment	transversal	vertical	sagittal
pivot	rotation about the invariant point	pitch	yaw	roll
lean	rotation about the optical axis			roll
move	translation along the optical axis	forth/back		
zoom	field of view	in/out		
focus	focal distance (if available)	in/out		
center	return to center (insertion) position			
home	find home position and center			

3 Evaluation

The evaluation of the clinical usability of different modes of operation included the rating of effectiveness, efficiency, learnability, reliability and user satisfaction [15].

3.1 User Test in Virtual Reality

At first, a simulation was implemented in stereoscopic virtual reality, as displayed in Fig. 4, to generally evaluate different modes of view control by head rotation. It ran on a standard PC interfacing the head-mounted display, the orientation sensor and the confirmation button. The first test persons were 3 neurosurgeons, 1 surgical assistant and 1 engineer.

Fig. 4. User test in Virtual Reality

A sequence of pseudo-randomly placed 3D objects was to be targeted by a reticle central to the image, mounted on the virtual scope. Control modes using head tracking (excluding focus) were tested under both position and rate control, i.e. the respective values or their velocity were adjusted proportional to head rotation. The program also measured and documented the time needed to reach the targets. After the test, each user rated the intuitiveness, comfort and controllability of the system using a questionnaire based on rating scales.

The comparison of position and rate control is resumed in Table 4. For each control mode, the mean relative difference was calculated from the measured time (efficiency) and the questionnaire ratings respectively.

The results show the clear advantage of position over rate control. The former was more intuitive, comfortable and controllable for all actions, a tendency increasing with the DOF to be controlled by the operator. A further advantage was the higher efficiency for actions with 3 DOF.

Table 4. Mean relative difference comparing position control to rate control [%]

mode	efficiency	intuitiveness	comfort	controllability
turn	36	16	16	24
pivot	20	13	18	22
lean	-29	7	2	16
shift	-10	11	11	16
zoom	-6	7	7	4

For actions with 1-2 DOF, however, especially lean, rate control proved faster. Users had sometimes to e.g. lean the exoscope more than anatomically possible in one step, thus releasing the button and straightening their neck before continuing in more steps.

In order to keep position control while overcoming its few initial disadvantages, a fast lean function was added. It adjusts the angle multiplied by a customizable factor, hence enabling even large changes in one step. Furthermore, the transmission ratios for shift and zoom were also increased.

3.2 Demonstration on a Phantom

After the implementation of the semi-robotic manipulators and all related soft- and hardware components including the user interface, the system was tested on a phantom together with the clinical partners in an operating room at the Clinic for Neurosurgery of the Mainz University. The initial test results of the system have been encouraging. The users stated that the workspace of the exoscope manipulator can even be reduced, which would automatically lead to a further reduction of its size and weight.

4 Conclusions

We developed an assistance system that enables freehand manipulation of an exoscope and an endoscope by the surgeon, who receives the stereoscopic images and controls the system through a head-mounted unit. The results of the first user tests and demonstration encourage the combination of a head-mounted binocular display, head tracking for analog position control, voice control for mode selection and a miniature confirmation button.

Further optimization of the system and user tests for performance evaluation are objectives of our ongoing work.

Acknowledgements

This research was supported by the German Ministry for Research and Technology (BMBF) within the MINOP 2 project (16SV1442/0).

References

1. Cleary, K., Nguyen, C.: State of the Art in Surgical Robotics: Clinical Applications and Technology Challenges. *Computer Aided Surgery*, November 2001
2. Taylor, R. H., Stoianovici, D.: Medical Robotics in Computer-Integrated Surgery. *IEEE Transactions on Robotics and Automation*, Vol. 19, No. 5, October 2003, pp. 765-781
3. Detter, C., Reichensperner, H., Boehm D.H., Reichart, B.: Robotic manipulators in cardiac surgery: the computer-assisted surgical system ZEUS. *Min Invas Ther & Allied Technol* 2001: 10(6), pp. 275-281
4. Berkelman, P., Cinquin, P., Troccaz, J., Ayoubi, J., Letoublon, C., Bouchard, F.: A compact, compliant laparoscopic endoscope manipulator. *Proc. IEEE Int. Conf. Robotics and Automation*, May 2002, pp. 1870-1875
5. Guthart G. S., Kenneth Salisbury, J. J.: The intuitive telesurgery system: overview and application. *IEEE International Conference on Robotics and Automation*, 2000, pp. 618-621.
6. Aiono, S., Gilbert, J. M., Soin, B., Finlay, P. A., Gordan, A.: Controlled trial of the introduction of a robotic camera assistant (EndoAssist) for laparoscopic cholecystectomy. *Surg Endosc* (2002) 16:, pp. 1267-1270
7. Buess, G. F., Arezzo, A., Schurr, M. O., Ulmer, F., Fisher, H., Gumb, L. et. al.: A new remote-controlled endoscope positioning system for endoscopic solo surgery. *Surg Endosc* (2000) 14: pp. 395-399
8. Kim J., Lee Y.-J., Ko, S.-Y., Kwon, D.-S.: Compact Camera Assistant Robot for Minimally Invasive Surgery: KaLAR. *Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, September 2004, pp. 2587-2592
9. Taylor, R. H., Fundal, J., Eldridge, B., Gomory, S., Gruben, K., LaRose, D. et. al.: A Telerobotic Assistant for Laparoscopic Surgery. *IEEE Engineering in Medicine and Biology*, May/June 1995, pp. 279-288
10. Berkelman, P., Boidard, E., Cinquin, P., Troccaz, J.: Control and User Interface Design for Compact Manipulators in Minimally-Invasive Surgery. *Proceedings of the 2005 IEEE Conference on Control Applications*, August 2005, pp. 25-30
11. Kaminsky, J., Brinker, T., Samii, A., Arango, G., Vorkapic, P., Samii, M.: Technical considerations regarding accuracy of the MKM navigation system. An experimental study on impact factors. *Neurol Res* 21, 1999, pp. 420-424
12. Lüth, T. C., Hein, A., Albrecht, J., Demirtas, M., Zachow, S., Heissler, E. et. al.: A surgical robotic system for maxillofacial surgery. *Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society (IECON)*, 1998, pp. 2470-2475.
13. Sugar, T. G., Fussell, P.: Mouth Operated Neurosurgical Robot. *Proceedings of the ASME Design Engineering Technical Conference*, September 2001, DETC01/DAC-21130
14. Serefoglou, S., Lauer, W., Perneczky, A., Lutze, T., Radermacher, K.: Multimodal User Interface for a Semi-Robotic Visual Assistance System for Image Guided Neurosurgery. H.U. Lemke et al. (eds.), *International Congress Series 1281* (2005), *Proc. CARS 2005*, pp. 624-629
15. Zimolong, A., Radermacher, K., Stockheim, M., Zimolong, B., Rau, G.: Reliability Analysis and Design in Computer-Assisted Surgery. *Universal Access in HCI*, Stephanides C, et al (Eds.), Lawrence Erlbaum Ass. Publ., 2003, pp. 524-528 (ISBN: 0-8058-4934-3)