

Robotic Control of a Traditional Flexible Endoscope

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INTRODUCTION

In flexible endoscopy the interior surfaces of the gastrointestinal, reproductive and respiratory tracts are assessed. The physician uses a flexible endoscope with a camera at the steerable distal tip that is introduced in the natural body openings. Instruments can be inserted in the endoscope. These protrude from the tip and enable performing interventions, like resection of small polyps. Current commercial available flexible endoscopes and its instruments have limited capacity to execute procedures that require advanced maneuverability. For that reason surgical procedures, like endoscopic submucosal dissection (ESD) of large lesions, are not generally adopted by gastroenterologists. The recent concept of natural orifice transluminal endoscopic surgery (NOTES) that asks even more dexterity is still in its infancy because of the lack of user-friendly sophisticated tools [1]. Main usability problems are related to the control section at the proximal end. Because of the configuration of control elements the physician often faces handling problems. For instance, approximately 20% of the physicians are using both hands for the control section, while an assistant manipulates shaft and instruments according to spoken instructions [2]. Drawback of this workflow is that the physician is missing valuable force feedback information on tissue interaction, and in addition communication errors easily occur. At present there are no flexible endoscopes available that can be controlled in an intuitive and user-friendly way by one person. Robotic technology has the potential to improve current practice and is likely to play a major role in performing advanced interventions easily and safely. Computer techniques, like motion scaling, can be implemented to support physicians. We propose a robotic system that interacts with a traditional flexible endoscope. In this way current endoscope qualities, like cleanability and good image quality, are maintained and costs related to replacement of endoscopic equipment is prevented.

Previous work [3] concentrated on redesign of the control section to obtain single person endoscope steering for diagnosis. With the addition of instruments in therapeutics, single person control can only be obtained if the flexible endoscope can be operated with one hand and instruments with the other. We combined the robotic steering module that actuates the distal tip in [3] with a newly designed robotic module that actuates



Fig. 1 Robotic control flexible endoscope: (1) Traditional endoscope with driving means for tip steering, (2) Manual instrument control (3) Multi-DOF controller for tip steering and shaft control, (4) Driving means for shaft actuation, (5) Training model, (6) Monitor.

the shaft of the flexible endoscope. The physician uses one multi-degrees-of-freedom (multi-DOF) input controller to steer, advance, rotate, and maintain the position of the motorized flexible endoscope, while the other hand is able to manipulate instruments, as shown in Fig. 1. The control handle of the input controller resembles the endoscope tip. The operator experiences control like directly holding the camera at the distal tip and movements of the physician's hand and the camera are matched to obtain intuitive manipulation.

Robotic control is not intended for endoscope advancement in diagnosis that requires precise interpretation of interaction forces between endoscope and lumen, but it enables the physician to intuitively manipulate the tip of the endoscope in the operating area. It creates a stable endoscopic platform without the need of an assistant and allows for small robotic movements of the distal tip when the spatial range of the instruments is too small. We evaluated the usability of the robotic endoscope to perform these tasks compared to current flexible endoscopy.

MATERIALS AND METHODS

In Fig. 1 the complete system is depicted that is used in our experiment to assess the intuitiveness and user-friendliness of robotic flexible endoscopy. The driving means for the endoscope tip consist of a motor unit that is connected to the navigation wheels of the endoscope to actuate left/right and up/down movements. The endoscope shaft is clamped between two V-shaped wheels that are actuated to advance the shaft. Axial rotation of the shaft is achieved by rotating the frame on

which the wheels are positioned. A Phantom Omni haptic device (Sensable Technologies) is a suitable input controller to steer these four degrees of freedom (4-DOF). We used position control as transfer function between user input and end effector displacement. Position control is most intuitive in tasks that require accurate manipulation in a limited workspace and is implemented for tip as well as shaft control [4]. A hold-to-run button on the control handle prevents unintended movements of the endoscope and locks it into position when releasing the input device.

We tested three setups in our experiment. In one setup we used conventional endoscope operation with assisted instrument control as a reference for robotic flexible endoscopy. The second setup allows 4-DOF robotic steering and shaft control with one hand and manual instrument control with the other hand, as described in this paper. The third setup uses the robotic steering module of [3] with a Phantom Omni controller to obtain 2-DOF single handed tip steering. The shaft is manually operated with the other hand and the instrument by an assistant. The last setup is added to evaluate the influence of bimanual endoscope control by the physician. The intuitiveness is expected to be higher when steering as well as shaft control is performed singlehandedly, as in the second setup.

Subjects, without experience in endoscope handling, were asked to perform 2 tasks that require advanced endoscope maneuverability. The absence of experience enabled testing of intuitiveness. First, subjects had to pick up a specific ring from a pion with a grasper and place it on a designated pion. Secondly a ring had to be guided from one end of a tortuous wire loop to the other end. Instrument control was limited to opening and closing the grasper. Each of the six possible orders of the three setups was performed equally often to correct for learning effects and fatigue. The 12 subjects (aged 19-50 years, 2 women and 10 men) were asked to perform task 1 once as exercise before the evaluation was started. Our focus was to test the control usability of the robotic endoscope. Usability is defined by the International Standardization Organization (ISO) as: "the extent to which a product can be used by specific users to achieve goals with effectiveness, efficiency, and satisfaction in a specified context of use". In our experiment the following dependent variables were measured:

- Tasks completed (effectiveness)
- Time required for tasks (efficiency)
- Workload analysis based on a modified NASA Task Load Index, measuring mental and physical demand [5] (efficiency)
- Rank interfaces to preference (satisfaction)

RESULTS AND DISCUSSION

The quantitative results of the experiment are depicted in Table 1. The results show that robotic control improves efficiency and satisfaction. All participants were able to complete the tasks with all setups, so improved effectiveness is not demonstrated in this

Table 1 - Quantative results experiment

Setup	conventional	robotic 2-DOF	robotic 4-DOF
Task 1 (sec.) ^a	356 (200)	158 (133)	148 (114)
Task 2 (sec.) ^a	183 (109)	98 (98)	84 (75)
Workload (max. 25) ^a	20 (4)	12 (3)	10,5 (2)
Preference (no.1/2/3)	0/1/11	1/10/1	11/1/0

^a Values are represented as median (standard deviation)

experiment. The results of the 2-DOF robotic setup show no significant differences compared to the 4-DOF setup. However, almost all subjects preferred the 4-DOF setup. Participants valued its intuitiveness, its accuracy, the feeling of being in control, and its single person setup. Additionally, about 50% of the subjects indeed complained about the 2-DOF robot being more mentally demanding. Some of them constantly switched between tip steering and shaft manipulation during the procedure. What subjects missed in all setups was independent axial rotation of the grasper to orient it to grasp a ring. Axially rotating the shaft resulted in translational movements of the tip when it was bent. In the 4-DOF robotic setup this could be compensated for by actuating tip steering in the opposite direction. This was not implemented yet.

The robotic system presented in this paper showed its usability, but is not ready to be implemented in the current clinical workflow. We are working on translating this proof-of-principle into a product, that takes safety, cleanability, and easy positioning close to the patient into account. Additionally all controls of the current endoscope for functions like insufflation, suction and rinsing are integrated in the control handle of the multi-DOF input controller. Expert testing is required to test performance in clinically relevant advanced procedures.

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