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Robotic Sensorized Gastroendoscopy with Wireless Single-Hand Control

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Abstract: The manipulation of flexible endoscopes is a procedure that requires great dexterity since it requires the synchronization and use of both hands in parallel. Imprecise handling during gastroendoscopy could harm the digestive tract. Our solution allows the physician to use only one hand to wirelessly control the forward, backward, and tip bending motion. The proposed system provides endoscopic vision and tactile impact force sensing at the tip to detect the force applied to tissue and thus avoid damage. We experimentally evaluate the handling of the robotic system in open space and inside a medical phantom. The results revealed a training effect with less time demand for task completion and reduction of average impact force after only 5 runs. The proposed system was successfully controlled using one hand and, together with the force information, could enhance the physician's experience during endoscopy. Future work will address axial control and an intensive user study with clinical experts.

Keywords: robotic gastroendoscopy, teleoperated, hand-held control, sensorized

1 Introduction

Upper gastrointestinal endoscopy (i.e., *esophagogastroduodenoscopy*) describes a minimally invasive procedure, in which an endoscopic device is manually inserted via mouth and pharynx and carefully moved into the esophagus towards stomach and duodenum. On the bendable tip, an optical camera, light, and integrated further instruments such as forceps allow for diagnostic and therapeutic intervention in a directed manner by a clinician. Conventional gastroendoscopes however are purely mechanically driven and require two-hand manipulation including steering wheels for a tendon-driven bending of the distal tip and linear motion, which is performed manually. This involves great dexterity and long learning curves, which could lead to a high cognitive load for the clinician [1]. Modern robotic surgical systems aim to assist with the manipulation, providing a control console for the medical expert for enhanced procedures [2]. One example is the Monarch®platform (Auris Health, USA), which offers novel robot-assisted flexible endoscopes for multiple specialties [3]. The setup however makes it necessary for the expert to leave the immediate environment at the operation table. Therefore, we propose a robotic gastroendoscope that can be controlled with a novel wireless hand-held control device, providing endoscopic view and all necessary controls via an intuitive user interface. Furthermore, impact force sensors attached to the gastroendoscope provide information about potential tissue damage during the procedure as a helpful feedback to the clinician [4]. Thus, clinicians may benefit from both, robotic manipulation support and immediate access to the patient from any desired position at the operation table. In addition, position and perspective of clinician and instrument can be changed as required during the procedure without the hazard and inconvenience of cables and further support infrastructure creating additional obstacles in the operation room. Here, we demonstrate a prototype of the the technical setup and provide fundamental evaluation in open space and within a medical phantom to pave the way for future studies with clinical experts.

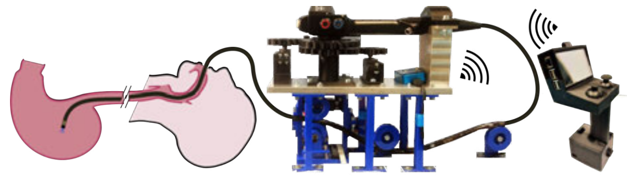

Fig. 1: Schematic setup of mechatronic gastroendoscope featuring a mobile hand-held control device with endoscopic view.

New robotic systems for endoscope control have been investigated and offer several advantages, such as ease of operation, safety, and efficiency. One example is the Three-Limb Teleoperated Robotic System, which proposes the remote manipulation of an endoscope from a leader system, using both hands and a foot, and with the help of a screen [1]. The robotic follower system is in contact with the endoscope and the patient, performing the movement of the endoscope tip and its instruments. The evaluation of the system includes measurement of the angle in two degrees of freedom (DOF) (up/down, left/right), using a camera and markers to detect the angle and reveals bending angles between $-100°$ and $100°$ (L/R) and $-30°$ and $30°$ (U/D). The Robotic-assisted flexible endoscope (RAFE) can be controlled remotely with one hand to simplify manipulation of the endoscope [5]. It consists of an endoscope

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holder, a motorized arm, and a leader controller. The endoscope holder controls the rotation of the endoscope tip, the motorized arm controls the entry of the endoscope through the patient's mouth, and the leader controller is a handle that allows control of the complete system. The RAFE system was experimentally compared to a conventional endoscope, where the time was measured that it takes for the equipment to perform a series of rotational and translational movements. The robot took an average of 20 s to complete the task, while the manual endoscope took an average of 50 s. Finally, the gastroscope intervention mechanism (GIM) proposes the control of a flexible endoscope by means of a pneumatic robotic system divided into two parts: the delivery arm and the operation arm [6]. The delivery arm controls the entry and orientation of the endoscope in the patient's mouth, while the operation controls the rotation of the endoscope tip, as well as the rotation of the endoscope around its longitudinal axis. The equipment was tested with a phantom of the upper gastrointestinal system (mouth, esophagus and stomach) and evaluated for insertion performance, axial and radial accuracy compared to a conventional system. Finally, an in-vivo animal experiment including a porcine esophagus and stomach was performed. Unlike the previously presented works, we propose a wireless hand-held user interface, which allows to control a robotic follower system. This solution will be detailed in the next section.

2 Materials and Methods

2.1 System Overview

In order to create our gastroendoscopic robotic system we steer a conventional, non-actuated gastroendoscope (SG22 13800PKS, KARL STORZ SE & Co. KG, Germany) with a bendable tip (9.1 mm diameter, 1100 mm working length) via two rotary gear wheels for single-hand use. The system can be controlled using one hand, thus leaving the clinician's second hand free to feed the distal end into the patient's mouth. In this work, we designed a mechatronic interface, which is able to mount the gastroendoscope on a table to manipulate both rotary gears and to realize an automatic feed. All degrees of freedom are remotely controlled by a wireless hand-held control device that integrates a screen for the endoscopic view. Communication between individual devices is realized through Bluetooth and WiFi, respectively. The robotic gastroendoscope is illustrated in Fig. 2.

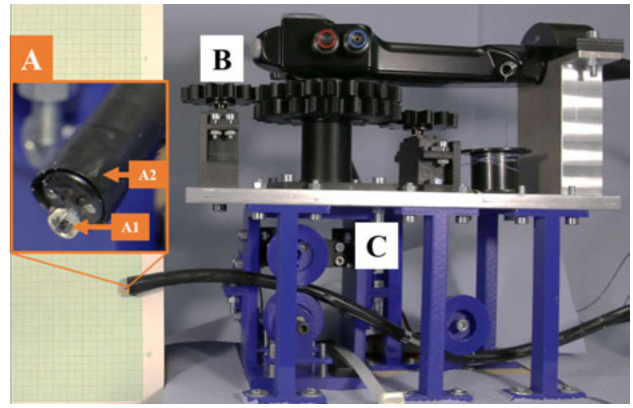

Fig. 2: Robotic gastroendoscope with enhanced distal tip (A) with miniature camera (A1) and tactile impact force sensor covered under insulation (A2). A mechatronic steering adapter allows for tip bending (B) and automatic feed (C).

2.2 Mechatronic Interface

To replace one human hand required for steering the gears, two electric gear-motors (FS5113R, FEETECH RC Model CO.,Ltd., China) drive two customized parallel gear sets, fabricated by 3D-printing (German RepRap X350pro, Germany) and as shown in Fig. 2-B. The objective is to sustain the provided conventional workspace of the gastroendoscope. A third motor realizes an automatic linear feed (Fig. 2-C). All three motors are controlled using a micro controller (Arduino UNO) linked to a micro computer (Raspberry Pi 3 Model B+).

2.3 Imaging and Sensing

Due to limited access to the original endoscopic image stream, we instead use a 1×1 mm miniature camera with 249×250 pixel resolution (NanEye, ams-OSRAM AG, Austria) that is loaded into the tool channel (2.2 mm diameter). Thus we gain immediate access to the video stream for broadcast on the hand-held control device (Fig. 2-A1). Compliant tactile impact sensors based on piezoresistive polymers as presented in [7] are mounted close to the distal tip of the endoscope (Fig. 2-A2). The sensors' electric resistance varies with the degree of deformation due to external forces. This particular type of sensor is chosen for it can be fabricated to fit a desired shape (here: cylinder shell surface) at a small sensor thickness of 350 µm. In this work, the sensor measures the impact force that is created by the gastroendoscope and directed at the phantom walls or tissue, respectively. Measurements are fed back to the clinician as float numbers or as a visual plot on the screen of the hand-held control device together with the video stream of the endoscopic camera. It is worth mentioning, that due to the aforementioned working principle of the sensor, it might

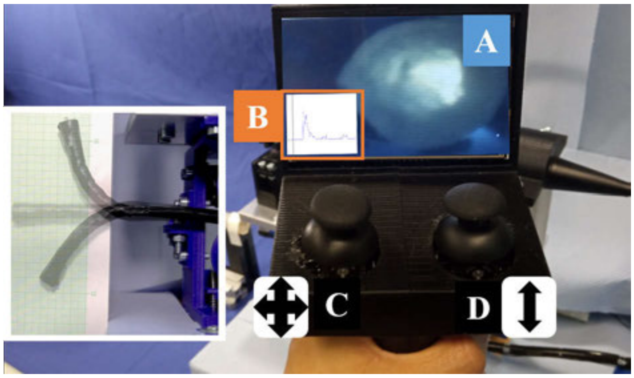

Fig. 3: Control of the distal tip with the remote device providing endoscopic view and impact force feedback.

also react to pure bending motion of the distal tip even in non-contact scenarios.

2.4 Hand-held Control Device

The hand-held control device is shown in Fig. 3 and comes with a 3.5" screen featuring 480×320 pixel resolution and in an ergonomic and lightweight design ($410\,\mathrm{g}$), including a mobile power supply providing 1000 mAh. Designed for single-hand use, the hand-held control device is equipped with a screen to show the endoscopic video stream (A), the graphed impact force feedback (B), and has two joysticks for tip bending (C) and feed control (D), respectively.

2.5 Experimental Evaluation

The technical evaluation includes investigation of maximum workspace, actuation speed of translation, and tip-bending. To investigate the workspace the manipulation is recorded in front of a reference background using a AI QUAD camera of 13MP (1920×1080, 30fps). Then, the workspace is characterized based on the video frames. To test the handling of the robotic system in open space, four target point are determined to form a simple parkour as in [5] and shown in Fig. 4a. A user is asked to steer the distal tip to the target positions in given order and back to initial position using the hand-held control device. The time for completion of a technical expert is tracked and the experiment is repeated five times (n=5) to evaluate the learning experience with the novel hand-held control device. Furthermore, the piezoresistive impact force sensor is actively monitored to explore the sensor behavior in non-contact scenarios. To demonstrate the system's ability to navigate in the gastrointestinal tract, a 3D-printed (Elastic 50A, Formlabs GmbH, Germany) phantom model of the esophagus and stomach [8] is fabricated. The technical expert must navigate through the

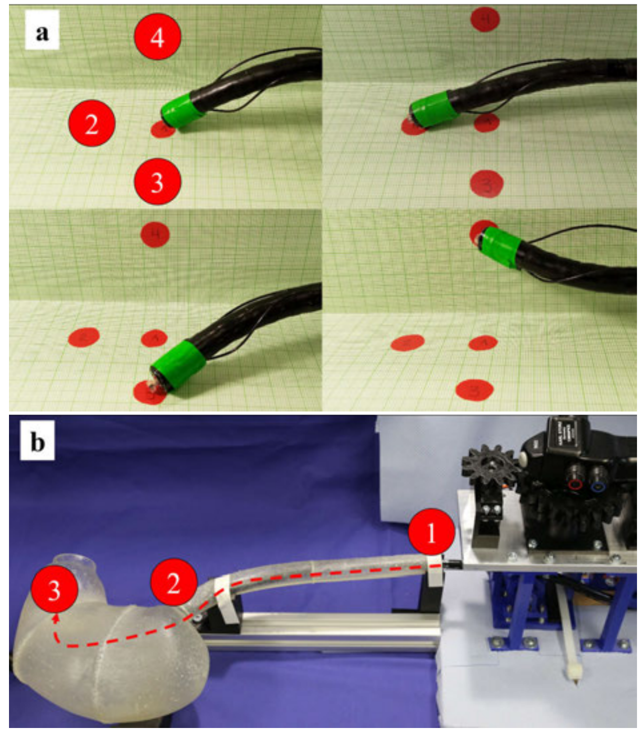

Fig. 4: Evaluation procedure for manipulation task with a parkour of dedicated target points (red) in open space (a) and within a medical phantom (b).

esophagus (1), enter the stomach (2), and reach a dedicated target point (3) to obtain an endoscopic view towards the duodenum (Fig. 4b). Then, the device must be exerted completely from the phantom. During the procedure, the sensor surfaces on the distal tip of the gastroendoscope track impact force between the tip and the phantom walls.

3 Results

Evaluation revealed maximum bending angles of $-64°$ and $64°$ (U/D) and $-55°$ and $55°$ (L/R). Our system achieved a continuous translation speed of up to $49\,\mathrm{mm\,s^{-1}}$ which a user can adjust intuitively via the hand-held control device. Thus, complete extension and retraction of $500\,\mathrm{mm}$ working length can be achieved within $10\,\mathrm{s}$. The results of the handling evaluation present that run duration decreases from $80\,\mathrm{s}$ for a first run down to below $40\,\mathrm{s}$ after only 5 runs indicating a training effect. Despite no physical contact between tip and ground, impact forces of up to $1.1\,\mathrm{N}$ are detected for all runs pointing out that pure tip bending already influences the sensor setup due to stress induction in the piezoresistive material. Fig. 5 graphs the result of the in-phantom evaluation. In this more complex scenario including tight space navigation, run duration

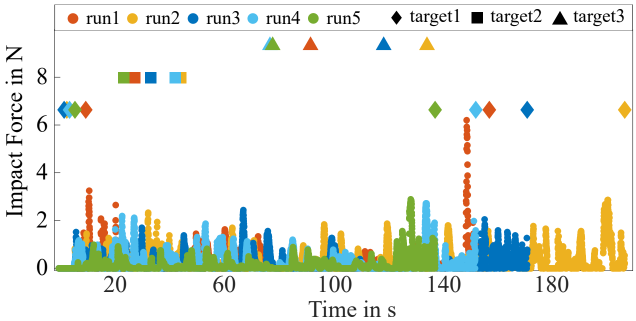

Fig. 5: Impact force tracked via piezoresistive sensing during phantom evaluation. Target parkour progress (1-2-3-1) is indicated.

decreases from 200 s to below 140 s after 5 runs. Impact forces can reach peaks of up to 6 N while on average stay below 2 N and a decreasing tendency is visible correlating with shorter parkour completion times and training effect.

4 Conclusion

In this work we presented an automated gastroendoscope with a bending tip and automatic feed, which is controlled by a wireless hand-held control device. The evaluation results with technical users demonstrated the controllable feed and tip bending, indicating a learning curve leading to faster parkour completion and less impact force after 5 runs. On the contrary, a parkour duration of 40 s for reaching simple targets in open space revealed a certain control challenge when no haptic feedback and no axial control are available. Among other limitations is the feedforward (open-loop) control of the motors which can cause excessive rotation if not steered properly by the user. However, the provided system allows the user to gain an additional free hand and the ability to move freely without limitations of hazardous cable connections. Future work may include further system optimization such as additional controlability of axial rotation and haptic feedback and an ex-vivo user study with clinical experts to investigate usability. In the same way, the previous experiments will be performed with a larger number of probands. Finally, experiments will be performed comparing the proposed system with a regular endoscope, in order to evaluate its strengths and weaknesses.

Author Statement

Authors state no conflict of interest.

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