

Intuitive Gaze-Control of a Robotized Flexible Endoscope

T.J.C. Oude Vrielink*, J. González-Bueno Puyal*, A. Kogkas, A. Darzi and G. Mylonas, *Member, IEEE*

Abstract—Flexible endoscopy is a routinely performed procedure that has predominantly remained unchanged for decades despite its many challenges. This paper introduces a novel, more intuitive and ergonomic platform that can be used with any flexible endoscope, allowing easier navigation and manipulation. A standard endoscope is robotized and a gaze control system based on eye-tracking is developed and implemented, allowing hands-free manipulation. The system characteristics and step response has been evaluated using visual servoing. Further, the robotized system has been compared with a manually controlled endoscope during a user study. The users ($n = 11$) showed a preference for the gaze controlled endoscope and a lower task load when the task was performed with the gaze control. In addition, gaze control was related to a higher success rate and a lower time to perform the task. The results presented validate the system's technical performance and demonstrate the intuitiveness of hands-free gaze control in flexible endoscopy.

I. INTRODUCTION

Flexible endoscopy is a routinely performed medical technique carried out by means of a flexible endoscope. The endoscope consists of a flexible tube, one or two working channels for flexible instruments to be inserted and a camera and light source at the distal steerable end (tip). The endoscopist can bend the tip left, right, up and down, by rotating with one hand two dials at the handle of the device (Fig. 2) and by advancing and rotating the shaft of the endoscope with the other hand. Endoscopy has traditionally been a diagnostic tool, allowing the exploration and the acquisition of tissue biopsies in the upper and lower gastrointestinal (GI) tract. Despite its wide adoption, diagnostic endoscopy presents several challenges, such as limited dexterity, decreased spatial awareness, loop formation and overall poor ergonomics [1].

Despite these challenges, endoscopes are increasingly adopting a more therapeutic role in lesion removal in the GI tract, with techniques such as Endoscopic Submucosal Dissection (ESD) slowly becoming more widely adopted. ESD involves an electrosurgical cutting tool introduced via the working channel of the endoscope. The aim is to dissect the submucosa, which is the tissue layer of the GI tract that supports the mucous membrane. Only limited control of the cutting tool is possible by pushing and pulling it inside the endoscope's working channel, while simultaneously steering the endoscope's tip using its control dials with the other hand. The lack of bimanual dexterity and tissue retraction -known as tissue triangulation- are the main reasons behind the technical complexity of ESD. Hybrid techniques have been

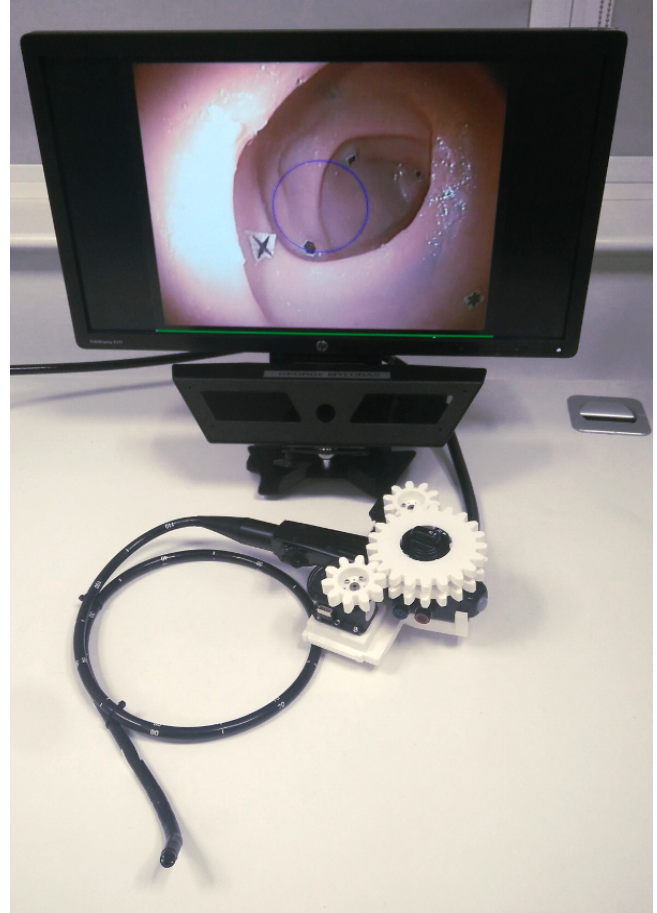


Fig. 1: The system setup: (1) The display with a snap from the endoscope during a colonoscopy training task. (2) The screen-based eye tracker. (3) The robotized endoscope.

investigated for ESD, offering only marginal improvement [2]. Furthermore, endoscopes with augmented functionality have been proposed. These include systems that can be manually controlled, such as the *Cobra* (USGI Medical, USA) [3] and *Endosamurai* (Olympus, Japan) [4], or robotically controlled, such as the *CYCLOPS* [5], the *STRAS* [6], the *MASTER* [7] or the *Flex* (Medrobotics, USA) [8]. These devices introduce externally controllable instruments at the tip of the endoscope, allowing bimanual dexterity and tissue triangulation. Robotic actuation is used to control the additional degrees-of-freedom (DoF) offered by the robotic attachments. However, control of the host flexible endoscope is still manual for some of those systems.

Despite the advantages of augmented endoscopes, the increased DoF require more operators. In this type of

*T.J.C. Oude Vrielink and J. González-Bueno Puyal are joint first authors.

The authors are with the HARMS lab, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London (email: t.oude-vrielink15@imperial.ac.uk)



Fig. 2: **Left:** Flexible endoscope handle illustration. The larger diameter dial (red) controls the up/down movement, while the smaller dial (green) controls the right/left movement of the tip of the endoscope. **Right:** The motorized system with gears placed on the dials.

situation an operator is needed to advance and steer the endoscope, while at least another operator manipulates the instruments manually or by using tele-manipulators. This introduces obvious new challenges, such as suboptimal collaboration, communication failures, space constraints and collisions, as well as increased cost [9] [10]. Therefore, a more intuitive human-endoscope interfacing approach is required to overcome the increased complexity introduced by augmented endoscopes. We hypothesise that by motorizing the flexible endoscope and by using eye-gaze control through eye-tracking, we can decrease the complexity introduced by the augmented endoscopes.

Previous studies explore the robotization of standard flexible endoscopes. In Kume et al. work, it is controlled with one haptic device, and used for releasing the endoscopist's other hand to control the *MASTER* device [11]. Similarly, in [12] the authors use a robotized flexible endoscope to perform automatic steering of the shaft for lumen centralization. It is important, however, to keep in mind the importance of intuitive user interfaces to increase the efficiency of the flexible endoscope steering, as underlined by [13]. A study performed by Dik et al. shows that during colonoscopy there is high correlation between the total gaze time spent in an area and its diagnostic interest [14]. Work presented in [15][16][17] further highlights how eye-gaze information can be used to augment and improve surgical practice. Finally, Noonan et al. control an articulated mechatronic laparoscope using 2D gaze and fixations as commands [18].

Based on this evidence, we use eye-gaze to control a robotized flexible endoscope. We prove that this approach can improve diagnostic endoscopy through intuitive and effortless control of the endoscope. To the authors' knowledge, this is the first time that gaze control of a robotized endoscope has been demonstrated.

II. SYSTEM DESIGN

This section considers the application of eye-tracking to create a user interface for controlling the 2 DoF bending of the distal end of a flexible endoscope. A first step

involving the motorization of the endoscope is described, followed by the gaze-data acquisition methodology and the implementation of the control system.

A. Robotic platform

The system is shown in Fig. 1. The flexible endoscope to be robotized was a Karl Storz 13801 PKS, with a 9.8mm diameter and a 1.1m long flexible shaft. An attachable actuation module was developed, allowing its immediate unplugging as a safety measure and permitting conversion from robotic to manual control. Gears were designed to fit the dials of the endoscope and to couple two motors (Dynamixel RX-24F, Robotis, Korea), interfaced to a computer using a USB2Dynamixel controller. The designed mechanism is shown in Fig. 2.

Reilink et al. [19] carried out torque and speed measurements using a Pentax EG-2930K gastroscope and identified the following operational requirements:

- The maximum torque needed with the larger dial is approximately $0.4N \cdot m$.
- The required velocity is $15rpm$. Faster movements were determined as not useful and resulting in a loss of spatial orientation.

Based on these specifications, the gears were designed to be able to provide $1.0N \cdot m$ torque and $50rpm$ angular velocity, ensuring sufficient power margin. Table I lists the selected design parameters for the gears, which can be applied for other standard flexible endoscopes. For the current application, the transmission ratio between the motors and the tip bending stands as approximately 0.36, meaning that a complete turn of a motor will steer the tip approximately 130 degrees in one direction.

B. Gaze control

As endoscopy requires the use of a screen to visualize the endoscopic video, a Tobii x50 eye-tracking device (50Hz sampling rate, 0.5-0.7 degrees of visual angle accuracy, 0.35 degrees of visual angle of spatial resolution) is positioned under the endoscopic screen as shown in Fig. 6. The eye-tracker is connected to a Windows XP machine, which is set-up to stream gaze data over an Ethernet connection with a User Datagram Protocol (UDP) to a Linux machine.

The control algorithm was developed in C++ in an Ubuntu 14.04 OS integrating the received gaze information and the motors' controller. A closed-loop system was implemented to control the robotic actuation. This approach aims to use the

TABLE I: Gears parameters

Parameter	Endoscope gears	Motor gears
Pitch radius	46mm	22mm
Number of teeth	23	11
Pitch	4mm	
Dedendum	5mm	
Adendum	4mm	
Clearance	1mm	
Pressure angle	20deg	

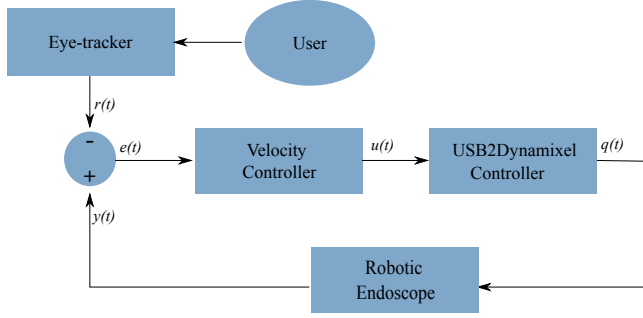


Fig. 3: Gaze control system diagram where $r(t)$, $y(t)$, $e(t)$, $u(t)$ and $q(t)$ correspond to the reference signal, the feedback signal, the error signal, the desired velocity and the voltage input respectively.

natural gaze of the user to facilitate the task of manipulating the endoscope. Whenever the user directs his/her gaze away from the centre of the screen coordinates $y(t)$, the distance $e(t)$ between the gaze point $r(t)$ and the centre of the screen is computed. This error signal is used as an input for the controller, as depicted in Fig. 3. A velocity based control was applied, where the desired velocity $u(t)$ of the motors is computed by using a proportional controller (gain set to 0.4125). A controller with an additional integration and derivative gain has been tested during development, though so far has not yielded better result. For use with gaze control an overshoot has shown to be confusing, and a fast response time was more intuitive than a small steady-state error. Thus far, any PID-controller with a response intuitive for the users had integral and derivative gains with negligible effect and therefore could be discarded. The desired velocity derived from the controller is used by the USB2Dynamixel to compute the corresponding voltage input $q(t)$ for the motors and steer the camera accordingly.

Measures were taken to ensure safety when using the gaze control. A 9-point user calibration is performed for each user in order to map user-specific gaze-direction dependent ocular landmarks to unique coordinates on the fixated screen. After calibration, while tracking the gaze, invalid eye-movements due to blinking or large head movements are discarded, as well as gaze-points corresponding to positions out of the screen. Saccadic and micro-saccadic movements can occur and need to be handled, as they constitute undesirable control commands. Saccades are very high speed ballistic eye movements occurring in between fixations, while micro-saccades are small amplitude and low frequency drift movements occurring during fixations [20]. A filter was therefore implemented to discard non-fixational gaze-data. A fixation was space-based defined, meaning that a set of consecutive gaze points that remain relatively constant in the screen are classified as fixation. A radius of acceptance of 5% of the screen dimensions was selected, corresponding to approximately to 2.5 degrees of visual angle. The fixation detection handles short noisy measurements and non-detected data, by allowing continuity in the fixation classification during

short interruptions. Finally, limits in terms of the velocity and torques exerted by the motors are applied by means of the USB2Dynamixel controller, in order to prevent any damage on the tissue or the endoscope.

III. VALIDATION METHOD

A. Benchmarking

A benchmarking study was used to measure the technical performance of the system. The first technical evaluation was the characterization of the system relating a given input motor's position to the tip response. It is important to assess whether the transformation from input position to output tip position can be simplified to a linear relationship. In case of a non-linear transformation, the response to input will depend on the the endoscope tip's position within the workspace. For the user, this will result in areas in which the system is more responsive to the gaze control input than others. The transformation was assessed by moving the motors with the measured input θ_x and θ_y and evaluating a metric of the resulting orientation of the endoscope's tip β . The value β is an angle calculated using the camera orientation vector V_n and the base-frame vector e_z :

$$\beta = \cos^{-1} \left(\frac{V_n \cdot e_z}{\|V_n\| \|e_z\|} \right) \quad (1)$$

where V_n and e_z are the normal vectors to the plane defined by the three markers on the tip and base, respectively. An optical tracking system (2x Prime 13 Optitrack Cameras, NaturalPoint, Inc.) is used to track the 3D position of the endoscope tip during these experiments (Fig. 4). Three passive optical markers are attached to the tip, using a lightweight nylon mount. Additionally, three markers are placed just before the flexible part of the tip, to act as a base frame.

A second technical validation was performed to characterize the controller. To make the evaluation consistent and cancel out any effects caused by voluntary and involuntary eye movements, this is performed without the gaze input from the user. Instead, a reference step input $r(t)$ is based on the position in the screen of an optical marker placed within the field of view of the endoscope, achieving visual servoing. The optical marker was placed in 12 spatially distributed positions. An adjustable rig to which the optical marker is attached is used to change the position throughout the field of view of the endoscope. The endoscope's light source was used to increase the intensity of the passive optical marker. In order to simulate the 2D coordinates of the gaze point, the marker was segmented from the grayscale image by using a binary threshold function combined with a circular morphological filter (OpenCV 3.2). Erosion and dilation were then applied to filter out noise. The setup, including the view from the endoscope, is shown in Fig. 5.

B. User Study

A user study was performed to validate the usability and effectiveness of the gaze control system. For this purpose,

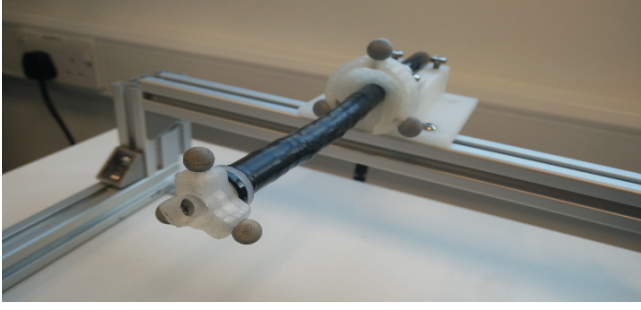


Fig. 4: Setup used for optical tracking of the endoscope tip for different motor input. Three passive optical markers are placed at the tip of the endoscope, and another three are placed at the base of the bending tip.

a plastic colon phantom corresponding to the anatomy from the rectum to the sigmoid colon, including the rectosigmoid junction, was used. A set of ten differently shaped targets was placed on its inside surface, as can be seen in the screen display of Fig. 6. Two of the targets were placed in challenging positions, namely behind an anatomical colon fold and after the rectosigmoid junction. The phantom was enclosed in a box, preventing participants from seeing the position of the endoscope within the phantom. The targets and phantom were maintained in a fixed position throughout the experiments to eliminate any possible variation between participants. Participants were asked to navigate through the colon model by manipulating the endoscope to bring the targets to the centre of the screen in a specified constant order, as prompted by an external assistant. This task allowed for the evaluation of a simulated clinical scenario, in which an endoscopist examines possible malignancies in a dexterous manner.

Eleven users were included in the study; ten novices and one expert endoscopist. Participants performed the task both in a traditional manner, where they controlled the endoscope with their hands, and with the eye-gaze. Which system was used first by each participant was randomised, in order to reduce the learning effect bias. Fig. 6 shows the experimental set-up. The eye-tracker was placed under the screen displaying the endoscopic video. Users were positioned in front of the monitor, and used their right hand to insert and rotate the shaft of the endoscope in the phantom, and the left hand or eye-movements to steer the tip of the endoscope.

Both approaches were evaluated through subjective assessment and objective measurements during the task. Firstly, to assess the task load, a NASA-TLX (System Task Load Index defined by NASA) questionnaire was used for each set-up, composed of 6 questions to assess the mental, physical and temporal demand, overall performance, frustration levels and effort during the task. To compare the user preferences in terms of user-friendliness, usability and intuitiveness, participants completed a Likert questionnaire consisting of the following questions:

- I was feeling more comfortable using the gaze control
- The gaze control was easier to learn than the manual

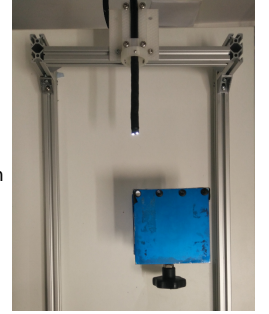
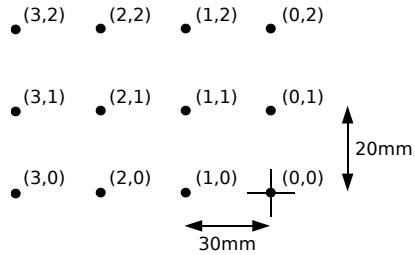
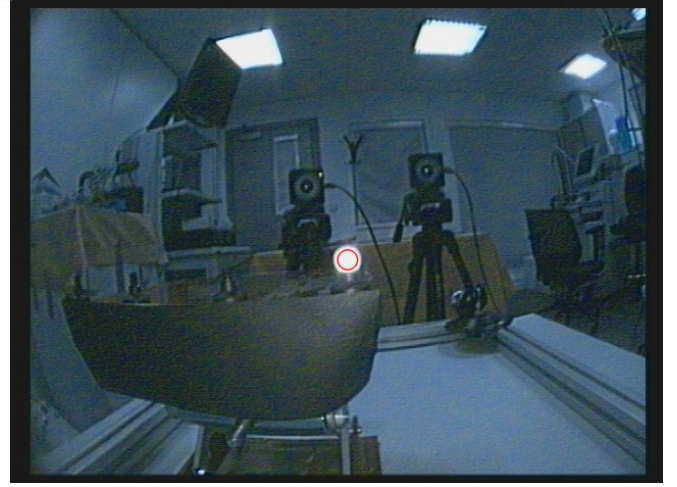


Fig. 5: **Top:** View from the endoscope during the visual servoing experiments. The passive optical marker is encircled in red. The (x, y) pixel position of the centre of the circle is used as input during these experiments. **Bottom left:** Data were collected for 12 spatially distributed marker positions. The spatial distribution is based on a XY plane 75mm in front of the endoscope. Point $(0,0)$ is in the centre of the endoscope's video at homing position, and is shown in the endoscopic image above. **Bottom right:** The top-view of the setup. The blue adjustable platform is used to change the on-screen Y position of the marker. To change the X position, the marker is placed on different locations on the platform.

control

- The gaze control was less stressful than the manual control
- The gaze control didn't interrupt the flow of the task
- Overall I would choose the gaze control rather than the manual control

Secondly, an objective evaluation was carried out for each type of control, assessing the time required to find each target and the success rate, where success is defined as the percentage of correctly located and centred targets.

IV. RESULTS

This section provides the results corresponding to the experiments described in the previous section. Firstly, the benchmarking experiments outcomes are presented, followed by the user study results.

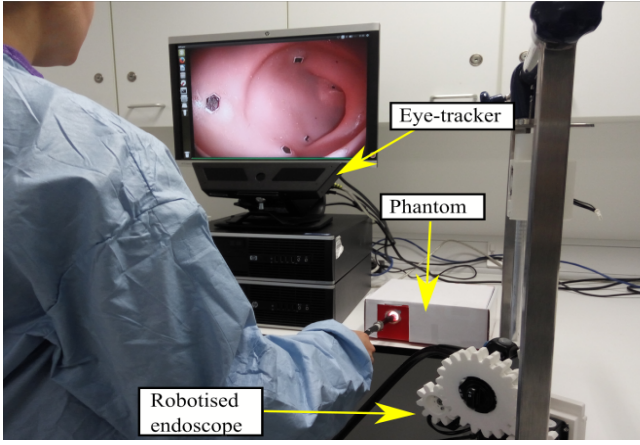


Fig. 6: A participant performs a task steering the tip of the endoscope with gaze, and inserting and rotating the shaft of the endoscope with the right hand.

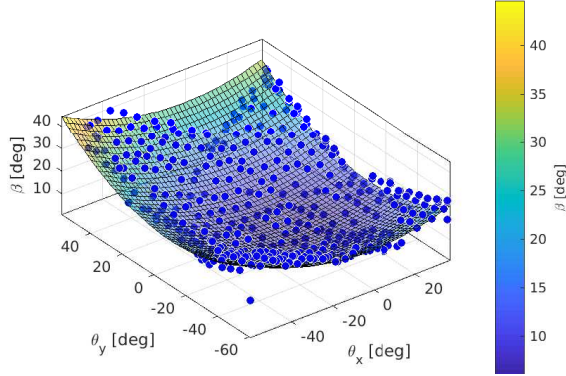


Fig. 7: The mapping from input motor angles θ_x and θ_y to the tip angle position β . The surface is fitted by a 2nd order polynomial, with parameters shown in Table II.

A. Benchmarking

The mapping of the motor inputs to the endoscope tip position and orientation is shown in Fig. 7. The surface is the 2nd order polynomial fitting of the data:

$$\beta(\theta_x, \theta_y) = a_0 + a_1\theta_x + a_2\theta_y + a_3\theta_x^2 + a_4\theta_x\theta_y + a_5\theta_y^2$$

The parameters a_i are found using MATLAB's (R2017a) *fit()* function and are shown in Table II. The RMSE for the entire dataset, and for each quadrant are shown in Table III. Higher order polynomials did not improve the RMSE fitting.

The visual servoing experiments showed that the control

TABLE II: Polynomial fitting parameters

Parameter	Value	95% confidence interval
a_0	6.534	(5.953, 7.115)
a_1	0.01069	(0.0002934, 0.02109)
a_2	0.1042	(0.09567, 0.1128)
a_3	0.004279	(0.003863, 0.004695)
a_4	-9.261e-05	(-0.000359, 0.0001737)
a_5	0.004988	(0.00471, 0.005266)

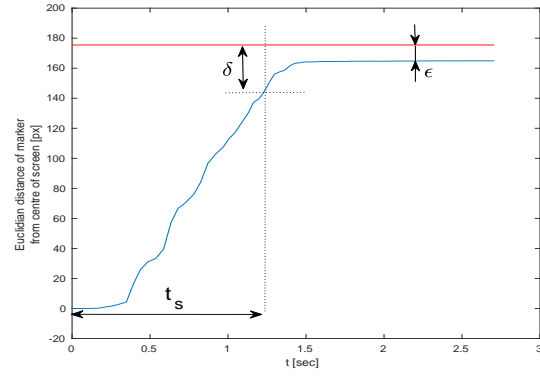


Fig. 8: The step response of the system at point (2,0) (as defined in Fig. 5). The average of 20 samples is shown here.

system does not exhibit any overshoot (Fig. 8). This is important as during user control overshoot might result in unexpected behaviour from the user. As the previous benchmarking showed similar behaviour for all quadrants of the endoscope's image, this experiment is only performed in the top-left quadrant (Q1, as defined in Table III).

For each marker position 20 repetitions were performed. Fig. 9 shows the settling time t_s , and the steady-state errors on the x and y position of the visual servoing of each marker (e_x and e_y , respectively). For all measurements the error on the steady-state was taken 5 seconds after the initial step input was given.

B. Gaze controlled endoscope validation

The evaluation of the intuitiveness, task load and preference of each system is shown in Table IV. As can be observed from the NASA-TLX results, the task load was greater when using the traditional control. Additionally, the Likert questionnaire shows an outcome of $89.1 \pm 16.40\%$, where a 0% would mean a complete preference of the hand control and 100% would mean a total preference of gaze control. Thus, users showed a clear preference for the new proposed robotic platform. It is important to note that the expert's subjective evaluations (NASA-TLX results of $53.3 \pm 15.0\%$ and $55.0 \pm 10.5\%$ for hand and gaze control respectively, and Likert result of $60.0 \pm 0.0\%$) did not present a strong preference for the traditional manual control they had been extensively trained for.

Fig. 10(a) depicts the success rate for each of the set-ups, where it is shown that targets were located successfully more often with the gaze set-up. 8 targets were found and centred correctly in every case for both approaches. The

TABLE III: Root Mean Square Error on the data fitting.

Dataset	Condition	RMSE [deg]
Entire Dataset	$\forall \theta_x, \theta_y$	3.1818
Q1: top-left image quadrant	$\theta_x > 0, \theta_y > 0$	2.5191
Q2: bottom-left image quadrant	$\theta_x > 0, \theta_y < 0$	3.7296
Q3: top-right image quadrant	$\theta_x < 0, \theta_y > 0$	3.4971
Q4: bottom-right image quadrant	$\theta_x < 0, \theta_y < 0$	2.7181

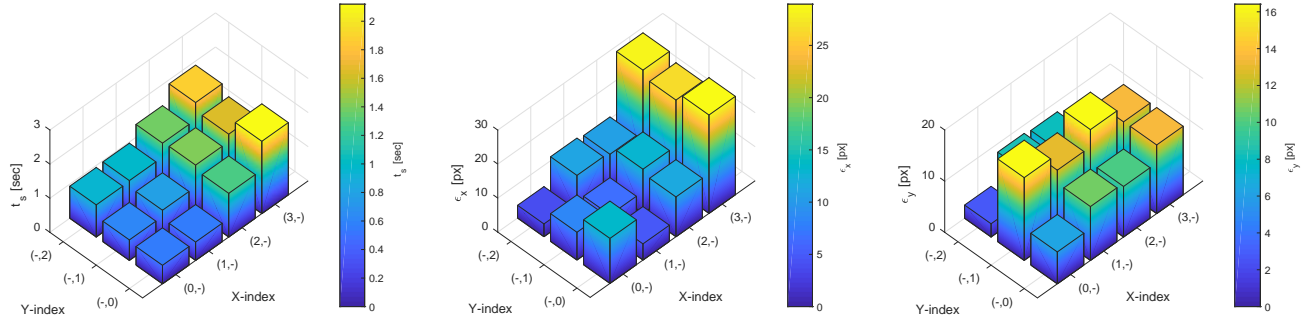


Fig. 9: The settling time t_s , and steady-state error on the X and Y response (ϵ_x and ϵ_y , respectively). For each point 20 repetitions are recorded, resulting in the average displayed ($n = 20$).

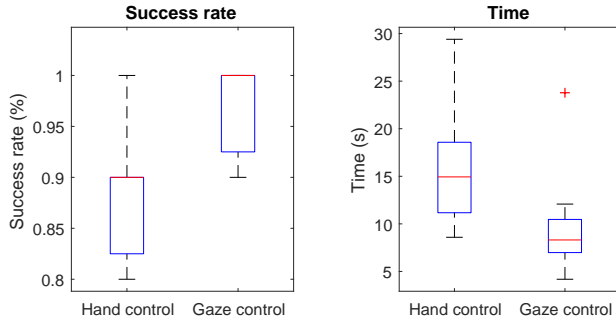


Fig. 10: (a) Box plot of the success rate to locate the targets by each participant both when using hand and gaze control. (b) Box plot of the average time to locate 9 of the targets with hand and gaze control.

other two targets proved to be more difficult to find due to their locations inside the phantom which required extreme rotations of the device. The rate of success for the first challenging target was 60% with manual control as compared to 100% with gaze control, and the success rate for the second target was 20% with manual control against to 70% with gaze control.

Fig. 10(b) shows the comparison of the average time taken to find each target by all the users between both set-ups. Only successfully located targets were taken into account for this evaluation. The time results for the most challenging target are not included, as they stood as outliers. As it can be observed, targets were found faster using the gaze manipulation. All users except for the expert completed the task faster with gaze control. For the expert endoscopist, this was due to the difference of time to find the most challenging task, as the median time is also lower with the gaze approach.

TABLE IV: Subjective evaluation: NASA-TLX and Likert questionnaires.

Questionnaire	Gaze control	Hand control
NASA-TLX	58.4 ± 2.75	79.6 ± 2.21
Likert	89.1 ± 16.40	

V. DISCUSSION

The benchmarking illustrates the relationship between the input and output and the response of the system to a simulated fixed gaze point using visual servoing. The quadratic surface fitting shows a relatively large offset parameter a_0 . The large offset is most likely attributed to imperfections in the setting of the homing position. Also, the RMSE of the fitting is high. Typically, an endoscope's tip is redundantly actuated as it consists of multiple links and therefore degrees of freedom, whereas it is only actuated in two DoFs. As a result, the final orientation β is not fully determined by the geometry of the system: if some links are constraint in their movement, other unconstrained links will still be able to move. In a clinical setting this is important as any anatomy constraining the movement of one section will not result in the full movement to be constrained. In the experiments this translates to the large RMSE found. With no external constraints, only the internal friction will play a role in the final orientation of the system and therefore resulting in a variation of angle β . In case of constraint situations, less links actively participate in the tip position and therefore larger angle β is expected for the same motor inputs.

The visual servoing experiments show the stability of the control system in different positions. The system is optimized for the unconstrained situation, in which no overshoot is presented. In case of constraints, the transmission from motor inputs to tip output is expected to increase, and therefore likely to add an overshoot before settling to the step response of the system.

It is important to note that the benchmarking has been done for one specific endoscope. As endoscopes have a similar mechanical design, a similar motor input to tip output mapping is expected, albeit with different fitting parameters. However, for sake of usability of different endoscopes by the endoscopists, these differences are not expected to be radically different. This should be evaluated in further development of the system.

The user studies included a more realistic scenario, in which the endoscope will inadvertently be constraint by the colon phantom and which the saccadic eye movement are included. Despite this more stochastic environment, the results show that gaze control was more intuitive and implied

a lower task load when compared to manual control of the endoscope. Also that gaze steering provides enhanced dexterity for navigation and accurate target location. These statements support the applicability of the gaze control approach for robotic endoscopy, validating the intuitiveness and effectiveness of the system. These results are encouraging, and further studies need to be performed to assess the effect of training in the proposed system.

The study presents an initial development of the platform, which is intended to grow towards a fully robotized system to be used in flexible endoscopy. Including motorization of the remaining DoF, namely insertion and rotation of the shaft of the endoscope, would allow a real hands-free control. However, a screen-based eye-tracker presents limitations to the use of the system, restraining the user's position strictly in front and at a set distance from the screen. This limitation could be overcome by the use of eye-tracking glasses [15]. For full implementation in clinical practice, the system needs further development to fit in the clinical workflow, requiring an improved design of the hardware that has no exposing active mechanical elements, allows for modularity to (a subset of) commercially available endoscopes and is quick to setup. Further evaluation of platform is required, to compare the system to traditional manipulation using expert endoscopists.

VI. CONCLUSION

A non-expensive modular prototype was developed to robotize the tip steering of an endoscope. An innovative control was applied, using gaze as human-computer interface to provide endoscopists with a hands-free control of a flexible endoscope. Results show that this platform was faster to manipulate in a colon navigation task than traditional endoscopy for novice users. Additionally, the interface allows to control the endoscope view in an intuitive manner, making use of the natural gaze of the user to steer the device. An objective evaluation of the platform shows that the time needed to perform a clinical simulated task is lower when applying gaze control, and demonstrates that centring features of difficult access in the screen is easier and more intuitive.

This paper presents a new, more intuitive and ergonomic framework that allows easier navigation and opens the door to wider adoption of complex robotic systems with added capabilities for Minimally Invasive Surgery.

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