Interventional Status Awareness Based Manipulating Strategy for Robotic Soft Endoscopy

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Abstract: Traditional soft endoscopy is operated with naked eyes and use of hands. Robotic soft endoscopy frees the hands of endoscopists, which reduces the labor-intensity and complexity of operation and improves the operational accuracy of endoscope, but it's hardly to be reliably performed because the operator lacks of situational awareness of endoscopic interventional status when the hands are detached from the endoscope. This paper first presents a method to perceive the interventional status of endoscope based on image processing, the interventional status includes insertion length and velocity. A manipulating strategy was designed according to the perceived endoscope interventional status and construction parameters of dual robotic arms in order to achieve reliable interventional endoscopy. Human phantom experiments are carried out to verify the effectiveness and feasibility of the proposed interventional status awareness method and manipulating strategy. The results show that the robotic soft endoscopy can be well performed with the ability of interventional status awareness and coordinated manipulation of dual arms. The perceived insertion length indicates the position of the tip of endoscope in human body and the designed manipulating strategy is effective in endoscopic shape retention and torque transmission.

Keywords: YunSRobot, Robotic soft endoscopy, Situational awareness, Interventional status, Manipulating strategy.

INTRODUCTION

Diseases of the digestive tract, urinary tract, respiratory tract and other natural orifice are seriously endangering the health of the people. According to the World Health Organization statistics, 70% of the people worldwide suffer from various degrees of gastrointestinal diseases and 5%-15% with urological calculi disease. Among all the deaths of cancer, the number of lung cancer deaths accounts for 1/5 [1]. In China, the incidence of digestive tract tumor, such as gastric cancer, esophageal cancer and large intestine cancer accounts for 42% of the world population and rises every year, the incidence of bladder cancer and prostate cancer ranks 6th and 7th respectively in the world. With the widely application of fiber optic technology in endoscopes, the interventional diagnosis and treatment of soft endoscopes such as gastrointestinal endoscopy, bronchoscopy and urinary endoscopy has become the main treatment for diseases in natural orifices due to the minimal invasive and rapid recovery [2-3]. During the endoscopy process, an endoscopist operates a flexible endoscope from mouth, urethra and other natural orifice into the stomach, duodenum, bladder and ureter. Tissues and lesions of the internal body could be observed by the embedded high definition camera of the endoscope. Surgical instruments such as biopsy forceps, electric knife, and stone basket are placed in the instrument lumen embedded in endoscope for tissue biopsy, resection, lithotripsy and other surgical operations [4-5].

In the traditional endoscopic diagnosis and treatment surgery, an endoscopist needs to hold the endoscopic operation part on the left hand side to adjust the bending direction of the tip of endoscope, while the right hand keeps delivering the endoscopic body into the cavity of the patient. During the interventional process, two control knobs should be manually operated to continuously adjust the bending direction of the endoscope to reach and observe the lesion area. Once the patient is diagnosed of needing a surgery, the assistant puts the surgical instrument into

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the endoscopic instrument lumen and then coordinates with the endoscopist to complete the surgical tasks such as ESD (Endoscopic Submucosal Dissection), EMR (Endoscopic Mucosal Resection), ERCP (Endoscopic Retrograde Cholangio-Pancreatography). The endoscopists need to undertake large operational tasks throughout the diagnosis and treatment process and a skilled endoscopist finds it challenging to stand for a long time while performing the operation. The frequent use of hands causes low surgical efficiency and high risk of complication such as bleeding and perforation [6].

With the combination of robotics and medical minimal invasive technology, robotic soft endoscopy has become a research focus in the field of minimally invasive surgery with the advantages of simple operation, high security and efficiency. Robot systems such as Aer-O-Scope, Endotics and Invendoscope have gradually came into view [7]. The Aer-O-Scope system which developed by GI View Company was equipped with a 360-degree panoramic camera to capture the bowel wall on both sides. The gasbag designed on the scope body could be adhered to the intestinal wall to form a confined space for enhancing the inflation effect of the cavity and reduce the damage between the scope body and the intestinal tissue [8]. The Endotics system applies biomimetic structure design to simulate the inchworm movement, which can self-propel in the intestine and reduce the risk of intraoperative complication [9]. The above-described endoscopic robotic systems with innovative configuration design have not only changed the traditional endoscopic design but also have increased the cost of clinical application and burdens of patient. Therefore, these robot systems have not been widely used in clinical practice and the traditional soft endoscopes are still in an irreplaceable position for a short time. Saglam *et al.* have developed the Roboflex Avicenna system to operate traditional ureterscope for calculi treatment, the robot can perform the endoscopic motion such as advancement and retraction, rotation and bending. At present, this system has completed clinical trials and achieved very successful experiments results [10]. The EOR system (Endoscopic Operation Robot) [11-13] and Advanced Endoscopy [14-16] were all based on the operation of traditional endoscope and doctor operates two joysticks based on master-slave control to finish the intervention of the endoscope. The above two robot systems have been researched and developed for a long time, a large number of experiments have been carried out and successful results have been achieved, which has important guiding significance for the research in the field of endoscopic robots.

However, the EOR system can only push the straight endoscope body forward into the human body because of the lack of active delivering mechanism for endoscope. Once the tip of the endoscope encounters large resistance, the endoscope body may show a distorted shape, which will significantly reduce the efficiency and safety of intervention. The Advanced Endoscope system has complete delivery and operation functions for endoscope intervention, but the operation part is immoveable and far away from the delivery part. Therefore, this robot system cannot achieve the full-length and reliable intervention, because the endoscope will be pulled and damaged when delivered to a certain insertion length. To increase the operability of endoscope, Li *et al.* have developed YunSRobot system with dual robotic arms [17], which allows the endoscopist to operate two joysticks which are deployed on the master terminal to control the movement of soft endoscope which is deployed on the slave terminal. However, the master-slave operation mode isolates the operator from the robot means that operator is far away from the actual surgical scene and lacks situational awareness, which has a fatal impact on the operational decision making during the surgery. According to our previous experiments [18-20], endoscopist sometimes forgets to observe the drag state of the endoscope and adjust the rotation and linear motion of operational arm, which causes the endoscope to be pulled forcefully.

To reduce the complexities and risks of robotic soft endoscopy, this paper presents a method to perceive the interventional status of the soft endoscope based on image processing. A manipulating strategy is design according to the perceived interventional status of the endoscope construction parameters of dual robotic arms to achieve the full-length and reliable intervention. The YunSRobot system had been presented in previous work [17]. The robotic operation analysis of interventional endoscopy is given in Section II. The awareness method of interventional status is described in Section III. The manipulating strategy of dual robotic arms is designed in Section IV, followed by experimental results of the interventional status awareness and manipulating strategy validation in Section V. Section VI, VII concludes this paper respectively.

ROBOTIC OPERATION ANALYSIS FOR ENDOSCOPIC INTERVENTION

In the traditional endoscopic diagnosis and treatment process, the endoscopist needs to hold the endoscopic operation part and the endoscope body by the left and right hand respectively. With the endoscope continues to be delivered into the human body, the left hand moves closer to the right hand with a specific trajectory, so as to insert all the length of the endoscope into the deeper section of digestive tract such as pylorus and duodenum while maintaining effective torque transmission of endoscope.

The YunSRobot has been equipped with dual arm structure to simulate the operation of endoscopist, the delivery motion and bending motion of endoscope were achieved by delivery arm and operation arm respectively, the initial and end state of endoscope intervention is shown in Figure **1**.

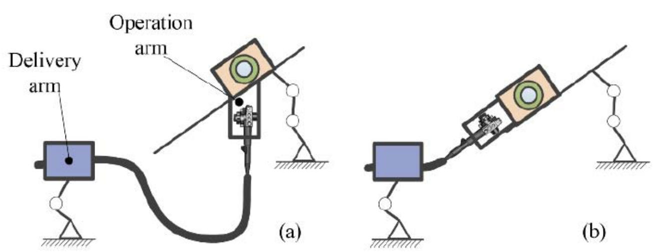

Figure 1: Initial and end state of the endoscope intervention. (**a**) Initial state and (**b**) End state.

During the whole interventional process, the delivery arm continuously delivers the endoscope, when the endoscope is delivered to a certain insertion length, the operational arm completes rotation and linear motion to follow the delivery movement of the endoscope. In theory, the insertion length and velocity of endoscope could be obtained by the motor encoder, then robot could control the rotation and linear motion of operation arm based on the detected interventional status and the geometrical relations of dual arm to achieve full-length and reliable intervention. However, the mucus of digestive tract always sticks on the surface of the endoscopic body during the surgical process which seriously affects the friction between endoscope and wheel so that the effective features of interventional status cannot be obtained by the encoder. In order to get the accurate real-time endoscope intervention status which includes insertion length and velocity, The HD camera (LT-SD14010, LTVS Inc. China.) was set on the delivered arm so that the interventional status of endoscope could be clearly monitored without interfering with the motion of the robotic arm (Figure **2**). The design of interventional status awareness method is described in the following section.

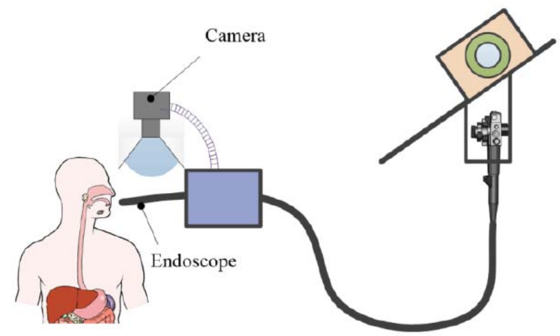

Figure 2: Monitoring scheme for endoscopic interventional status.

DESIGN OF INTERVENTIONAL STATUS AWARENESS METHOD

Overview of the Method Process

The awareness method presented in this paper is shown in Figure **3**. The ROI image is first extracted from the image captured by the HD camera, and then a series of image processing such as grayscale, filtering is completed. The pixel physical dimension in ROI image is calculated according to the diameter and inclination angle of endoscope in the ROI image. Finally, the delivery velocity and insertion length of endoscope are calculated according to the pixel position of the white line which adheres on the endoscope surface.

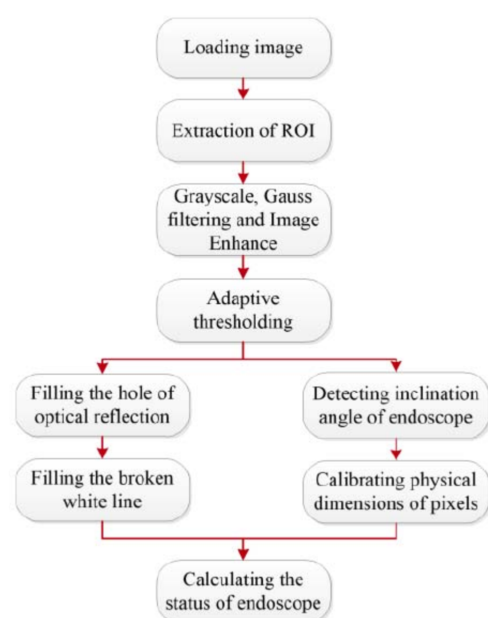

Figure 3: Algorithm diagram of endoscope interventional status awareness.

ROI Extraction and Process

During the actual robotic endoscopy, there are some unexpected external disturbances which could penetrate the camera field of view, such as surgical instruments or endoscopist's arm. In order to minimize interference factors, ROI extraction should be completed firstly. The monitoring area is set on the endo-image to avoid the irrelevant features (Figure **4b**). Then, grays and filters the ROI by Gauss linear filter to reduce noise. The gray value of ROI is stretched to [0, 255] by contrast stretching to enhance the features of endoscope (Figure **4c**). To detect the white line position clearly, adaptive threshold (opencv 2.4.8, Adaptive Threshold Function) method is applied to process the image (Figure **4d**).

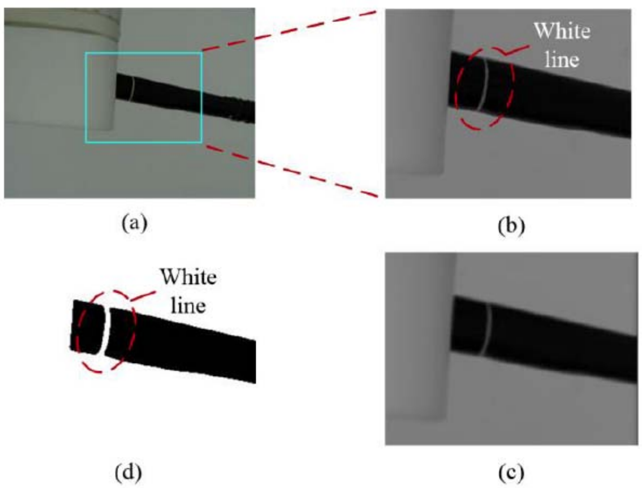

Figure 4: ROI extraction and image processing flow. (**a**) Extract ROI from the original image, (**b**) ROI image, (**c**) Filtered and enhanced image and (**d**) Binarized image.

Detection of the Inclination Angle and Physical Dimension of Single Pixel

The supporting shaft of camera is flexible to adjust the position relative to the delivery arm and the endoscope monitored by camera could not always be parallel to the field of view (Figure **4a**). Therefore, inclination angle detection of the endoscope in the ROI image should be finished before calculating the insertion length. The Canny edge detector (opencv 2.4.8) is applied to extract the outline of the endoscope body and the first white pixel of each column is preserved (Figure **5c**). The interference point which caused by the white line are removed by detecting the Euclidean distance between the adjacent white pixels to reduce the fitting error, then the least square method is used to fit all the points (the outline of the upper side of the endoscope body) to get the inclination angle of the endoscope. The slope β_1 and intercept β_2 of the fitted line are calculated as:

$$\begin{cases} \beta_2 = \dfrac{n\sum \boldsymbol{X}_i\boldsymbol{Y}_i - \sum \boldsymbol{X}_i \sum \boldsymbol{Y}_i}{n\sum \boldsymbol{X}_i^2 - (\sum \boldsymbol{X}_i)^2} \\ \beta_1 = \dfrac{\sum \boldsymbol{X}_i^2 \sum \boldsymbol{Y}_i - \sum \boldsymbol{X}_i \sum \boldsymbol{X}_i\boldsymbol{Y}_i}{n\sum \boldsymbol{X}_i^2 - (\sum \boldsymbol{X}_i)^2} \end{cases} \quad (1)$$

Where n provides the number of the white pixels (Figure **5c**), and $\boldsymbol{X}_i$, $\boldsymbol{Y}_i$ represents horizontal and vertical value of i th point, respectively. The inclination angle θ can be simply calculated by the β_1 and it not only used to calibrate the physical dimension of single pixel, but also could be applied to validate whether the endoscope is well assembled.

In order to accurately calculate the insertion length of the endoscope in real time, the actual physical dimension of single pixel must be obtained. The number of black pixels in each column is calculated by scanning each column of the binarized image (Figure **5a**). Therefore, the physical dimension of single pixel l_{pix} is calculated as:

$$l_{pix} = \frac{d}{(\sum_n q_i/n) * \cos(\theta)} \quad (2)$$

Where n is the number of the columns (column with too few black pixels have been removed) in the binarized image, q_i is the number of black pixels in ith column (Figure **5a**), θ is the inclination angle and d provides actual physical diameter of the endoscope (9.5mm of insertion tube diameter, GIF-XQ230, Olympus Inc. Japan).

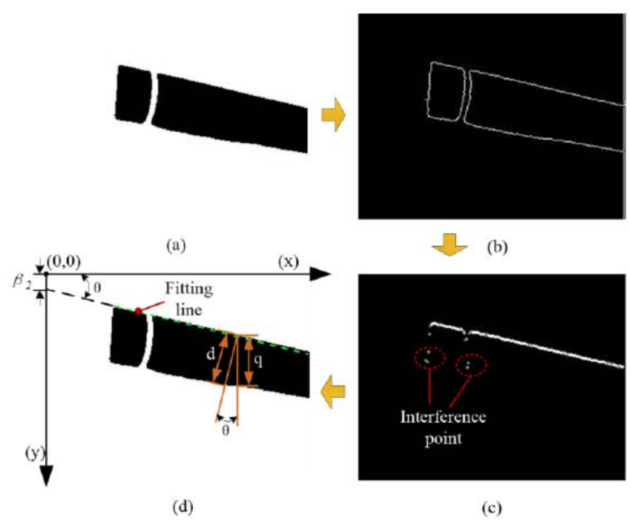

Figure 5: Detection of endoscopic inclination angle. (**a**) Binarized image, (**b**) Edge of the scope body, (**c**) Interference point caused by the white line, (**d**) Straight line (green dotted line) fitting by least square method.

Filling Process of the Spots and White Line

In the bright surgery environment, the endoscope body could reflect the light because of the glare or white medicines (Lidocaine gel, local anesthesia and lubrication for upper digestive to patients before gastroscopy intervention) stick on the body so some spots will appear in the image which cause the white line position could not be detects precisely (Figure **6b**). To decrease the influence of glare, the Flood Fill algorithm (opencv2.4.8 floodFill Function) is employed. Creates a black template (the pixel value is zero) with height and width more two pixels than the image and then copy to the template ((1, height+1), (1, width+1)). Sets the seed point position at the (0, 0) of the image coordinate system and the holes in the region connected with seed points are filled in white (Figure **6c**).

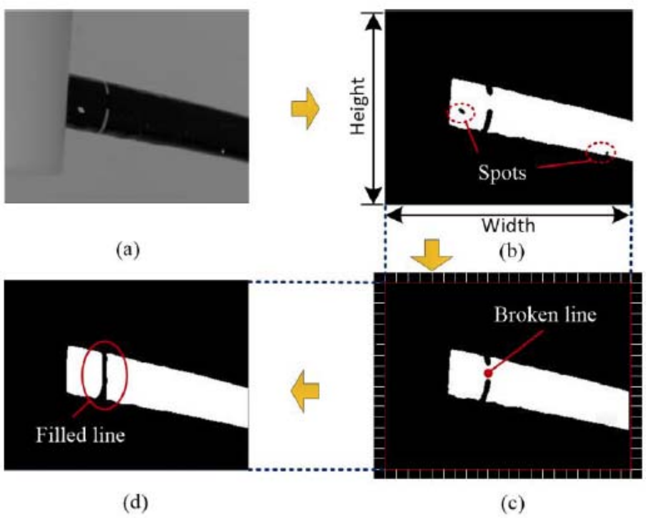

Figure 6: Process flow of filling spots. (**a**) Medicine sticks on the body in ROI image, (**b**) Spots appear in the binary image, (**c**) Fills the spots by Flood Fill method and (**d**) Fills the broken white line.

To observe the anatomical structure of digestive tract such as the stomach fundus during the endoscope intervention, there are many times are required to rotate the endoscope. However, the white lines on the endoscope body are not closed because of manufacturing processes. After the endoscope body rotates to a certain angle, the white line is broken. To fill the white line, morphological operations (e.g. dilation and erosion), straight-line detection and other method were applied, but the detect accuracy and stability are not well. The method proposed in this paper to fix the line was relatively simple that detects the column position which has the minimum number of white pixels. The width of the consecutive columns with shorter white pixels is detected to match the physical width of the actual white line (1mm, GIF-XQ230, Olympus Inc. Japan.) to ensure the validity of the method and then broken white line was stitched by filling the white pixels of these columns into black (Figure **6d**).

Calculation of the Insertion Length and Velocity

When the broken line has been filled, sets the middle column of columns which are filled with black pixels as the location of the white line. The insertion direction of the endoscope is from left to right, so the physical length from the white line position to the right border is the remaining length of a segment of endoscope (white line to white line, 50mm), once the white line crosses the right border of the view, the insertion length of endoscope increases by 50mm. In this paper, only the white line which closest to the right border could be shown in ROI image, the pixels in the column on the left of the white line position are set to zero (Figure **7**). The basis for white line crossed the border is whether the length difference detected between the adjacent frames exceeds the threshold value (40mm). The insertion length l_{ins} and velocity v_{ins} of endoscope are calculated as:

$$\begin{cases} l_{ins} = 50 \times n_{count} + \dfrac{n_{border}}{\cos(\theta)} \times l_{pix} \\ v_{ins} = \dfrac{l_{cur} - l_{pre}}{t} \end{cases} \quad (3)$$

where n_{count} presents the number of the white lines that have passed through the right border, n_{border} is the number of the pixels between white line position and right border of ROI image, l_{cur} and l_{pre} provide the insertion length value of the current frame image and the previous frame image respectively, t is the time difference between adjacent frames processed by computer.

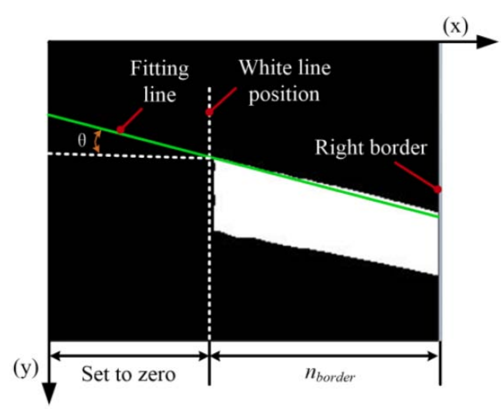

Figure 7: Pre-processing before insertion length calculation.

When the endoscope moves backward (from right to left), the calculation formula of the insertion length is the same as Eq. (3) and once the white line appears on the right border, n_{count} minus one. In the operation of robotic soft endoscopy, interferences such as fingers or arms of endoscopist may bump into the camera vision during the operation of surgical instruments and the n_{count} will be changed, the subsequent surgery operation is difficult to be continued. To minimize the influence of the above situation, the n_{count} designed to be manually changeable, whenever the endoscope is out of the camera vision and n_{count} will be manually inputted after the camera posture had been readjusted to ensure the accuracy of the insertion length during the whole operation.

DESIGN OF MANIPULATING STRATEGY FOR DUAL ROBOTIC ARMS

When the endoscope is delivered to a certain length, the operation arm needs to take corresponding motion to autonomously cooperate with the endoscope delivering, so as to ensure the full-length and reliable intervention. The manipulating strategy of dual robotic arms based on detected interventional status will be introduced in the follows.

The operation arm has 2 DOFs which perform the rotation and linear motion respectively. According to the insertion length of the endoscope, the process of robotic endoscope intervention is divided into four states (Figure **8**): Initial state, operation arm rotation motion, operation arm linear motion and final state (full-length intervention).

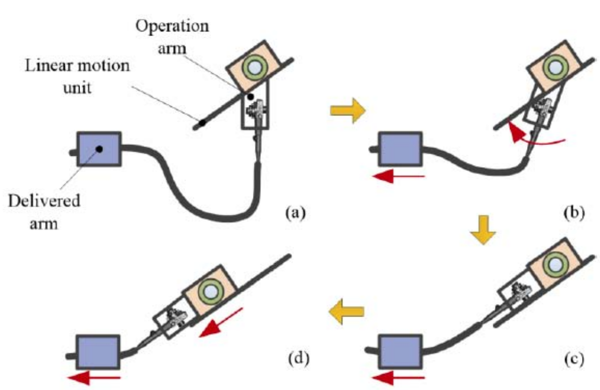

Figure 8: Interventional status of the endoscope. (**a**) Initial state, (**b**) Operation arm rotation, (**c**) Cessation of rotation motion and (**d**) Linear unit move to target position.

During the initial state (Figure **8a**), the operation arm is vertical to the ground and the tip of the endoscope is manually placed on the delivery arm by the assistant. The endoscope presents a draping state between the delivered arm and operation arm because of the large length of endoscope and the limited operating space of two arms, once the endoscope begins to be delivered, the operation arm performs rotation motion to avoid dragging the endoscope (Figure **8b**). When the operation arm rotates to parallel with the linear motion unit (Figure **8c**), the rotation motion of the operation arm is stopped and the linear motion starts which is accomplished by a lead screw (LXR3005C-S1-N8-400, MiSUMi-VONA). In the case where the insertion length of the endoscope is sufficient to diagnose the digestive tract, the proximity switch of the lead screw was set up to prevent the endoscope from being damaged because of the transitional delivery (Figure **8d**). In the whole interventional endoscopy process, the conveyor wheel mechanism which was equipped on delivery arm has been working at all times. The backward process of the intervention is completely contrary to the linear process, the linear motion unit moves upward to the limit position and then the operation arm performs rotational motion to the initial state.

The key to the successful implementation of the above strategy is how to autonomously adjust the rotation motion velocity and linear motion velocity of the operation arm. The analytical solution between the delivery velocity v_{ins} of the endoscope and the rotation velocity ω_r and the linear velocity v_l of the operation arm can be obtained by analyzing the relationship between the spatial position and relative motion of the two arms (Figure **9**).

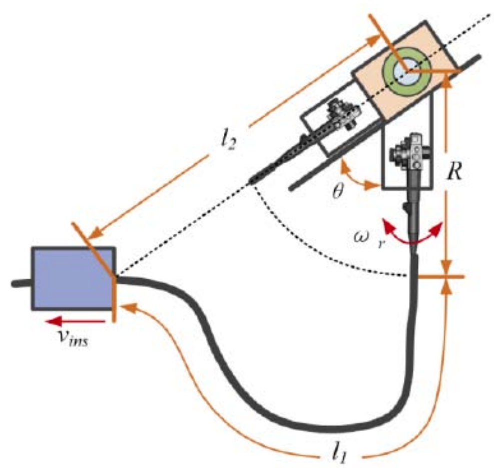

Figure 9: Rotation motion analysis of operation arm.

During the rotation motion state, the ω_r is calculated as:

$$\omega_r = \theta \times \frac{v_{ins}}{l_1 - (l_2 - R) \times \eta} \quad (4)$$

Where θ presents the angle of rotation of operation arm, l_1 is the total length of endoscope intervention, l_2 is the distance from the center of rotation to the endoscope entrance of delivery arm, R is the radius of rotation of the operation arm and η provides a safety factor (greater than one) to avoid excessive tightening of endoscope at the end of the rotation of the operation arm. l_2 and R can be measured manually.

When the insertion length reaches l_1-(l_2-R), the rotation motion is stopped and the operation arm autonomously starts linear motion. During the linear motion state (Figure **10**), the v_l is calculated as:

$$v_l = \frac{v_{ins}}{\eta \times (l_2 - R)} \times l_3 \quad (5)$$

Where the l_3 presents the linear motion distance of lead screw.

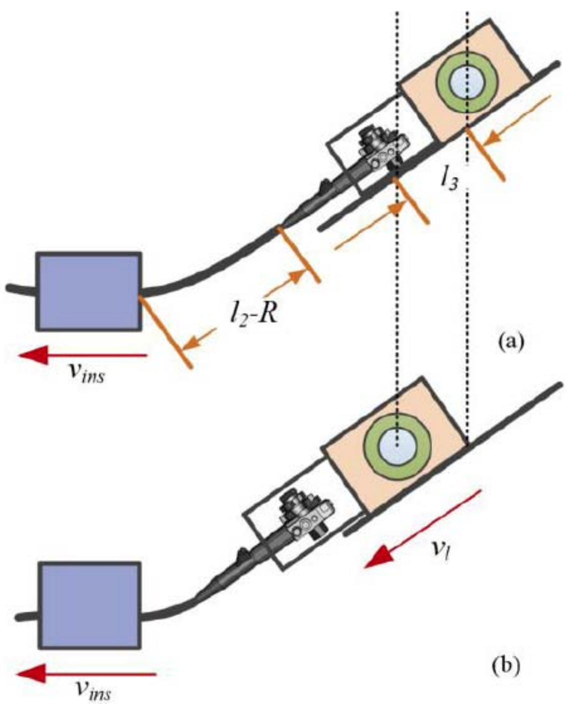

Figure 10: Linear motion analysis of operation arm.

EXPERIMENTAL VERIFICATION AND DISCUSSION

Experiments of Interventional Status Awareness

In order to verify the validity and accuracy of the method for detecting the endoscope interventional status, the experimental platform was set up as shown in Figure **11**. The system mainly includes HD camera (25fps, Computar, Japan.), linear motion unit (XA-35L-100, SUS Inc. Japan.), a segment of the endoscope and the measuring board.

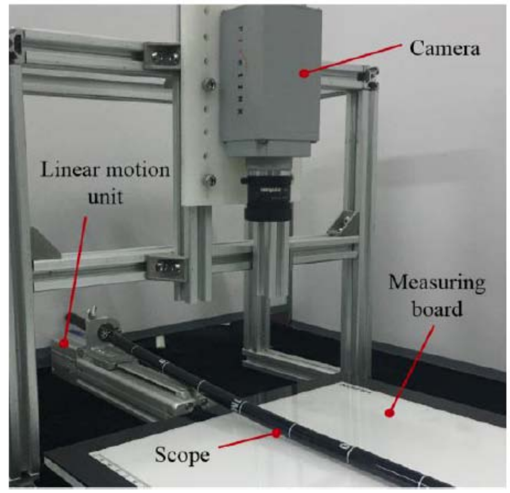

Figure 11: Experimental platform for intervention status awareness.

In order to test the accuracy of interventional status awareness method under different operating conditions, the linear motion unit drives the endoscope to move forward or backward by computer programming, the endoscope is forwarded 20mm, 50mm, 30mm at the speed of 2mm/s, 4mm/s, 2mm/s respectively and the back movement is completely reversed. The results of the interventional status awareness for three tests are shown in Figure **12**. The red line represents the input (displacement in (a) and velocity in (b)) of the linear motion unit, the three dashed lines in blue, green and black respectively represents the results for perceived intervention status in three tests. During the whole detecting processes, the maximum detection error for insertion length which occurs in the backward motion is about 6mm (Figure **12a**), The average insertion length error of the three experiments is 2mm. The insertion velocity (Figure **12b**) of endoscope is obtained by calculating the ratio of the difference of insertion length between adjacent frames to the time (consumed by algorithm operation). the average velocity error is about 0.6mm/s by calculation. There are 4 major short time fluctuations in the velocity detection because the light environment affects the width of the white line (Figure **12b**), in aim to reduce the effect of velocity fluctuation on operation arm motion control, the average value of insertion velocity is calculated once every 10 frames as the control input of the rotation and linear motion of the operation arm.

Experiments of Upper Digestive Tract for Human Phantom

Robot assisted gastro endoscope intervention for upper digestive tract of human phantom was carried

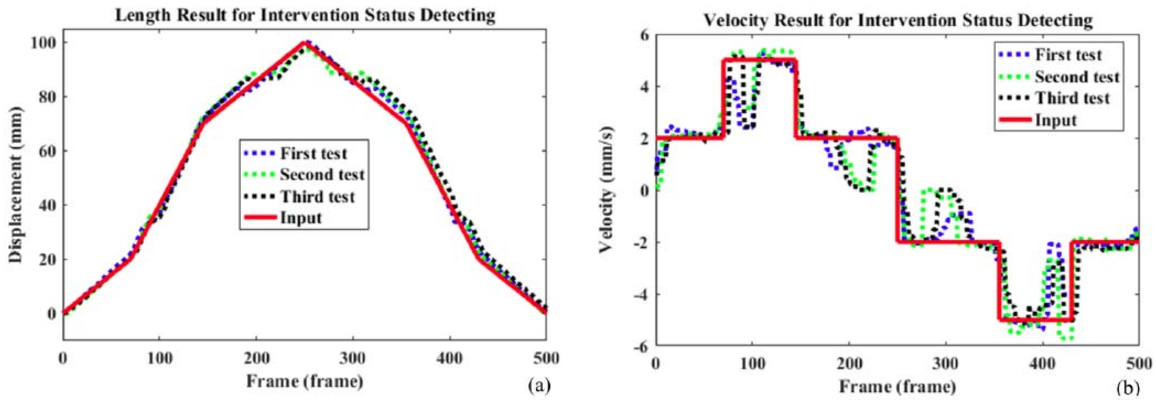

Figure 12: Three tests for interventional status of endoscope. (**a**) Insertion length detection and (**b**) Insertion velocity detection.

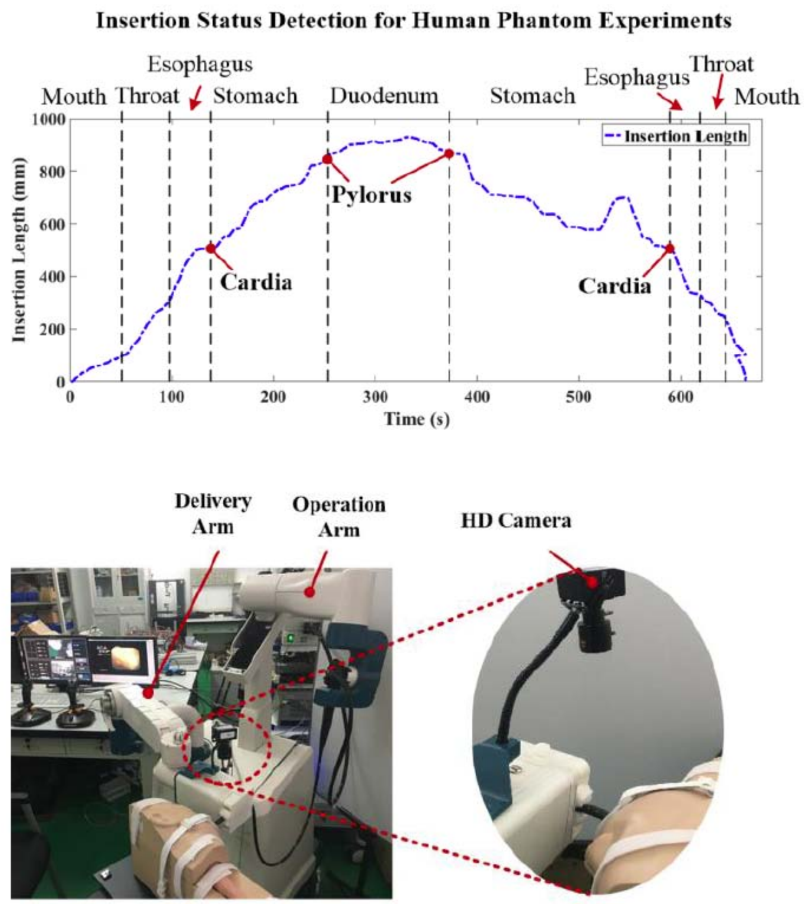

Figure 13: Endoscope intervention study on a human upper digestive phantom.

out to verify the practicability of the endoscope interventional status awareness method and manipulating strategy. The experimental set up was arranged in an upper digestive model (LM-103, Koken Inc. Japan.), the endoscopic robot controlled by the doctor operates the gastroscope (GIF-XQ230, Olympus Inc. Japan.) to complete an interventional experiment for the model (Figure **13**). Doctor operates two joysticks to control the motion of the endoscope (forward and backward, bending and rotation) by observing the image fed by the embedded camera. The gastroscope passes through the mouth, throat, esophagus, cardia respectively and then reaches the gastric body. In the stomach, endoscopist operates endoscope to observe the greater curvature, lesser curvature, antrum and gastric angle and fundus ventriculi, and finally control the endoscope through the pylorus to observe the duodenal papilla and descending part. The perceived results of the insertion length of the endoscope during the whole intervention process are shown in Figure **13**.

Discussion of Experimental Results

The human model phantom experiments show that the proposed manipulating strategy of dual robotic arms based on interventional status awareness can achieve full-length and reliable interventional endoscopy. During the interventional process, the shape changes of the endoscope can ensure the safety of endoscope while maintaining effective torque transmission, just like the traditional manual operation. but the above mentioned 'reliable' is fully based on the accurate insertion length. The principle of the insertion length detection method proposed in this paper is to detect the position of the white line which adheres on the endoscope surface, once the camera's visual field is too narrow, there may be no white lines detected because the spacing between each two white lines is 50mm. the resolution of length detection will be reduced to 50mm so that the algorithm can only be used for white line counting. Then the manipulating strategy will change to rely solely on the insertion length to adjust the operation arm motion because the insertion velocity is no longer detectable. In response to this situation, we have matched the motor pulse of the rotation and linear motion of operation arm with each 50mm of insertion length, the intervention can also be done in human model phantom experiments, so we can conclude that robot-assisted endoscope intervention is somewhat tolerant of endoscopic shape requirements, but the best torque transmission shape is still needed to explore and research in future work.

In addition, we have got another result. As shown in Figure **13**, each insertion length corresponds to a specific anatomical structure of the digestive tract. For example, when the insertion length reaches 500mm and 900mm, the end of the endoscope reaches the cardia and pylorus respectively. Therefore, the location in human body of the tip of endoscope can be determined according to the insertion length, which will help endoscopic robot perceive the external environment when the endoscopic camera vision is blocked and the image process method is ineffective. Of course, a more accurate positioning of anatomy of digestive tract requires a combination of endo-image process and insertion length detection, just like the judgment of endoscopists in traditional endoscopy.

CONCLUSION

This paper has presented a method to perceive the interventional status of the soft endoscope based on image processing. A manipulating strategy of dual robotic arms has been designed according to the perceived interventional status to overcome the difficulties and complexities of master-slave robotic operation which caused by the lack of situational awareness of interventional status. The human phantom experiments have shown that the robot performed interventional endoscopy is reliable and the endoscope is kept in effective torque transmission shape during the whole interventional process. The detected insertion length can also indicate the position of the tip of endoscope in human body, which will be very helpful for the further study of robotic interventional endoscopy technology.

The future work on autonomous robotic interventional endoscopy using machine learning method in combination with various types of sensory information (endoscopic morphological characterizes, insertion force, insertion length, endoscopic image and so on) to give the doctor and robot a situational awareness is under the author's investigation.

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