An optical colon contour tracking system for robot-aided colonoscopy

Localization of a balloon in an image using Hough-Transformation

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Abstract. During colonoscopy there is a risk that the intestinal wall may be injured or may pain occur by the insertion of an endoscope. Surgery through endoscopes must be learned by physicians through extensive training. To simplify the insertion of endoscopes, research is being carried out on robotic - aided systems. Here, a sensor is needed to detect the contour of the intestine in order to enable an injury - free and painless insertion of the endoscope. In this paper a tube - balloon is designed for a gentle contour tracking of the intestinal anatomy. This is inserted through the working channel of the endoscope and placed in the intestinal lumen in front of the endoscope's head in the field of view of the camera. A Matlab - algorithm is used to detect the balloon in each image. The balloon appears as a two - dimensional circle, which can be detected using a Hough - Transformation. The displacement of balloon after touching the intestine wall is calculated as a vector between the circle's center and the image center. This ensures that the robot - aided endoscope can follow the intestinal contour.

1 Introduction

Colonoscopy is used to detect colorectal cancer at an early stage in the average - risk population [1,2]. The conventional method is established on a large scale in everyday clinical practice. In Germany, 58.5 % of women and men over the age of 55 have had such an examination carried out within the last 10 years [3]. However, pain or even injuries at the intestinal wall can occur [4]. In order to compensate for these disadvantages, innovative approaches are under development to improve the requirements in terms of clinical applicability, user - friendliness, and functionality of the instruments. A trend towards robot - aided flexible endoscopes with multiple working channels, called overtubes, is emerging [5,6,7,8,9].

Nevertheless, the insertion of such endoscopes into the body can be difficult and time consuming. Thus, an integration of a precise, automated insertion instrument as a sensor or reference point to determine the individual anatomy should facilitate a simplified insertion. This should increase usability and user-friendliness of such a device and reduce the operating time. In this paper an optical colon contour tracking system for robot-aided colonoscopy is presented. To achieve this a balloon as a sensor for determining the contour and thus the curved pathway of the intestine with real-time image analysis is investigated. It is examined how long the image evaluation takes with regard to the calculation time and whether the balloon as sensing element is detected reliably.

2 Material and methods

To capture the information of the curved pathway of the intraluminal individual anatomy of the intestine, a balloon is placed in front of the overtube in the camera's field of view via the working channel of the overtube (see Fig. 1). This balloon is flexibly attached on a tube, which is bent away by the intestinal wall. Using image processing, the balloon can be detected and its position relative to the overtube can be determined. If the balloon is moved away by the intestinal wall, the position relative to the overtube also changes. Since the image center is known and the robot-aided overtube is bendable in x− and y−directions, it is able to follow the balloon. Thereby, the overtube follows the individual anatomy of an intestine.

2.1 Mechanical Setup

The complete system consists of a balloon prototype, a camera module, a single-board computer for image acquisition, and a PC for image analysis (see Fig. 1). In the prototype the balloon is made of natural rubber. It is fixed to a polyurethane tube $\varnothing_{\mathrm{Out}} = 2\,\mathrm{mm}$, series PUN-H (Festo SE & Co. KG, Germany) using heat-shrinkable tubing. Radial holes allow air to enter and inflate the spherical balloon. The balloon is filled with 10 to 20 ml ambient air and reaches a diameter

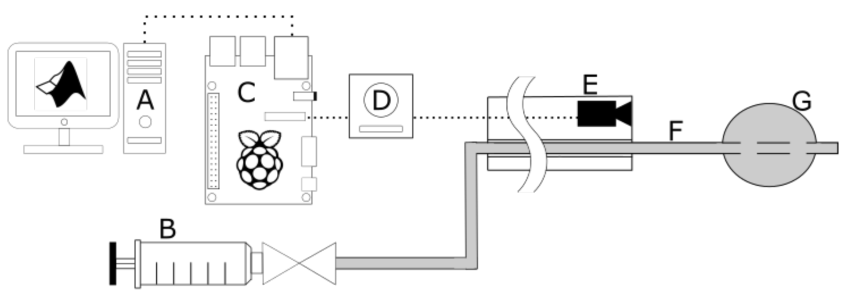


Fig. 1. Schematic of the test bench (A: PC running Matlab, B: syringe and valve, C: Raspberry Pi 3 model B, D: camera module, E: overtube with camera, F: tube, G: Balloon).

of about 27 mm. Air is supplied via a Omnifix® Solo disposable syringe 30 ml (B. Braun AG, Melsungen, Germany) and a Luer Luck valve (three-way valve from Teqler, NetMed S.à.r.l., Wecker, Luxembourg).

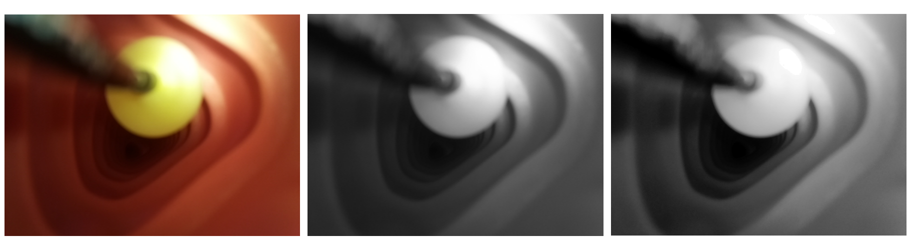
For image recording a Raspberry Pi 3 model B with a camera module RASP CAM 2 (Raspberry Pi Foundation, UK) is used, on which a mini camera RPI V22 with 8 MP, 77,6 ° (Denash, Chengdu, China) is connected. This camera is placed at the head of the overtube (see Fig. 1 – E). The Raspberry Pi is connected via Ethernet to a PC (ASUS UX310U, Intel® Core™ i7-6500U CPU @ 2.50 GHz, 16 GB RAM), on which image processing is performed by MATLAB® R2019a (The MathWorks, Inc.).

2.2 Algorithm

The aim of the algorithm is to identify the inflated balloon as a circle and its center in an image. For this purpose, the camera takes images, which are loaded as PNG files into the Matlab workspace. Subsequently, each image is pre-processed to finally identify a circle. The first steps are to convert the original image into a grayscale image and increase the contrast as well as to limit the image size to 640x480 pixels to create an defined starting position (see Fig. 2). The coordinate origin is located in the upper left corner. Afterwards, the Hough-Transformation (HT) [10,11] is used to detect the balloon as circle in an image.

The HT is a standard procedure for the detection of parameterized curves and very robust but also very complex to calculate [12]. Even if the circle is covered, e.g. supply tube for the balloon, the HT can be successful. It is assumed that only the balloon with a specific radius range is detected as a circle with the correct settings, since other circular patterns such as circular cross-sections in the intestine or shadows lie outside the radius of the searched circle.

A circle is described as a function of $r^2 = (x_i - a)^2 + (y_i - b)^2$ in a two-dimensional space. Where r is the radius, a and b are the center of the circle. From the input image (Fig. 2c, increased contrast) an edge image is generated (Fig. 3a) via a binary image depending on the threshold. In the image, edges are represented as black pixels and the remaining pixels are shown white. The HT has to recognize which edges form a circle. For this purpose, a circle with the predefined radius r is drawn at each edge point and its circle points are temporarily stored in an accumulator field (Fig. 3b). Since in an accumulator



(a) original (RGB) (b) grayscale (c) increased contrast

Fig. 2. Pre-processing of images in steps (a),(b),(c).

field several circle points can be found at the same place, this place is counted up, similar to a voting. Once all edge points in the algorithm have passed through, the accumulator field is evaluated. The point that has the highest value (most votes) or exceeds a certain threshold is the center of the identified circle (Fig. 3c). If the radius r of the circle to be searched is not known, the radius can be variable within a certain range and runs through the algorithm several times with the different radii.

Once the center of the circle has been determined, a vector can be calculated to the image center. The image center represents the point where the overtube will move by a straight movement. The vector indicates where the camera or overtube should move to.

2.3 Experimental Setup

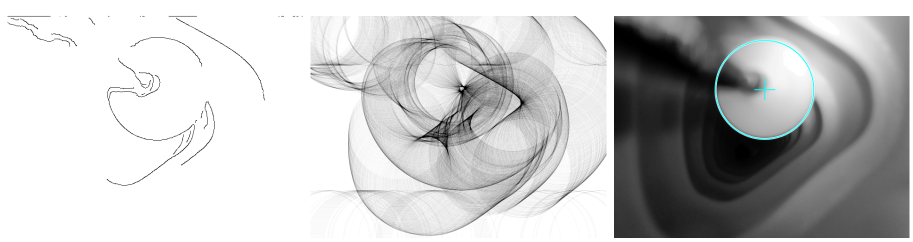
To validate the algorithm, 400 images were acquired in a colon model (M40 Colonoscope Training Model, Kyoto Kagaku Co., LTD, Japan). The settings in the algorithm, in which range the searched radius lies, was for a minimum radius of 100 px and maximal radius of 110 px.

Calculation time is of interest and has been investigated offline. The function *stopwatch* (*tic toc*) was used in Matlab. It was examined how long it takes to find one circle, as well as the cases when no or several circles are found.

3 Results

The construction allows a flexible placing of the balloon in front of the camera. The balloon is pushed away from the intestinal wall and consequently changes its position relative to the overtube. Using the system of a camera, Raspberry Pi, and Matlab, 5 images per second could be processed. The visualization of the image with the determined circle and values are shown on a monitor. Fig. 4 shows a sample image as it appears on the PC screen, with the identified circle, its coordinates and vector v for the direction of movement.

A total of 400 images were evaluated to determine the balloon as expected as a circle. In 353 images (88 %) only the balloon was detected. In the remaining images 38 times (10 %) no circle was identified and 9 times (2 %) more than



(a) edge image (b) accumulator field (c) identified circle

Fig. 3. Working principle Hough - Transformation (HT).

one circle was identified. The analysis of the calculation time of the Hough-Transformation was 125 ms (standard deviation (SD) = 17 ms). The calculation time was an average of 122 ms (SD = 14 ms) if one circle was detected, an average of 130 ms (SD = 20 ms) if no circle was detected and an average of 119 ms (SD = 16 ms) if more than one circle was detected.

4 Discussion

With this setup, it is possible to obtain information on the curved pathway of the intestine. The use of a balloon as a sensor or reference point is possible. It can be easily integrated in robot-aided overtubes. With the Hough-Transformation the balloon can be recognized as a circle in an image. Thereby, the balloon is localized in an image and thus also in the intestine and a robot-aided contour tracking can be realized. To generate a higher probability of success, several approaches were investigated. It turned out that the edge of the balloon is often only partially recognized. In order to clearly discriminate the balloon from the rest of the image and thus enable sufficient edge detection, it should be well illuminated. For this reason the balloon should be clearly distinguished in the image and no shadows should appear which are falsely detected as circles.

It should also be mentioned that the images were taken on a phantom. In reality, soiling is to be expected, which can have a negative effect on the detection.

To ensure that it can be used in the medical field in the future, the process time should be reduced. Currently, the calculation time of the Hough-Transformation is at 125 ms (SD = 17 ms). It is clear that the high computational effort of the Hough-Transformation is accompanied by a loss of speed.

Looking closer at the images it becomes apparent that the balloon occludes a considerable part of the image. Since this visual impairment can lead to a lack of acceptance by some of the personnel, a solution should be sought that limits the visual impairment to a minimum.

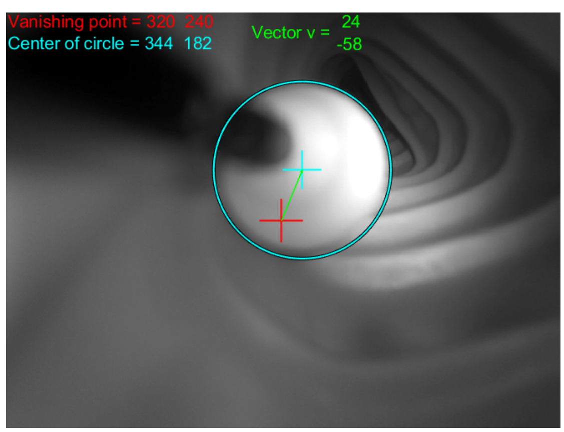


Fig. 4. Visualization of identified circle and calculated vector.

The balloon can be removed through the working channel after reaching the desired sites. The field of view is therefore not restricted during actual surgery. Furthermore, through the working channel other instruments can be applied.

To conclude, a proof of concept is shown. It is possible to use a balloon to sense the contour of the intestinal wall and capture it in images. This allows a localization of the overtube relative to the balloon and thus to the intestinal wall.

5 Acknowledgement

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