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Time-of-Flight Based Collision Avoidance for Robot Assisted Minimally Invasive Surgery

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***Abstract*—In minimally invasive surgery navigation and orientation are major issues due to the limited field of view. To ensure the safety while navigating through the patient´s abdomen it is of high importance to avoid collisions with surrounding tissue and organs. Recently, intelligent assistance systems have been developed to eliminate the error prone navigation of surgeons and replace it by indirect navigation using a robot. To ease the navigation and guarantee that the endoscope always keeps a fixed distance to the operation site we introduce a Time-of-Flight based module for robotic assistance systems. Our module allows the endoscope to hover over the situs to avoid collisions with healthy tissue.**

Keywords—endoscopy; Time-of-Flight; SOLOASSIST; navigation; robot

I. INTRODUCTION

Minimally invasive procedures are of growing importance in modern surgery. These interventions aim at reducing pain, scars and recovery time compared to conventional surgery. Navigation and orientation are challenging tasks for surgeons due to the limited field of view with conventional endoscopes. In conventional minimally invasive procedures instruments and endoscopes are navigated by a surgeon. Especially during long interventions this includes the risk of a jitter as an additional source of error and leads to unstable blurry images during the intervention. By erroneous navigation of instruments or the endoscope the surgeon may harm surrounding healthy tissue.

Fig. 1. The three components of our enhancement module. From left to right: PMD CamBoard nano, Adruino Uno micro controller, L12 linear servo motor.

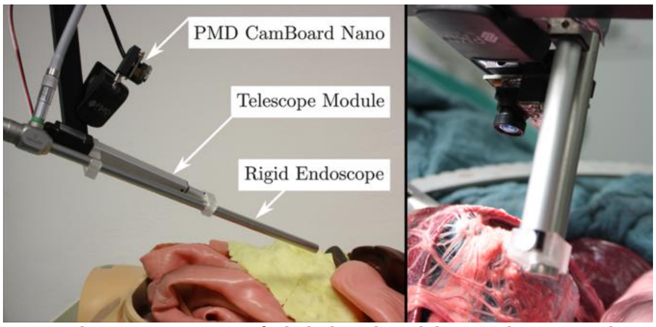

Fig. 2. The prototype Time-of-Flight based module in a phantom study on the left and in an in-vivo study on a pork on the right. Due to the prototype status the in-vivo experiments were performed in an open surgery manner.

To compensate for the issue of jitters robotic assistance systems have been proposed to allow indirect navigation by the use of joysticks [1, 2, 3]. Although, jitters are avoided by these systems, navigation with the joystick is even less intuitive. Hence, for direct and indirect navigation the problem of erroneous movements caused by misinterpreted images and an insufficient field of view remains. The avoidance of risk situations in minimally invasive procedures has been addressed by several research groups [4, 5]. Speidel et al. propose an approach using a stereo endoscope and a knowledge representation system [4]. The endoscopic tools are tracked in 2-D and located in 3-D. Based on the defined logic the surgeon is warned in case of any risk situations. In [5] Haase et al. describe a 3-D tool localization algorithm based on a Time-of-Flight/RGB endoscope that holds potential for avoidance of risk situations using 3-D metric information. Nevertheless, both approaches require a specific 3-D endoscope and a learning phase for interpreting the additional information.

Our approach is also based on Time-of-Flight (ToF) technology but integrates seamlessly into the current workflow without the need of expensive hardware and any further learning phase concerning new software. We propose a supervision module for any robotic endoscope holder that keeps a safety margin between the endoscope and the operation site by extending or retracting a telescope that is directly attached to the endoscope. The adjustment is based on range images acquired at high framerates. Our approach includes preprocessing of the range images for improved robustness. For clinical scenarios real-time constraints are fulfilled by using state-of-the-art hardware and software optimization. This module holds the potential to improve the safety for patient´s and simultaneously ease the navigation for surgeons.

II. Time-of-Flight Guidance Module

Our enhancement module is composed of three parts: The distance measuring sensor, the telescope module and a micro controller for communication. Fig. 1. illustrates those three components and Fig. 2. depicts our assembled prototype attached to a robotic endoscope holder. Though our setup is generic for different endoscope holders, for all our experiments we used the SOLOASSIST [1] robotic endoscope holder, which imitates a human arm and is navigated by small joystick that allows free movements in all three dimensions.

For distance measurement a ToF camera acquires range information in real-time [6]. Current ToF sensors hold the benefit to acquire dense range data by calculating the phase shift of a frequency modulated emitted near infrared light ray and its received counterpart reflected on any surface. In comparison to stereo vision [7] or structured light techniques [8] this excludes processing of the images to get 3-D data and works well even on textureless surfaces. Therefore, ToF distances are a pure physical measurement allowing acquisition speeds of up to 90 Hz. Besides range images current ToF sensors also acquire grayscale images of the scene by using the amplitude information of the acquired signal. Furthermore, a binary validity map is acquired that denotes for each pixel whether the measured range is reliable or erroneous due to total reflections or insufficient signal strength. For our experiments the CamBoard nano (pmdtechnologies GmbH, Germany) was chosen as it combines an adequate resolution (160×120 px) in a small housing (37×30×25 mm). However, due to a low signal-to-noise ratio, preprocessing range images is an essential step. To satisfy real-time constraints we use the RITK [9] to build a preprocessing pipeline on the graphics card using CUDA. As ToF sensors suffer from temporal and spatial noise, preprocessing in both domains is required. First, we perform a temporal averaging on a few consecutive frames and then apply the bilateral filter [10] for edge-preserving spatial denoising. For robust results the median distance value of a region of interest is calculated as input for the distance correction.

The telescope module executes the actual distance adjustment. Depending on the range information of the ToF device we adjust the length of the telescope to fit the safety margin. A fast length adaption and a small housing is an essential requirement in a clinical setup. For our prototype we have attached a L12 linear servo motor (Firgelli Technologies Inc., Canada) to the robot assistance system. It allows adjustments at a speed of 23 mm/s and a maximum extension of 100 mm.

Communication of the telescope and the computer that acquires range data using the ToF sensor is handled by a micro controller offering a Labview interface. In our prototype module the open source hardware micro controller Adruino Uno [11] is used for simple data processing and instructing the telescope.

III. Workflow

An initial software setup is required before using our module the first time. Due to the generic framework all configurations in terms of preprocessing can be set up once and kept for further interventions.

Before the intervention, the supervision module needs to be attached to the endoscope holder. Instead of the actual endoscope we attach the telescope to the assistance arm and attach the endoscope to the telescope. This allows navigation of the robotic arm and correction of the distance between the endoscope and the operation site without the need of manipulating the actual endoscope holder. The ToF device is then attached to the fixed part of the telescope. In a final version of our module all components will be kept in one housing for easier usage.

During the intervention the surgeon navigates the endoscope using the joystick of the robotic assistance system. Depending on the range image of the ToF sensor the telescope then automatically adjusts its length to protect healthy tissue by avoiding collisions. Furthermore, this guarantees a sufficient field of view by keeping a maximal distance to the observed surface.

IV. Experiments

The experiments are split into two parts. First, we measure the accuracy of the ToF sensor in a quantitative manner. Second, we demonstrate the ability of our module in an in-vivo pork study. However, due to size limitations of our prototype the experiments are performed in an open surgery manner. For all experiments the entire data processing pipeline using RITK operates at a framerate above 20 fps.

Fig. 3. demonstrates the accuracy of the PMD CamBoard nano. We measured a wooden step phantom with step heights of 12 mm. The ground truth data was depicted manually by an expert analyzing the grayscale images of the ToF sensor and is colored in green. Red denotes the measured median distances in a region of interest acquired by the ToF sensor after applying the described preprocessing pipeline. Note that our measurements follow the ground truth data with a mean distance offset of less than a millimeter.

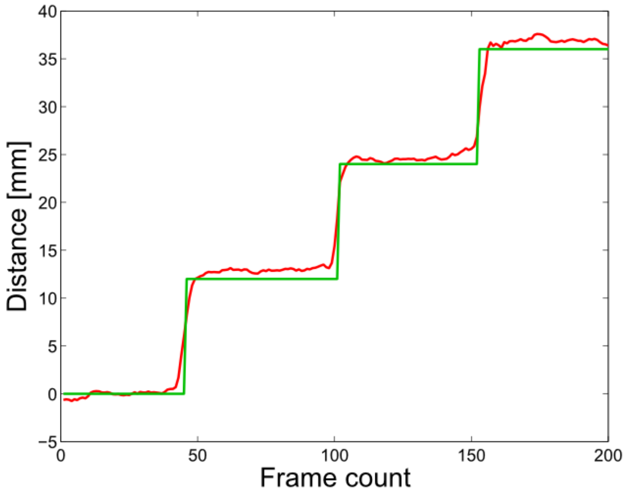

Fig. 3. Plot of a measured step phantom. In red the preprocessed Time-of-Flight data and in green the ground truth distances with 0 mm denoting the initial distance.

Fig. 4. The setup in an in-vivo pork study. The upper left image is a grayscale image acquired by the Time-of-Flight sensor. The upper right image is the corresponding color coded range image.

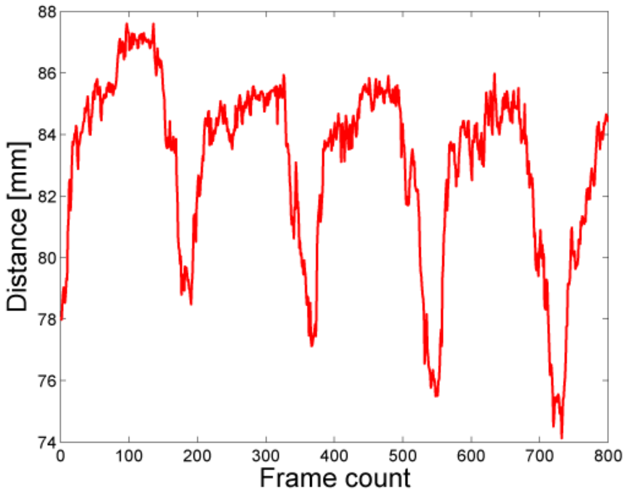

Fig. 5. Median distance values during artificial respiration. Note for interpretation as the breathing amplitude the vertical axis needs to be flipped.

For qualitative evaluation we utilize our prototype in a pork study in an open surgery manner as illustrated in Fig. 4. During the intervention the endoscope is navigated across the situs resulting in several different range plateaus. The dark blue area in Fig. 4 denotes an organ close to the sensor. After navigating to the dark red area, the telescope extends to keep the desired distance and shortens after returning to the blue spot. Besides the change of distance due to navigation to different operation spots we also address respiratory motion in the pork study. Fig. 5 illustrates the median value of a fixed region of interest for several seconds. Within this experiment, the respiration amplitude was increased artificially using a ventilator. The plot shows the increasing amplitude by a decreasing distance to the sensor. Note that the maximal exhale state remains almost constant.

V. DISCUSSION

Our experiments have shown that the proposed module is feasible to supervise minimally invasive interventions and ensure a safety margin by adjusting the telescope length and thereby adjust the distance between the endoscope and the operation site. The change of distance can either be induced by navigation of the endoscope or by organ movements due to respiratory motion. The robustness of our range acquisitions depends on the size and the position of the region of interest. Due to occlusion artifacts the module is not yet capable to guarantee safety in all directions. In terms of module size upcoming ToF device are expected to satisfy the required dimensions to allow further experiments in realistic scenarios for minimally invasive surgery. The speed of the telescope motor is sufficient for smooth navigation but is expected to be increased with upcoming hardware.

VI. CONCLUSION

In this paper we proposed a new guidance module for robot assistance systems for minimally invasive interventions. We enhanced an endoscope holder by a Time-of-Flight camera to measure the distance of the observed tissue and used a telescope to adjust the distance of the endoscope. This ensures a safety margin from healthy tissue and thereby eases the navigation for surgeons. An in-vivo pork study in an open surgery manner has shown that our module adjusts the distance to the surface and additionally allows compensating respiratory motion. Future work will address further miniaturization and a single housing for the module to allow first in-vivo experiments in a minimally invasive manner.

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