A03-KB102
Autonomous Control of a Surgical Assistant Robot with a Stereoscopic Endoscope That Can Obtain Depth Information in Real Time
- Progress Overview FY2017-FY2018 -

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***Abstract*—As AI technologies are developing in a very rapid rate and researches about autonomy of surgical assistant robots are drawing increasingly more attention. In the past two years, we have focused on the intraoperative combination of RGB and depth images obtained from a stereo endoscope, and the three-dimensional information of surgical instruments, an endoscope, and the surgeon's upper limb through an optical tracking device so as to contribute to the improvement of the degree of autonomy of surgical assistant robots.**

I. Introduction

As AI technologies are developing rapidly, researches about autonomy of surgical assistant robots are drawing increasingly more attention [1]. Based on the six levels of auto-driving cars [2] defined by the Society of Automotive Engineers International, Yang et al. [3] have proposed six levels of autonomy, LoA for surgical robots. Chinzei et al. have discussed the importance of risk analysis for auto-diagnosing devices with AI technologies and AI-based surgical robots from the viewpoint of regulatory science [4]. There are also technical reports about the degree of autonomy, DoA, including robots, in international standards [5]. However, even da Vinici (Intuitive Surgical Inc.) [6], the most widely used surgical assistant robot does not exceed LoA level 0. Under such a circumstance, LoA and DoA improvements for surgical assistant robots are becoming vitally important areas to work on indeed.

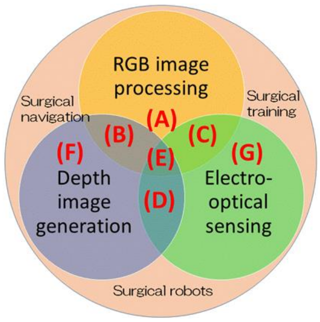

Fig. 1. The relationship between intraoperative sensing information and research topics (A) - (G)

In the past two years, we have focused on the intraoperative combination of RGB and depth images obtained from a stereo endoscope, and the three-dimensional information of surgical instruments, an endoscope and the surgeon's upper limb through an optical tracking device so as to make this research contributing to the improvement of the LoA and DoA of surgical assistant robots.

II. Research Plan of 2 Years

The relationship between intraoperative sensing information and the following seven research topics (A) - (G) is shown in Fig. 1. In our research plan, there are five parallel implementations, namely (A), (B), (C), (D), and (E).

(A) Visual tracking of the tips of surgical instruments, particularly focusing on the colour information for controlling an endoscope-holding robot

(B) Tracking of multiple surgical instruments and contact-estimation between surgical instruments and organs by the combination of RGB and depth images

(C) Image-based estimation of the loads of the tip of surgical instruments by the integrated usage of 3D measurement and endoscope image processing

(D) Image-based estimation and evaluation of the contact point between the central axis of instrument and organ surface for controlling a surgical instrument-holding robot

(E) Proposal and evaluation of endoscopic field-of-view evaluation criteria based on the linear approximation hypothesis of the transformation from a visual space to a joint space

Besides, the following two additional topics are also included in our plan since 2018.

(F) Generation of depth images from surgical videos taken by a stereo endoscope and the release as open-access contents

(G) Collaboration with the planned research group A03-3, which is closed related to our research

III. Progress Overview (FY2017-FY2018)

A. *Visual tracking of the tips of surgical instruments, particularly focusing on the colour information for controlling an endoscope-holding robot*

A new method of visual tracking of the tips of surgical instruments was developed in our research as important reference for the autonomous control of endoscope-holding robots. The position of the tip of surgical instruments in endoscope is considered vitally important. In this technology, only RGB images are used, no external sensor nor instrument-mounted marker is needed. It is applicable to different endoscopic images, including those with gallbladder and fat. Simultaneous detection and tracking of more than one surgical instrument are also feasible with an upper limit of two instruments without any overlapping (the solution in this case is shown in section III-B). The proposed algorithm avoids the use of absolute threshold to the greatest extent. Thus, it focuses on the relative relationships among R, G, and B values of organ surface and tissue, and detects non-organ/tissue region as the instrument region. Fig. 2 shows an example of using four kinds of image sequences (100 frames respectively). In this technology, the pixel error (Euclidean distance) between the tip position of the surgical instrument and its actual value was below 32 pixels (images were either 300 x 225 pixel or 400 x 225 pixel large). The average image processing time was 3.6ms/frame. As for the detection rate of instruments, three out of four image sequences showed 100%, and the remaining one was 75%.

Other intraoperative sensing technologies studies using only RGB images include tract-organ feature recognition [8], mist detection in using electric cautery [9], and endoscope robot operational interface using the instrument detected in image processing as a pointer during surgery [10].

B. *Tracking of multiple surgical instruments and contact-estimation between surgical instruments and organs by the combination of RGB and depth images*

The technology in section III-A was used to track up to two surgical instruments in the endoscope image when they do not overlap each other. While in this research, we have successfully developed a new tracking technology that can distinguish farer and closer surgical instruments by using depth information from stereo endoscope (Fig. 3). In addition, there was also development and research for the estimation of the contact between instruments and organ as an elaboration of the technology using depth images (Fig. 4).

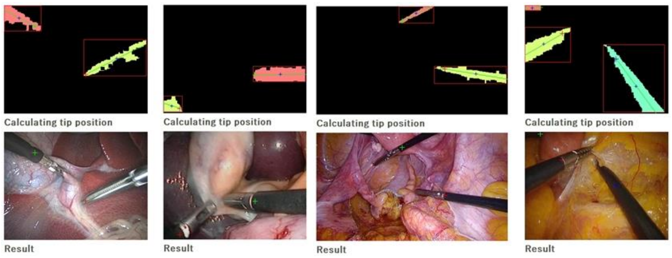

Fig. 2. The visual tracking of the tips of surgical instruments

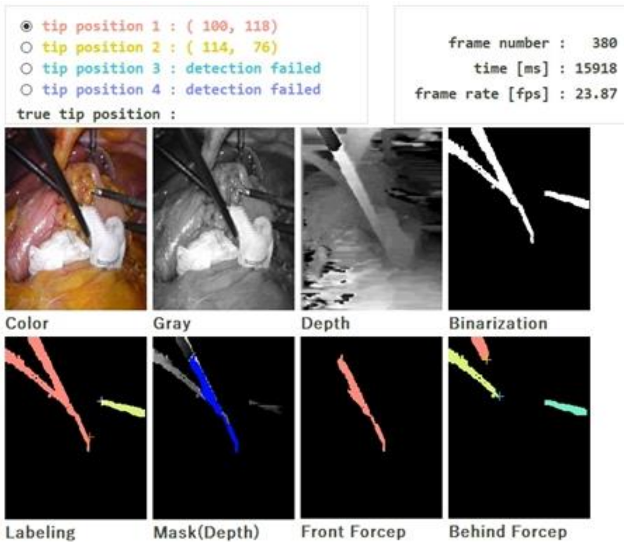

Fig. 3. The tracking of multiple surgical instruments overlapping each other

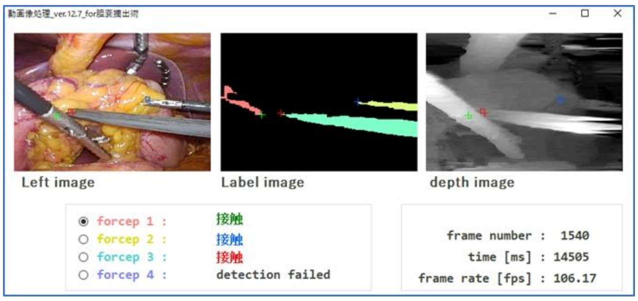

Fig. 4. The estimation of the contact between surgical instruments and organs

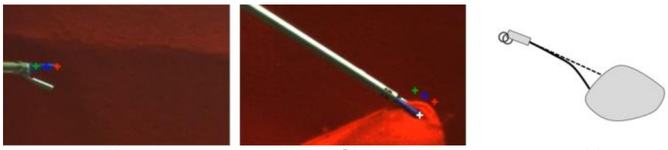
(a) (b) (c)

Fig. 5. The comparison of the integration of 3D measurement and image processing when the instrument is not tugging with the organ (a) and when it is tugging with the organ (b), as well as the displacement (deflection) diagram of the instrument (c).

C. *Image-based estimation of the loads of the tip of surgical instruments by the integrated usage of 3D measurement and endoscope image processing*

In this research, a tip load calculation system for surgical instruments that made use of both optical three-dimensional measurement device and image processing was developed with consideration of the autonomous control of the instrument-holding robot. Since the instrument would bend when it provides counter-traction against the tissue, its tip position is estimated through a 3D measurement device in a linear manner so through image processes we can visualize positional differences at the tip of the instrument (Fig. 5). Making good use of the difference, the deflection at the tip of the instrument can be estimated, so after the instrument modelling as “a cantilever under concentrated load at the tip end part”, the load at the tip of the instrument (beam) can be estimated. Experiments have been conducted to show the difference between an expert surgeon and novices, focusing on the difference in their counter-traction. As the result, we found that the counter-traction force of the expert was much stable and his task completion time was shortest; the relationship between counter-traction and quality of dissection was thus proved. It reveals that the system is applicable in surgical robots, and also surgical education and training.

D. *Image-based estimation and evaluation of the contact point between the central axis of instrument and organ surface for controlling a surgical instrument-holding robot*

Through integrating stereo camera and optical 3D measurement device, two fundamental technologies for controlling surgical instrument-holding robots were developed in this research, which were (1) the estimation of distance between the tip of the surgical instrument and the organ surface (the insertion direction distance), and (2) directional control of the instrument. The greatest feature of this technology is the usage of two (real and virtual) disparity information simultaneously and respectively attained by stereo camera and 3D measurement device, intersection (contact point) of the central axis of the instrument and the organ surface can be calculated, thus the insertion direction distance can be successfully estimated. Moreover, by integrating these proposals, two functions were installed in ZEUS (Computer Motion Inc.), an instrument-holding surgical robot (Fig. 6). The first one is the autonomous control to adjust any out-of-sight instrument to the centre of the image, and the second one is the calculation and display of the insertion direction distance so that a target point on the image, given by one mouse click, can be tracked by the robot. These two new functions have received positive comments from surgeons, which indicates that they are definitely needed in practice related to surgical robots.

E. *Proposal and evaluation of endoscopic field-of-view evaluation criteria based on the linear approximation hypothesis of the transformation from a visual space to a joint space*

The research aims at quantifying subjective judgement of the goodness of endoscopic field-of-view from surgeons for the improvement of LoA and DoA of endoscope-holding robots. To be more concrete, a linear approximation hypothesis of the transformation from a visual space to a joint space in endoscopic surgery was set up, and based on that, a number of field-of-view evaluation criteria for endoscope surgery were designed. Afterwards, the applicability was evaluated by using AESOP (Computer Motion Inc.), an endoscope-holding robot in the experiment from an expert surgeon and novices (Fig. 7). The result showed that the criterion of “the volume of the set of possible points in the joint velocity space under the condition that the norm of velocity in a visual space is 1 or less (which is equal to the absolute value of the determinant of a Jacobian matrix)” was the most efficient set. Such Jacobian matrix can be calculated from the image coordinates of the tip of the surgical instrument through RGB image processing, and the time-series estimation of the angle of the upper limbs of the subject through optical 3D measurement device. Furthermore, it is worth mentioning that the Jacobian matrix for the virtual endoscope position can be calculated through the 3D coordinates of the tip of the instrument estimated from the stereo endoscope.

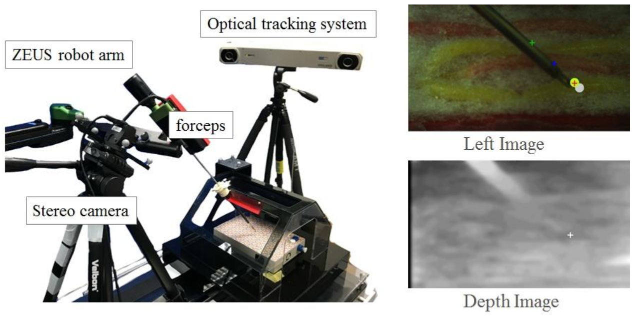

Fig. 6. The control of instrument-holding robot with the use of depth images

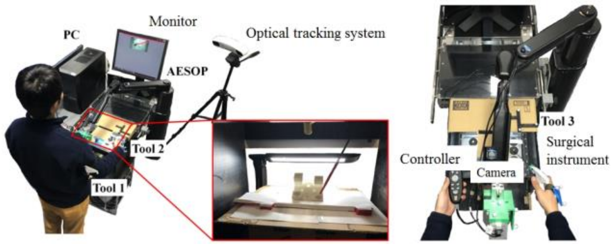

Fig. 7. The verification experiment to evaluate the endoscope field-of-view by using an endoscope-holding robot

F. Generation of depth images from surgical videos taken by a stereo endoscope and the release as open-access contents

We, until 2017, had been working on the development of a stereo matching engine that can control the trade-off between the correct matching rate and processing speed [11] [12]. From March 2018, based on surgical recording videos taken by a stereo endoscope and through the methodology as stated in reference [11] we have estimated depth information, converted them into displayable video format in a multi-view point eyeglass-less 3D display, and released these video contents to "Weshare3D", the international WWW database exclusive to 3D visions. They [13-17] are all free and open access at https://www.weshare3d.com/.

G. Collaboration with planned research group A03-3

Force measurement forceps [7] developed by the planned research group A03-3 (PI: Assoc. Prof. Etsuko Kobayashi) has been based on different principles from our group's. We have started information exchanging activities with an aim both to combine our research with theirs and to apply the results on our robots. Yet, there were no collaboration with other teams nor globally with overseas researchers in these two years.

IV. CONCLUSION

This paper briefly reported on the research progress by the public offered research group A03-KB102 in two years, FY2017-FY2018. The stereo endoscope system developed in this study is an intraoperative 3D reconstruction system that can probably be a new modality in the construction of "multidisciplinary computational anatomy model". It would be great if we could have made a new collaboration with many researchers in the planned and public offered research groups for our further studies in the future.

ACKNOWLEDGMENT

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