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科研費
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研究課題名（和文）Novel surgical endoscopic instrument: implementing bird's-eye view in minimally invasive surgery

研究課題名（英文）Novel surgical endoscopic instrument: implementing bird's-eye view in minimally invasive surgery

研究代表者

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研究成果の概要（和文）：低侵襲手術における狭視野の問題に対処するため、本研究では、複数の魚眼カメラを内蔵し、隣接する領域を異なる角度から可視化する画像処理アルゴリズムを伴う、新しい手術器具を提案した。各モジュールは、魚眼カメラのカップルによって構成され、相対的な距離と角度を変えながら既知の位置に回転・並進させることができます。画像処理アルゴリズムは、カメラ画像をつなぎ合わせて、臨床医にリアルタイムで表示される拡大画像を作成します。画像処理アルゴリズムが失敗すると、画像は別々に表示され、器具の周辺を見ることができます。提案されたシステムは汎用性があり、狭い空間を探索する他のアプリケーションに採用することが可能です。

研究成果の学術的意義や社会的意義
The main features of the proposed system are its modularity and versatility. It is possible to change the type of cameras, employ more module together and adapt the designed device and image processing algorithm to different surgical operations and applications dealing with narrow space exploration.

研究成果の概要（英文）：To cope with problem related to the narrow field of view in Minimally Invasive Surgery (MIS), this research proposed a novel surgical instrument, which embeds multiple fisheye cameras, accompanied by an image processing algorithm to visualize the adjacent area from different angles.
Each camera module is composed by a couple of fish-eye cameras that can rotate and translate to fixed known positions changing the relative distance and angle between them. The image processing algorithm, implemented using OpevCV, stitches the camera images together creating an extended view shown to the clinician in real-time. When there aren't enough overlapping features between the images the stitching algorithm fails and the images are shown separately providing a view of the area around the instrument.
The proposed system is versatile: it can be used for different surgical operations, and it can also be adapted for other applications dealing with narrow space exploration requiring a broad view.

研究分野：Robotics

キーワード：Medical robotics　Multi-camera system　Visual system　Fish-eye cameras　Extended view　Modular mechanism　MIS　Image stitching

１．研究開始当初の背景

Minimally invasive surgery (MIS) encompasses any type of medical procedures that is less invasive than traditional open surgery. MIS is becoming the standard of care for a wide range of medical conditions ①. Medical practitioners skilled in MIS insert long and thin surgical instruments, equipped with cameras and lights, into the patient's body, insufflating with carbon dioxide, through natural openings or small incisions performed on the skin. The movements of the surgical instruments can be controlled through a robot (robotic surgery) or manually (laparoscopy). The advent of MIS offers many benefits for the patients, as the incisions are smaller, the trauma is reduced and the recovery time is faster, but it is more cumbersome for surgeons in comparison to traditional open surgery ②. It has been determined that in some surgeries, such as laparoscopic cholecystectom, the rate of injury increased significantly respect the traditional open surgery ③. One of the critical problems in MIS is the loss of natural visual feedback. In fact, while in traditional methods doctors can look directly at the operating area, touch the area of interest, and have a wide Field of View (FoV) and viewing angles, in MIS only images of the area near the end-effector of the surgical instruments are showed to the clinicians in a 2D flat screen. **The narrow FoV make it difficult for a doctor to see a full picture of the operation area**, furthermore as only 2D information are available, it is very difficult to recognize depth as well as the relative position of the anatomical areas from the surgical instruments. **Hence, since it is not possible to fully visualize the surroundings of the surgical instruments, unwanted touches and perforations may occur** ④. Organs can also be injured because of uncontrolled movements during insertion. Recent study underlined that intraoperative adverse events during MIS happen relatively frequently but are poor documented, although the objective measurement and quality assurance of operative performance are strictly correlated to patient's safety ⑤.

To overcome problems related to the narrow FoV and lack of depth information stereo-endoscopic system, able to provide surgeon 3D information have been introduced ⑥. However, those systems provide only local information of the area surrounding the end-effector of the instruments and present excessive costs. Images based method have also been adopted in MIS, in those method 3D scenes are reconstructed from images recorded by a single moving endoscope, although recent results are promising they cannot cope with real-time requirements ⑦. Analysis shows that novel medical devices and methods are needed to overcome the problems that occur with the current equipment and improve the outcome of the MIS procedures and the experience of the medical experts ⑧.

２・研究の目的

In the literature, there have been many attempts to extend the surgical FoV, either mechanically or through images processing algorithms. To cope with the problem of narrow FoV images taken from a moving endoscope have been used to create a panoramic image mosaic in ⑨,⑩, ⑪, ⑫. This method it is also known as image stitching. Multi-camera systems were recently introduced into laparoscopy to increase the narrow field of view of the surgeon. The video streams are stitched together to create a panorama that is easier for the surgeon to comprehend ⑬. To provide surgeons with a broad field of view and 3D images of the surgical area new mechanisms have been developed and embedded in the surgical instruments. Sun et al. ⑭ recently developed a variable baseline stereoscopic camera with fast deployable structure for natural orifice transluminal endoscopic surgery which adjust the baseline in function to the observed depth. A new endoscope, the 3DMISPE was presented in ⑮. The system alternate video stitching algorithm and 3D reconstruction based on disparity map. The Enhanced Laparoscopic Vision System (ELViS) was also developed to allow surgeons to view the zone surrounding the surgical area from a distance and early detect adverse events ⑯. A trocar-camera assembly (TCA) embedding by 4 cameras was developed in ⑰.The system increases the FoV and improve efficiency and range of operation while compared to a single camera. **Most of the**

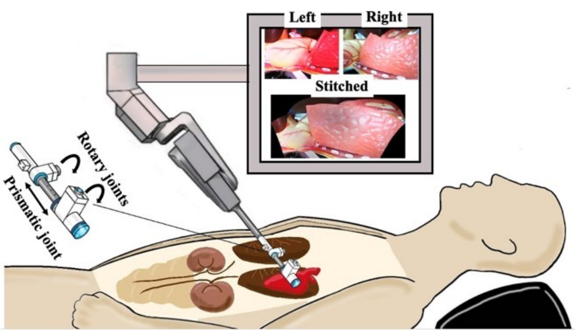


Figure 1. Multi-camera system in minimally invasive surgery: the rotary and prismatic joints are used to move the cameras in a specific position and capture a broad view of the surrounding anatomical areas.

developed approaches try to combine images from cameras placed on the tip of the instruments itself, keep the position of the cameras static and are difficult to miniaturize and scale for human model. To cope with some of the limitations of MIS we propose a novel low-cost multi-camera system as shown in Figure 1.

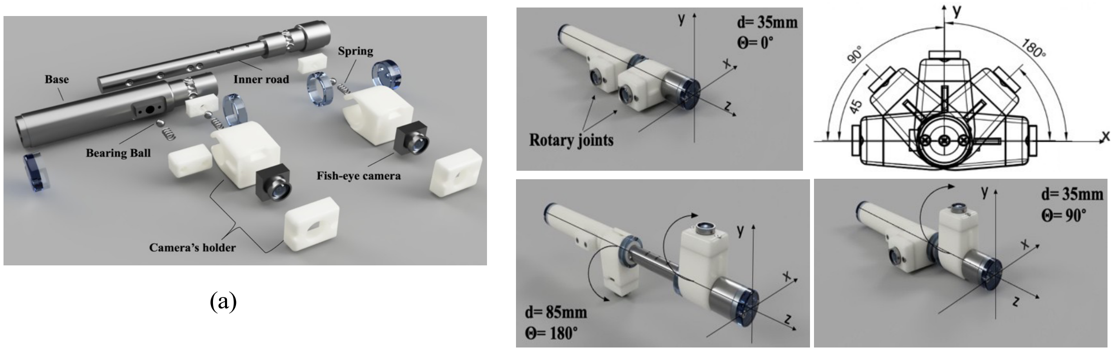
The proposed system benefits from a novel design in which miniaturized cameras are directly positioned on the surgical instrument body and can also change the relative position between them. By embedding the proposed multi-camera system in the surgical instrument, it will be possible in the future to visualize the surrounding area more accurately, bypassing the use of a separate endoscopic camera, thus avoiding the additional risks associated with it, without interfering with the movements of the instrument.

The developed multi-camera-system presents two main advantages: it is scalable, visualization accuracy can be improved with additional cameras without major design modifications; and it is versatile, i.e., it can be used for different surgical operations, but can also be adapted to other applications dealing with narrow spaces exploration and requiring a broad field of view.

３・研究の方法

(1) MULTI-CAMERA SYSTEM: DESIGN

A multi-camera system module is composed by two fisheye cameras, two camera's holder, three springs, three bearing balls, an inner road and a rigid base. The device has been designed using Fusion 360, the 3D CAD software by Autodesk ⑱. An exploded view of the prototype is shown in Figure 2(a). The two camera's holder are attached to the rigid base which embeds the inner road. The mechanism composed by the bearing balls, the inner roads and the springs allows the rotations of the cameras to a specific angle as well as their translation. The system is extensible.
i.e. is possible to add more modules, however, in the following analysis we will use only one. The length of the device is 176.69 mm, the diameter of the rigid base is 19.73 mm and the one of the camera's holder is 26.27 mm. The minimum distance between the cameras' centers is 35 mm while the maximum is 85 mm. Both cameras can rotate independently around the base to predefined angles. Some possible configurations during rotation are showing in Figure 2(b), where θ represents the angle between the two cameras. In this first prototype the rotation and translation of the mechanism is done manually but it can be easily automatized by adding motors in the device. The system has been manufactured using epoxy resin material.



(a)

(b)

Figure 2. Multi-camera system module: (a) exploded view, (b) top view of rotation setting and configuration at different rotation and translation.

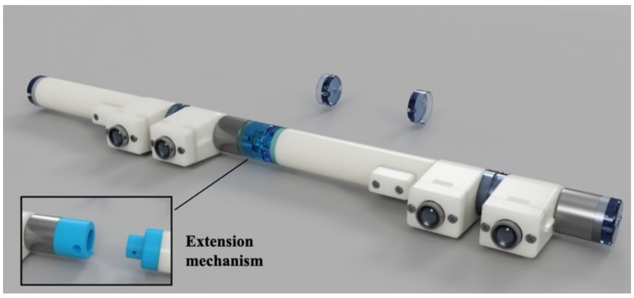


Figure 3. Multi-camera system extension mechanism: connection between two modules.

The camera used in this prototype is a customized version of the Mini Micro Security Camera by AutoGuard ⑲, in which we eliminate the microphone. This is a small size light weight camera with a FoV of 170 degrees, resolution of 782x492 and a frame rate of 30 frame per second (fps).The modularity of the design allows to easily change the type of cameras by changing the cameras' holders. Moreover, although in this study we will focus on only one module, an extension mechanism to easily connect more modules has been realized as shown in Figure 3.

(2) IMAGE PROCESSING ALGORITHM

The image processing algorithm creates a panoramic view by stitching the two camera images together. When there no features overlapping in the set of images, for instance when θ is equal to 180°, the algorithm shows the two images separately. The first step of the image processing algorithm consists in the calibration of the cameras. The pinhole camera model which is compatible with cameras of FoV up to 195°, was used during this phase.

The open source library OpenCV was used here to find the intrinsic parameters of the camera for calibration. In this process a check board pattern is used as a fixed world coordinate system to find the correspondence between a set of known 3D points and their corresponding pixels location. More information on how the calibration is performed and on how to use the library can be found in ⑳.

The calibration process provides the distortion coefficients and the camera matrices, containing the focal length and the optical centers, used to remove distortion in the image. The result of the calibration provides a cropped image where there are no distortions, in which distorted fish-eye images of a check board are properly pictured in the calibrated image.

Image stitching is a state of art image processing algorithm used in many non-medical applications, which is recently also being explored in MIS. The idea is to combine multiple images with overlapping FoVs and produce a segmented panorama. Here we used the image stitching pipeline of Opencv in Python. Given the calibrated fisheye camera images with difference and/or rotation between them, the algorithm employs the following steps to create a stitched panorama:

1. Detection of keypoints and extraction of their local invariant features descriptors using the scale-invariant feature transform (SIFT). SIFT allows to detect salient, stable features in an image and it also provide the descriptors, vectors containing a set of features that characterize a small image region around the points.
2. Descriptors matching between the two input images to find their Euclidean distance.
3. Random sample consensus (RANSAC) iterative method to estimate the homography matrix which best fit the relationship between the matched descriptors.
4. Warping transformation using the obtained homography matrix.

The computation of the homography matrix, which maps the corresponding point of an image to another, it is essential for the stitching algorithm, however, it is also computationally heavy. Thanks to the mechanical design constraints of the multi-camera system module, the cameras can assume only predefined fixed position and hence, the estimation of the homography matrix is performed only one time allowing real-time performance. It must be notice that, when the angle between the cameras increases and it is not possible to compute the homography, the stitching algorithm fails. In this case the cameras' images will be shown separately. This problem will be solved in future work by adding more modules together to have always at least couple of two images in the same FoV and hence, be able to stitch them. The source code of the developed algorithms can be found in the repository containing the customizable cad models of the device and developed software: https://github.com/AngelaFiska/Multi-camera-system.git.

４．研究成果

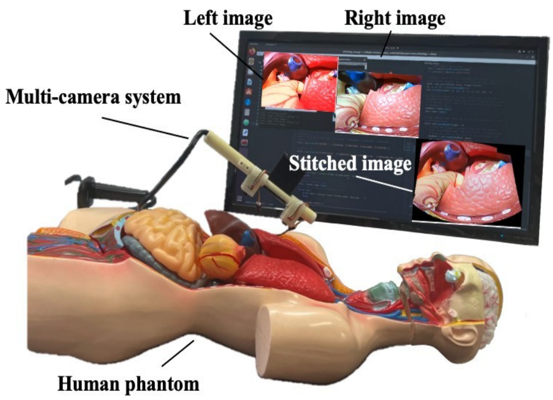
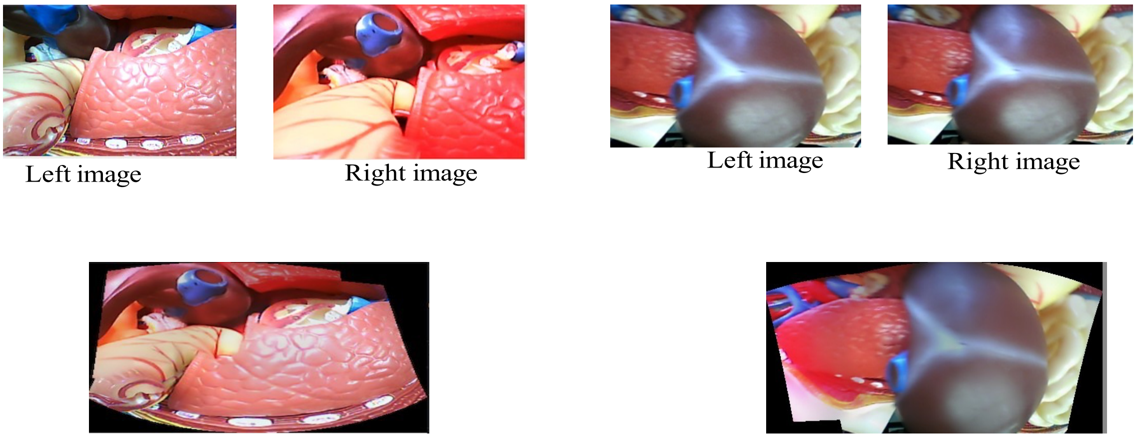


Figure 4 Experimental setup: the multi-camera system is placed on the top of human-phantom and images from the fish-eye cameras are processed and stitched together.

The experimental tests have been performed using an Intel®Xeon(R) CPU at 1.60 GHz running Ubuntu 20.04. Experimental tests have been performed using a phantom that mimics the anatomical structure of the human body as shown in Figure 4. The multi-camera system was placed on a fixed position on the phantom and images from the cameras were processed to evaluate the performance of the image stitching algorithm in different configurations. Stitched images are often affected by the following problems: background blur, distortions, duplicate elements, disappearing elements and discontinuities. The most critical problems in a stitching algorithm for MIS are duplicate or disappearing elements ⑯.

The input images and real-time stitched panorama for two of the configurations are shown in Figure 5. From the experimental results it can be noticed that the image stitching algorithm presents the best performance when the cameras are lying on the same baseline, i.e. $\theta = 0^{\circ}$ and are very close to each other d=35*mm* as there is a big overlapping of the FoVs and hence there are more keypoints for the computation of the homography matrix. Moreover, although there is no blur, when θ=0° discontinuities appear in the borders, as shown in Figure 5(a). This is due to the perspective warps algorithm required to construct the panorama which affect the contours of the stitched images and create the black area in the border. When θ>0, as there are fewer matching futures between the two images, not only discontinuities but also disappearing elements affect the stitched images, Figure 5(b). The algorithm fails when the rotation angle θ is bigger than 45°. In this case the images from the cameras will be shown separately.



(a) Stitched image θ=0° and d= 35mm

(b) Stitched image θ=45° and d= 65mm

Figure 4. Experimental results: stitching algorithm

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５．主な発表論文等

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１．著者名 Faragasso Angela、Mitchel Scean、Cosentino Sarah、Asama Hajime	４．巻 7
２．論文標題 Toward Multicamera Systems for Minimally Invasive Surgery	５．発行年 2023年
３．雑誌名 IEEE Sensors Letters	６．最初と最後の頁 1～4
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LSENS.2023.3240745	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Faragasso Angela、Bonsignorio Fabio	４．巻 10
２．論文標題 Reproducibility challenges in robotic surgery	５．発行年 2023年
３．雑誌名 Frontiers in Robotics and AI	６．最初と最後の頁 1～10
掲載論文のDOI（デジタルオブジェクト識別子） 10.3389/frobt.2023.1127972	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Lu Xiaojun、Woo Hanwool、Faragasso Angela、Yamashita Atsushi、Asama Hajime	４．巻 37
２．論文標題 Robot navigation in crowds via deep reinforcement learning with modeling of obstacle uni-action	５．発行年 2022年
３．雑誌名 Advanced Robotics	６．最初と最後の頁 257～269
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/01691864.2022.2142068	査読の有無 無
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１．著者名 Sun Yilun、Liu Yuqing、Xu Lingji、Zou Yunzhe、Faragasso Angela、Lueth Tim C.	４．巻 5
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オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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1．発表者名 Angela Faragasso
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３．学会等名 The 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2019)（国際学会）
４．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関