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Reconfigurable Micro-Camera Array with Panoramic Vision for Surgical Imaging

Aditi Kanhere, Bader Aldalali, Jacob A. Greenberg, Charles P. Heise, Li Zhang, and Hongrui Jiang

***Abstract*—We present a prototype of a micro-panoramic vision system that includes four micro-cameras controlled simultaneously by mechanical arm-like actuators, structurally similar to umbrella ribs. Each camera rests on an arm that can be oriented at an angle simultaneously with the other three arms. This arrangement offers reconfigurable angle of view and depth perception. Stitching of the images from the four cameras in any one configuration yields a horizontal field of view (FoV) of approximately 45°. Dynamic stitching of panoramas from different configurations can increase the composite horizontal FoV to up to 130°. This micro-camera set is configured in the context of laparoscopic surgery and single-port surgery. Our prototype yields a significantly larger FoV as compared to a commercial laparoscopic camera. [2013-0065]**

***Index Terms*—Camera array, depth perception, micro camera, panoramic vision, reconfigurability, surgical tools.**

I. Introduction

Micro cameras are very critical components in laparoscopic and single port surgery [1]. Two of the important desired features in surgical imaging systems are panoramic vision and depth of field. Panoramic vision in these camera systems is very useful in increasing the field of view (FoV) for the surgeon [2]. Enhanced depth perception in surgical imaging systems is known to increase speed and precision in surgery [3], [4]. The current approach for surgical imaging is to employ a single camera with a fisheye lens. However, a fisheye lens provides a hemispherical FoV at the expense of poor off-axis resolution and chromatic aberration [5]. Even in systems using two fisheye lenses for enhanced depth perception, the problem of reduced peripheral resolution persists. An alternative technique is to combine the images from multiple cameras with small lenses for added flexibility and redundancy without distortion. However, existing multi-camera systems are macroscale and hence unsuitable in the microscopic world, especially medical applications. We previously reported a concept of a multi-camera system [6]. Here we report on a further miniaturized design with more detail and extended functionality in terms of the horizontal FoV, compared to a 0° laparoscopic camera. Our prototype consists of a micro-panoramic vision system that includes four micro-cameras controlled simultaneously by mechanical umbrella rib-like actuators, offering reconfigurable angle of view and depth perception. This system is configured in the context of laparoscopic surgery and single-port surgery.

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A. Kanhere and B. Aldalali are with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA (e-mail: kanhere@wisc.edu; aldalali@wisc.edu).

J. A. Greenberg and C. P. Heise are with the Department of Surgery, University of Wisconsin School of Medicine and Public Health, Madison, WI 53706 USA (e-mail: greenbergj@surgery.wisc.edu; heise@surgery.wisc.edu).

L. Zhang is with the Department of Computer Science, University of Wisconsin, Madison, WI 53706 USA (e-mail: lizhang@cs.wisc.edu).

H. Jiang is with the Department of Electrical and Computer Engineering, the Department of Biomedical Engineering, the Materials Science Program, and the McPherson Eye Research Institute, University of Wisconsin, Madison, WI 53706 USA (e-mail: hongrui@engr.wisc.edu).

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II. Mechanism

The concept of our work as indicated in Fig. 1 was designed for laparoscopy as a target application. In laparoscopy, an access port is used for insertion and maneuvering of instruments during surgery. Our design incorporates the imaging system on the periphery of such a port to ensure minimum interference with the surgical instruments. Fig. 1(a) and (b) show 3-dimensional (3D) schematics of three representative configurations of the camera array, the transition between which can be achieved with mechanical actuators. The actuation was realized by using a network of four ribs each supporting one camera; the structure operates similar to an umbrella. The rib movement can be controlled simultaneously to orient the cameras at a desired angle. The goal of this design is to keep the device positioned closely around a laparoscopic port during insertion into the body. During surgical operation, the surgeon can flare out the array so that the cameras are oriented at desired angles, for an extended FoV.

By simultaneously changing the orientation of the four cameras, we can obtain variations in the viewing perspectives, depth of field and horizontal FoV. Dynamic stitching of panoramic views from multiple configurations can aid in a much greater horizontal FoV and depth, as compared to any of the individual configuration alone. For example, images from configurations in Fig. 1(a) [and (c)] and Fig. 1(b) [and (d)] together increase the horizontal FoV by approximately 85(and yield an increased depth of field as compared to Fig. 1(a) [and (c)] or Fig. 1(b) [and (d)] alone. A real-time video display of composite of scenes from different configurations can greatly enhance the view of the surgical field.

III. Fabrication

The key to the success of coordinated functioning of the camera array is precision in symmetric positioning (and repositioning) of a camera with respect to the laparoscopy port and the other cameras, to achieve maximum horizontal FoV. To this end, we fabricated a polydimethylsiloxane (PDMS) structure to maintain the alignment of the four cameras.

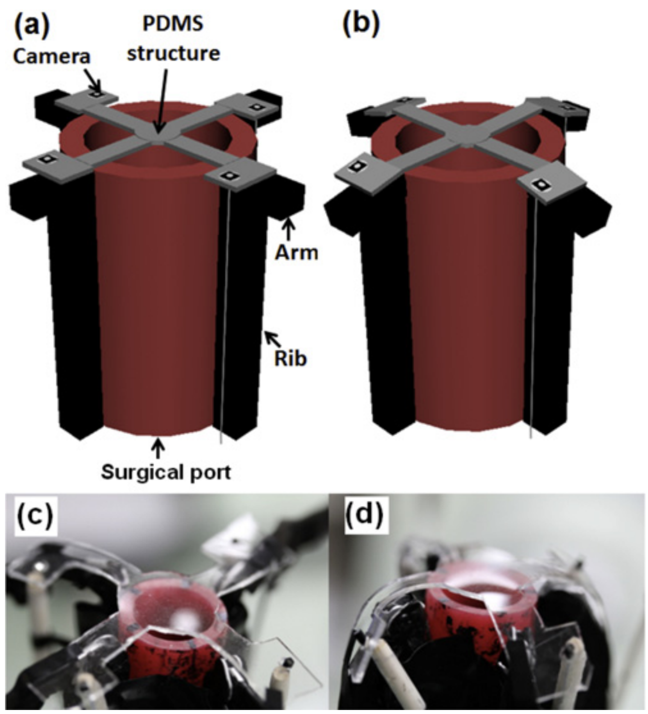

Fig. 1. Prototype of the micro-camera array. (a) and (b) are 3D schematics of two different configurations of the camera array while (c) and (d) are corresponding photo images of these two configurations of the four-camera imaging system around a surgical port.

Fig. 1(c) and (d) show the micro-camera array. It includes four 1 mm × 1 mm NanEye cameras (AWAIBA Lda, Madeira, Portugal) integrated with convex lenses (focal length, $f = 5.0$ mm) and connected together by a PDMS structure. The PDMS structure comprises of a circular center with four bridges radially pointing outward with one camera holder at the end of each bridge. The center of the PDMS structure is pinned to the laparoscopy port. This ensures that when the mechanical arms supporting the four cameras move simultaneously, the relative positions of the cameras with respect to the port and each other remain unchanged. As shown in Fig. 1, the PDMS bridges flex or stretch when the orientation angle of the cameras is changed, to keep their alignment intact. Batch production of all the PDMS camera holders and interconnecting bridges was possible using the process shown in Fig. 2.

Fig. 2 shows the fabrication process of the PDMS bridges and lens holders. A 350-μm-thick chamber was first filled with a photopatternable prepolymer isobornyl acrylate (IBA), made as per the recipe found in [7], [8]. The prepolymer IBA was then exposed under ultraviolet light at 8.3 mW/cm^2 for 26 s using a photomask to define the mold for the bridges and lens holders. Uncured PDMS was then poured over the poly-IBA mold and cured for 4 h at 80 °C to yield the final PDMS structure.

IV. Experimental Results

The experimental setup as demonstrated in Fig. 1 was achieved by symmetric placement of the mechanical actuators and the cameras around the port. Motion of the four arms supporting the cameras was controlled simultaneously by umbrella rib-like actuation. Images from the four cameras were obtained for different configurations. Panoramic views for each configuration were obtained by stitching the four images.

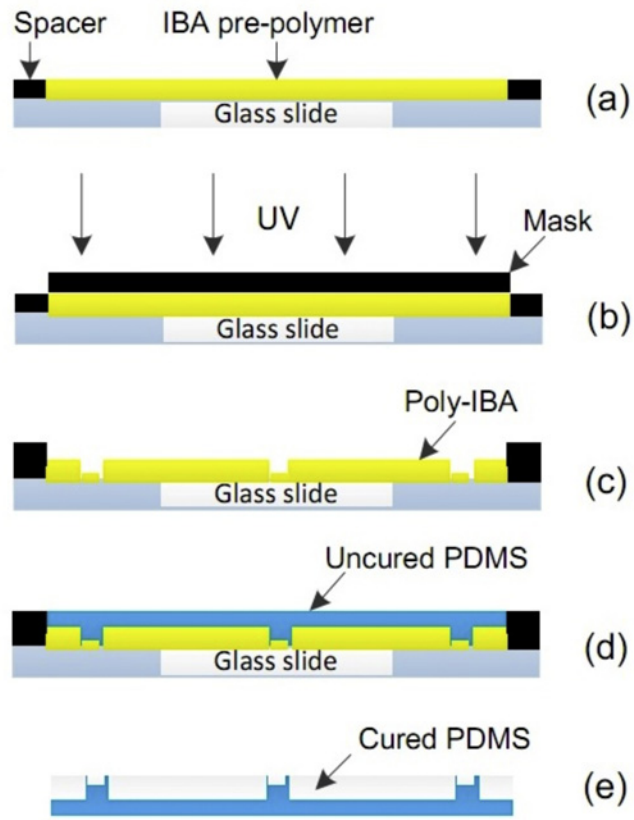

Fig. 2. Batch fabrication process for all PDMS camera holders and bridges. This framework is critical for alignment of the four cameras symmetrically around the laparoscopy port and with each other. (a) Spacers on a glass slide are used to define thickness of poly-IBA structure. (b) Mask with spacers forms a cavity filled with IBA. UV exposure is used to cure the IBA pre-polymer. (c) Poly-IBA mold for bridges and lens holders is formed. (d) Uncured PDMS is poured onto the poly-IBA mold and cured for 4 h at 80 °C. (e) Final PDMS camera holders and bridge structure.

The test scene comprised of 17 dice, labeled with letters, forming a cross. The center of the laparoscopy port was placed perpendicular to the center of the central dice labeled "A," at a distance of 8 cm away from the top of the dice for all the experiments.

Fig. 3 shows a dataset of images obtained from configuration shown in Fig. 1(a) and (c) as well as a panoramic image combined from those four images. The images were combined using a commercial software, PTgui$^{\text{TM}}$. The resulting image lends an extended FoV with no visible seams. The achieved horizontal FoV is 45°. In all our experiments, since the scene is much far away relative to the distance between the cameras, the FoV can be approximated as the total sum of FoV of individual cameras minus the overlapping FoV between cameras. The resulting panorama shows a slight distortion that is not seen in the individual images due to limitations of the commercial stitching software.

The critical requirement for obtaining a meaningful panorama from any configuration of the camera array is that

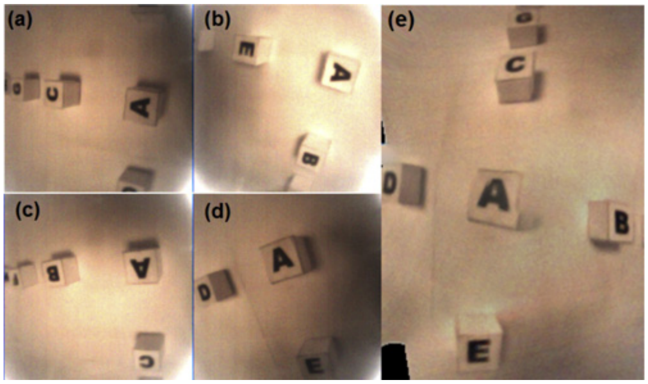

Fig. 3. (a)–(d) Individual images captured by the four cameras placed in a configuration shown in Fig. 1(a) and (c). (e) The panorama obtained by stitching (a)–(d).

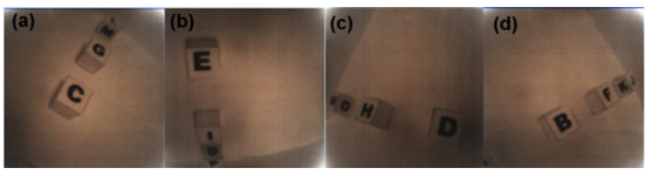

Fig. 4. (a)–(d) Individual images captured by the four cameras configured as shown in Figs. 1(b) and 1(d).

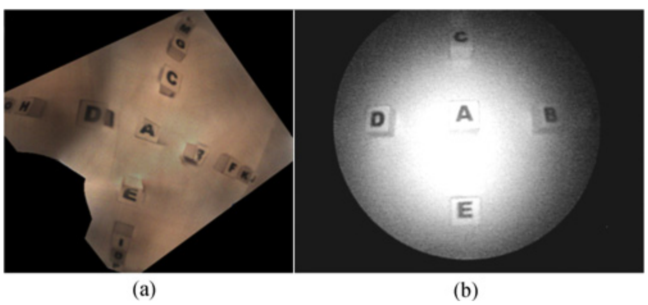

Fig. 5. (a) Composite image obtained by stitching images from Figs. 3(a)–(d) and Figs. 4(a)–(d). (b) Image obtained by a 5-mm 0° laparoscopic camera with same experimental parameters. Significant increase in the FoV is achieved in (a) as compared to (b).

the four individual images should have a sufficient overlap with each other so as to enable the stitching operation. The simultaneous actuation of the mechanical arms along with the camera alignment achieved with the PDMS holders ensures precision of the orientation angle of each arm within $\pm 5^\circ$ of the desired angle.

Fig. 4 shows another dataset of images for the same scene, captured with a different camera configuration shown in Fig. 1(b) and (d).

Images from different configurations contain information of the same scene from distinct viewing perspectives. Hence stitching of images from two different configurations would result in an image with a greater horizontal FoV and a better depth of field. Fig. 5(a) demonstrates such a composite image obtained by stitching images in Fig. 3(a)–(d) and Fig. 4(a)–(d). The horizontal FoV increases from 45° in Fig. 3(e) to 130° in Fig. 5(a).

To compare our images with existing laparoscopic imaging, we repeated our experiment with a commercial 5 mm 0° laparoscopic camera (Stryker, Kalamazoo, MI). The laparoscopic camera was also placed 8 cm away, perpendicular to the center of the dice labeled "A." The acquired image, as shown in Fig. 5(b), clearly shows that the current laparoscopic imaging system suffers from lower resolution, smaller FoV and aberrations near the edges. The panorama obtained from configuration shown in Figs. 1(a) and 1(c) has a FoV comparable to the image in Fig. 5(b). However, as seen from Fig. 5(a), stitching of panoramas from multiple configurations significantly increases FoV, compared to a laparoscopic camera.

V. Conclusion

We demonstrated an experimental prototype of a multi-camera micro-panoramic vision system. The device uses mechanical arms as actuators to provide reconfigurable angles and positions of the cameras with respect to a laparoscopic surgical port. Our prototype yields a significantly larger FoV as compared to a commercial laparoscopic camera. Future work includes higher-level integration of the flexible structures, image sensors, optical components, all connectors and cables, and further miniaturization of the whole system. Our ultimate goal is to realize a spherical vision system with capabilities for real-time tracking of surgical instruments as well as 3D rendition of the surgical scene. Minor modifications in the arrangement of the cameras can make the system applicable in other non-surgical applications where the maneuvering space is limited.

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