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Bio-inspired Fluidic Lens Surgical Camera for MIS

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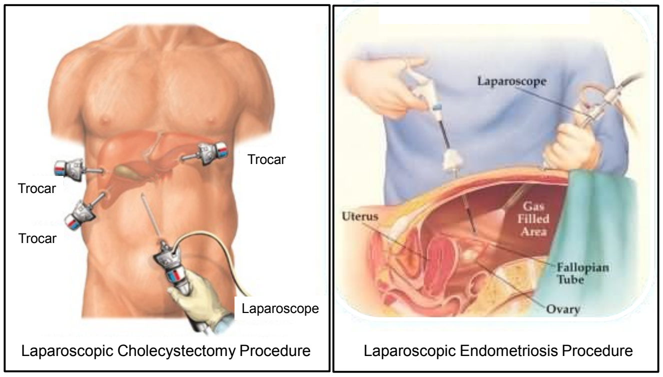
Abstract—**We report a new type of surgical camera that will greatly improve minimally invasive surgery (MIS). The key enabling technology for this camera is a unique type of lens--bio-inspired fluidic lens, which is a bio-mimetic lens that can change its curvature, just like the way human crystalline lens can accommodate. Because of its curvature changing capability, it is now possible to design a new regime of optical systems where auto-focusing and optical zoom can be performed without moving the lens positions, as is done in typical cameras. Hence, miniaturized imaging system with high functionality can be achieved with such technology. MIS is a surgical technique where small incisions are made on the abdominal wall as opposed to a large cut in open surgery. This type of surgery ensures faster patient recovery. The key tool for MIS is its surgical camera, or laparoscope. Traditional laparoscope is long and rigid and limits the field of view. To further advance MIS technology, we utilized bio-inspired fluidic lens to design a highly versatile imager that is small, can change its field of view or zoom optically, works in low light conditions, and varies the viewing angles. The surgical camera prototype is small (total track < 17 mm), possesses 3X optical zoom, operates with light emitting diode (LED) lighting, among many other unique features.**

I. INTRODUCTION

As opposed to open surgery, Minimally Invasive Surgery (MIS) require a few or even a single small incision on the body. MIS is now the standard of care for most adrenalectomies, Nissen fundoplications, cholecystectomies, and other procedures [1]. Typically, 3-5 small skin incisions are made on the abdominal wall, as shown in Figure 1 (a), and the trend moves toward ultra minimally invasive surgery with a single incision. A plastic sheath, which is called a trocar, is inserted through each incision into the abdominal space. These trocars serve as the ports to enter the abdomen. After insertion of the trocars, the abdominal cavity is inflated with CO_2 gas to create a working space, as shown in Figure 1 (b). The trocars accommodate long instruments, which are manipulated by the surgeon, and a laparoscope, which acquires live video images from inside the abdomen. Overall, due to the small incisions made in MIS, patients recover faster with few respiratory complications [2], lower incident of wound infection, and nearly invisible scars.

To further advance MIS technology, surgeons are exploring a new type of surgical technique called Natural Orifice Translumenal Endoscopic Surgery (NOTES) [3], which is an experimental surgical technique where all surgical tools enter the human body through a natural orifice, such as the mouth, vagina, bladder or colon. The incision is usually made internally, at the stomach or at the vagina, thus eliminating abdominal incision. This will further improve patient recovery. However, one major limitation of this path of technology migration is in the laparoscope, which is a straight, rigid tube about 12-15 inches long and about 10 mm in diameter.



(a) (b)

Figure 1. Example laparoscopic procedures: cholecystoetomy in (a) and endometriosis in (b). As shown in (a), 3-5 small incisions are made in MIS for the trocars to go through. The laparoscope then passes through the trocar. To have room to work in the abdominal space, CO_2 gas is pumped into the abdominal cavity to create a work space. Patients recover faster from MIS because of the smaller incisions. However, multiple incisions are still needed and the laparoscope needs to be switched between different incisions to provide extra angle of view during surgical operations. [4]

Made with conventional optics, the laparoscope provides neither auto-focusing nor optical zoom. To compensate for this lack of capability, laparoscopes are designed to have high F/# to provided extended depth-of-view. However, by having a high F/#, the laparoscope cannot work under low light conditions and external Xenon lamp is needed with the light energy introduced through a thick fiber. Also, to switch angle of view, laparoscopes have to be removed from one trocar and inserted into another trocar. This means that extra incisions are required during surgery. Overall, laparoscope has 4 major disadvantages: (1) limited and inflexible field of view; (2) lack of functionality in microscopic range; (3) restricted movement – switching angle of view requires new incision; and (4) high F/# resulting in need of strong external lighting.

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To advance the MIS technology and make NOTES feasible, surgeons need a surgical camera better than today's laparoscope, a camera that can be mounted onto the abdominal wall during surgical operation and doesn't require strong external lighting. The purpose is such that fewer incisions can be made through the abdominal wall.

Such an advanced surgical camera is difficult to design with traditional optical lens technology; and a new type of optical lens technology is required. We find that the ideal new optical lens technology is the bio-inspired fluidic lens. Utilizing bio-inspired fluidic lens, we designed a small camera (total track < 17 mm) that has > 3X optical zoom and auto-focusing capability. Due to the small size and its optical function, the fluidic surgical camera can be mounted onto the abdominal wall during a surgical operation. The surgical camera can also be operated in very low light conditions, which eliminate the need for strong external lighting. A special spherical mirror system also provides an extra angle of view for the camera, eliminating the need for multiple incisions to obtain different angles of view.

II. BIO-INSPIRED FLUIDIC LENS – A CURVATURE-CHANGING LENS TECHNOLOGY

The first animal eyes were simple photo detectors. Then, lenses are evolved to create images of higher resolution and better sensitivity. The structures and properties of lenses in animal eyes are significantly different than human-made lenses found in all imaging devices such as cameras and microscopes. The vast majority of human-made lenses are rigid with fixed shape and curvature. As a result, the only way for a conventional camera to zoom or focus is to change the distance between the lenses. This is rather different from the crystalline lenses in human eyes where the shape and curvature change by moving the ciliary muscles.

Because of the advancement of micro-fabrication and micro-fluidics technology, it becomes possible to fabricate lenses of tunable curvature. There have been numerous studies on different structures of curvature changing lenses based on different mechanisms and designs. Among them are electro-wetting effect [5], dielectrophoretic effect [6], and the structure of fluid-filled chamber covered by an elastomer membrane [7, 8], just to name a few. In considering which lens technology and structure is best for advanced surgical camera, we considered the following figures of merit: tuning range, scalability, mechanical and thermal stability. Tuning range determines the functionality and performance. A small tuning range yields a limited focal range for auto-focusing capability as well as small amount of zoom. Scalability refers to the range of optical clear aperture (or lens diameter) a technology can produce. Typically, the larger the aperture, the better the image quality and the better the light capturing capability the lens can have. A surgical camera that can work under low light condition is preferable. Finally, to work as a surgical camera, the lens needs to be mechanically robust and thermally stable. We have found that fluid-filled, elastomer-membrane lenses perform well in all the above areas.

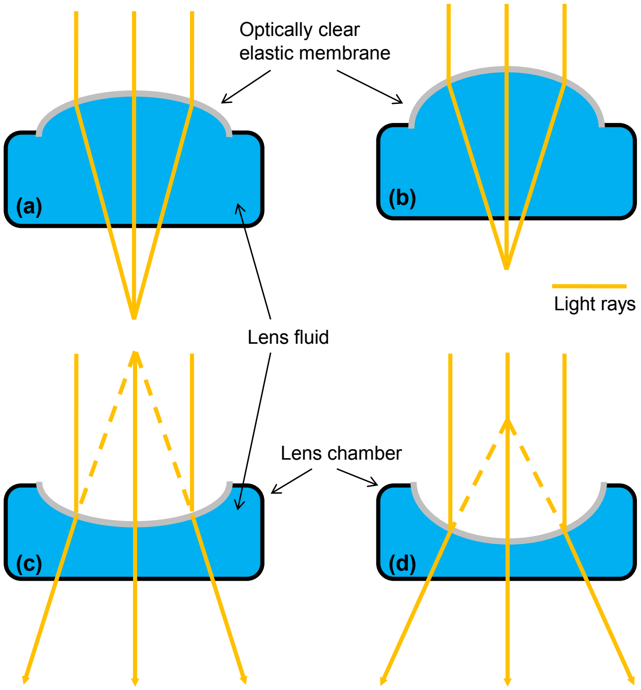


Figure 2. By changing the curvature of the bio-inspired fluidic lens, the rays can converge or diverge to different levels. By applying different pressure to the fluid, the focusing power of the lens changes by changing the curvature of the membrane.

The bio-inspired fluidic lens structure and operation is shown in Figure 2. The index of refraction difference between air and the optical fluid as well as the curvature of the lens determine the lens power. Deformable membrane is used to constrain the fluid and produce the desired lens profile under given pressure. Changing the pressure in the fluidic lens chamber changes the curvature of the lens and results in a change in the focusing power of the lens.

III. COMPACT SURGICAL LENS DESIGN WITH BIO-INSPIRED FLUIDIC LENS

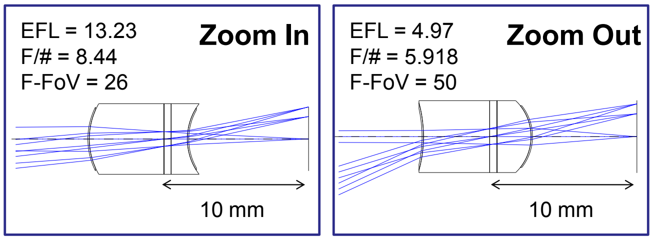
By placing two membranes together, fluidic lenses can form a zoom lens system by changing between a telephoto configuration and a reversed-telephoto configuration. Due to the tremendously large tuning range of the fluidic lens, the zoom lens can be made to be very small and still have over 3X optical zoom.

The operation of the fluidic zoom lens is shown in Figure 3. In (a), the front lens is tuned to a convex lens and the back lens is tuned to a concave lens. Such a configuration is equivalent to a telephoto system, an optical system that has a very long effective focal length (EFL) in spite of its short physical length. This configuration provides a zoomed-in view to enable surgeons to see the details of the object. By changing the curvature of the fluidic lenses, as shown in Figure 3 (b), a reversed-telephoto system consisting of a concave front lens and a convex back lens can be created. A reversed-telephoto system has a short EFL, enabling surgeons to see the overall abdominal cavity to minimize surgical accidents due to limited or truncated field of view. The reverse-telephoto configuration is widely used in fish-eye lenses, such as the lens on doors.

The respective polychromatic diffraction modulation transfer function (MTF) of each configuration is shown in Figure 4 (a) and (b).

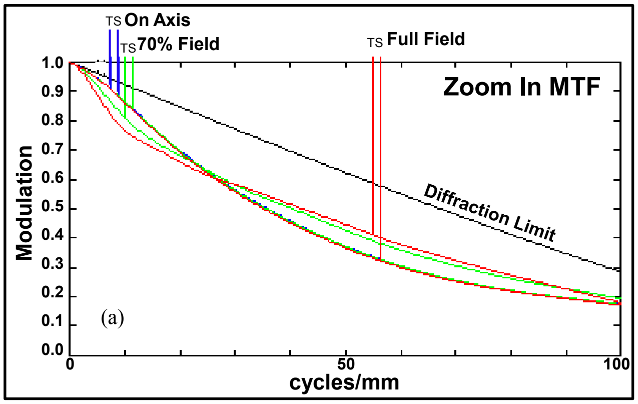
The small zoom lens compounded with a satellite spherical mirror will provide an extra angle-of-view for the camera. The low F/# of the zoom lens system enables the system to work under low light conditions, which eliminates the need for external lighting.

This self-contained multi-angle zoom system is shown schematically in Figure 5. The camera is first mounted on the abdominal wall. A satellite spherical mirror that can orbit around the camera is extended out from the camera. The camera can either zoom in and out at the object of interest, or can aim and zoom in at the spherical mirror. When the camera aims at the spherical mirror, an extra 20° angle of view is obtained. This is particularly important when the surgeon needs a different perspective to avoid blockage of view by obstacles such as fat or organs in the way.



(a) (b)

Figure 3. Miniaturized zoom lens consisting of only two fluidic lenses. By switching between (a) a telephoto (smaller field of view) and (b) a reversed telephoto (large field of view) configuration, zoom effect can be achieved. The effective focal length (EFL) and the diagonal full field of view (FFoV) are shown on the upper left of the lens plot.



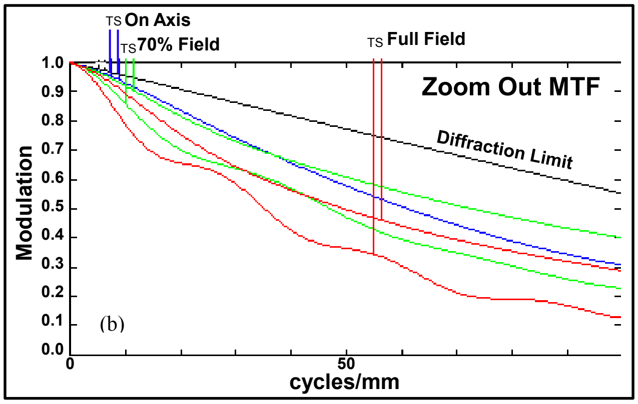
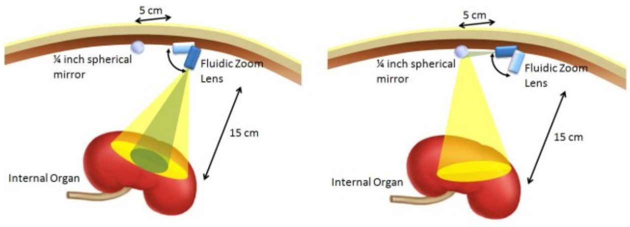


Figure 4. Polychromatic diffraction MTF plots considering C-d-F (656.3-578.6-486.1 nm) wavelengths for miniaturized fluidic zoom lens. The object distance is 12 cm. The MTF of on-axis field, 70% field and full field are shown. The tangential and sagittal MTF for each field are also shown and labeled with 'T' and 'S'. (a) MTF for Zoom-in, corresponding to the configuration in Figure 4(a); and (b) MTF for Zoom-out, corresponding to the configuration in Figure 4(b).



(a) (b)

Figure 5. The bio-inspired fluidic surgical camera is small (< 17 mm total track length) and has over 3x optical zoom. Because of the small size and the zoom capability of the lens, this lens can be mounted on the abdominal wall as shown in (a). With an extended miniature spherical mirror, different angles of view is possible, as shown in (b).

IV. FABRICATION AND EXPERIMENTAL RESULTS

To fabricate the surgical camera, we start with preparing lens membrane mount. The first step is to mix, degas, and spin-coat prepolymer Gelest 1.41, which is a type of polydimethylsiloxane (PDMS), onto a Chlorotrimethylsilane-coated silicon wafer at 1000 rpm. The Gelest-coated wafer is cured in a 65°C oven for 4 hours to form the optically clear elastic membrane. The membrane is then bonded to a precision-machined aluminum ring using the UV ozone surface treatment process. After bonding, the PDMS membrane is detached from the silicon handle wafer and the excess PDMS membrane outside the aluminum ring is trimmed off. This membrane/aluminum ring is then mounted onto a precisely machined lens chamber made out of Delrin, a type of polyacetal. This chamber is finally vacuum-filled with optical fluid. The structure of the surgical camera module is shown in Figure 7. The details of the fluidic lens fabrication process can be found in reference [8].

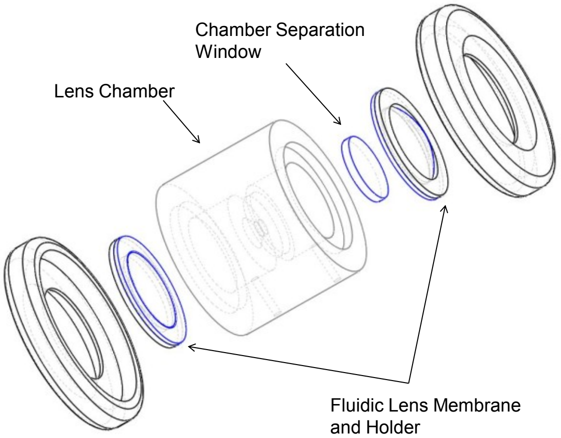


Figure 6. Surgical Camera Structure

After the fabrication of the surgical camera module is complete, we mounted the lens module onto a 1/3" optical format sensor. Finally, a ring of light emitting diodes (LEDs) is mounted onto the camera to provide lighting.

To test the surgical camera, we placed a life-size pancreas model at 12 cm distance from the bio-inspired fluidic lens. Measured by a lux meter (LX-101A, LT Lutron), the amount of light that reached the pancreas from the LED ring was 374 lux, as shown in Figure 7. The power consumption of the LEDs at this brightness is 383 mW. By tuning down the power of the LED, a good image of the pancreas is still achievable at 160 lux.

To test the overall multi-angle-view function, a spherical lens was placed at 9 cm distance from the surgical camera. First, we zoom in and out of the small intestine, as shown in Figure 8 (a) and (b). Then, we turned the camera to face the spherical mirror. By zooming in onto the 1/2" spherical lens, an extra angle of view is achieved. This is shown in Figure 8 (c). The spherical mirror allows for some rotational movement, and this provides an even wider field of view if that movement is allowed. In Figure 8 (d), we demonstrate that the right-side of the abdominal cavity can be seen by simply rotating the satellite spherical mirror.

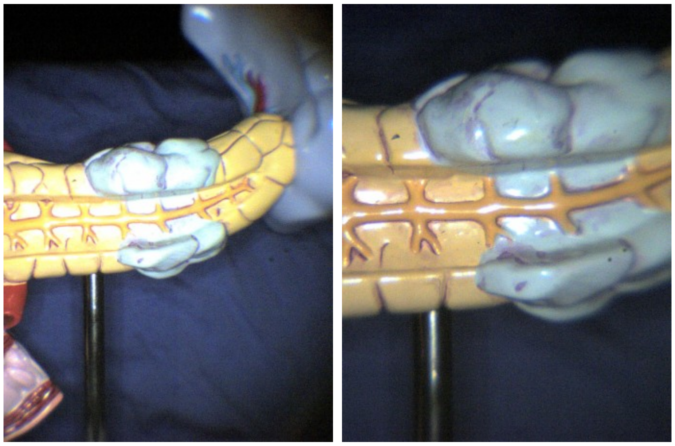


Figure 7. With a life-size pancreas model placed at 12 cm distance from the bio-inspired fluidic lens (relevant distance for MIS operations). The illumination comes from LED and is measured to be 374 lux. The zoom out image (left) and zoom in image (right) both show good image quality.

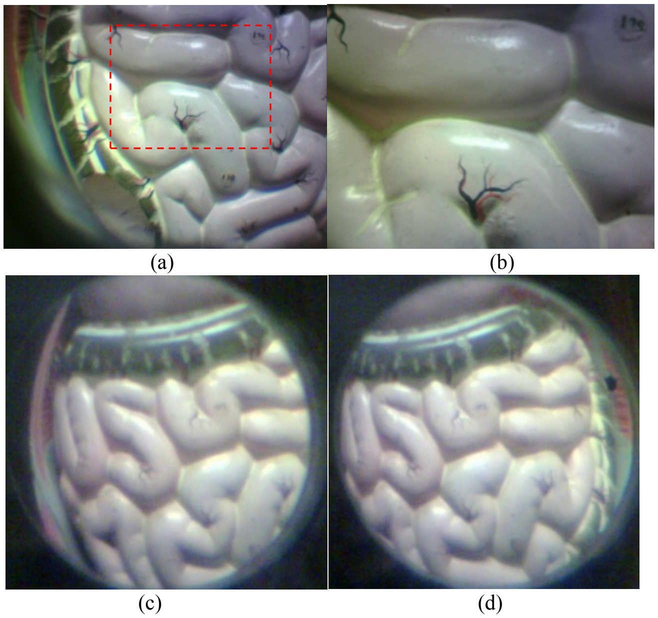


Figure 8. Multi-angle view function. With an extra spherical mirror, we can obtain an extra perspective and an extra angle of view. With just the fluidic surgical camera, we can see the (a) zoom-out and (b) zoom-in view of the small intestine. If the surgeons need a different angle of view, a 12 mm spherical mirror inserted from the same incision can provide the extra viewing angle without additional incisions, as shown in (c). By rotating the spherical mirror, the right side of the abdominal cavity can be seen (d).

V. CONCLUSION

The new function and high performance of bio-inspired fluidic lens enables us to design miniature optical devices benefiting the MIS. The new surgical camera can be mounted on the abdominal wall, zoom optically, have superior low light sensitivity, and provide multiple angles of view with an additional miniature spherical mirror.

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