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A Novel Laparoscopic Camera Robot with *In-Vivo* Lens Cleaning and Debris Prevention Modules

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Abstract— **Robotic systems have recently drawn attention in minimally invasive surgeries due to their increased dexterity feature. A major drawback of these systems is image blurring due to lens contamination which cause imaging impairment during up to 40% of surgery time. This paper demonstrates a novel laparoscopic magnetic driven camera system with implemented *in-vivo* lens cleaning and debris prevention systems. This camera robot can cover 150 degrees field of view inside the abdominal cavity and provide adjustable illumination system to improve the video quality. Design details for different modules, such as anchoring, actuation, video capturing, illumination, debris prevention and lens cleaning of this robot have been provided and discussed. This camera robot can decrease the possibility of lens contamination by creating CO_2 gas barrier in front of lens. In case of contamination it can clean the lens in-vivo without removing the camera from abdominal cavity. The lens cleaning module has been tested for water vapor and water droplets. The robot is manufactured and each module has been validated by designed experiments.**

I. INTRODUCTION

Minimally invasive surgeriy (MIS) is becoming more popular as a replacement for open surgeries. MIS helps the patients to suffer less post-operative pain and decreases their recovery and hospital stay time. Reduction in scarring and cosmetic issues makes MIS even more preferable. These operations are done by inserting surgical instruments through small incisions and mostly consist of gripping, cutting and suturing tools.

In past decade, MIS, single incision laparoscopic surgery (SILS) and natural orifice translumenal endoscopic surgery (NOTES) have drawn attention since they can reduce the surgical incisions to minimum and ease the recovery difficulties at post-operative stage. Manipulating surgical instruments from outside of surgical spot and performing surgery needs precise hand-eye coordination which is provided by insertable cameras. These cameras are usually inserted by a standard trocar through one of the incisions, mostly less than 25 mm in diameter, into the abdominal cavity to provide the video feedback for the surgeon to operate. The limitations caused by operating the surgery through tiny skin incisions decrease the surgeons dexterity. A major challenge in SILS and NOTES is the shared use of incision for both surgical instruments and camera trocar. This will make the control of surgical tools more complex and as a result, dexterity will be degraded. Also, the quality of video feedback is decreased since it may not be able to cover the proper view angles needed for the surgery by trocar pushing.

Several robotic systems have been developed to improve the dexterity of camera systems in surgeries. Hu et al designed laparoscopic camera with DC servo motors for pan and tilt motion and used suturing for fixation [1], [2]. Castro et al designed a wireless laparoscopic camera that uses piercing needle for anchoring [3]. Using suture and pierce mainly will disable the camera system to be translated to new positions inside the abdomen. Wheeled surgical camera systems have been proposed to enable the translation of camera robots to desired locations [4]. The drawback of wheeled systems is the poor and near-horizontal view angle during the surgery which decreases the quality of hand-eye coordination for the surgeon. Robotic endoscopy and colonoscopy systems also provide video feedback for diagnostic procedures [5], [6], but can not be implemented in laparoscopy surgeries. One possible improvement for these designs is the application of a magnetic driven systems which traverse abdominal wall ceiling and can provide proper view angle for video capturing [7]–[12].

A major drawback of most reviewed studies is ignoring the lens cleaning challenge during surgery. Yong et al conducted a research which shows that more than 40% of laparoscopy surgery time is done by impaired image. This will reduce the hand-eye coordination and surgeon's dexterity as a result. Also it causes the interruption in the surgery work flow which influences the performance of surgical team. In the following we will elaborate the detailed state of the art for laparoscopic lens cleaning systems.

A. Problem Description of Lens Cleaning

Clear image feedback of the surgical area is crucial in laparoscopic surgeries. Clarity of the image ensures safety and effectiveness of surgery, maintains surgury flow and enhances the surgical team function [13], [14]. Contamination of lens not only impairs the surgical view, it also affects the surgeons mood [13]. When lens contamination happens, the surgeon can either operate with a poor view or pause the surgery. A research found that 56% of surgery time was performed with a clear display, while 37% of it was operated by impaired vision and 7% of the operation was spent for lens cleaning [15].

The standard procedure of lens cleaning during a laparoscopic surgery is: 1) removing the camera from abdominal cavity through port; 2) wiping the lens with gauze; 3) defogging the lens with hot water or solution. These steps can cause a delay, interrupt the surgery work-flow,

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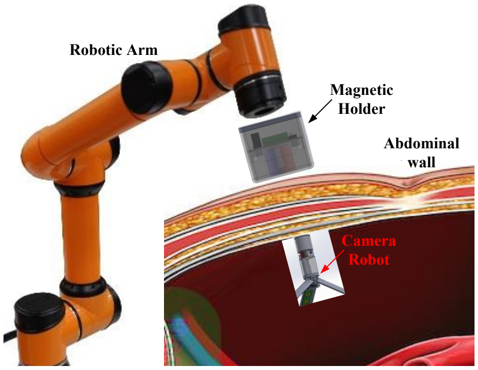

Fig. 1. Camera robot concept: magnetic holder can be controlled by robotic arm to manipulate the robot nside the abdominl cavity.

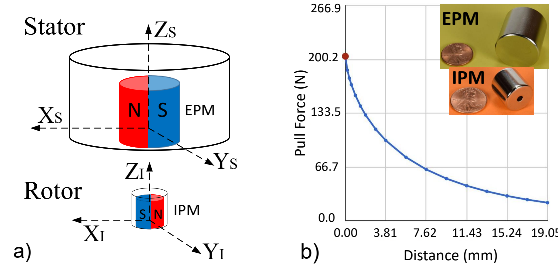

Fig. 2. (a) Magnetic Coupling of EPM and IPM provides motion in X_I-Y_I plane and rotation around Z_I; (b) Pull force graph for EPM and IPM.

increase surgery time and increase the costs as a result. Unnecessary interruptions can cause anxiety and errors in judgment, technique and may potentially cause injury to the patient. Lens removal and cleaning is the most frequent cause of interruption in advanced surgeries [16] which results in longer operation time and increased costs.

Condensation on the lens frequently happens due to differences between room and intra-abdominal temperatures. Despite using anti-condensation solutions, it can not be solved entirely [17]. Removal of lens will cause a secondary issue and that is the port contamination, which requires extra time for cleaning per each lens removal [18]. In rare case, some patients are allergic to povidone-iodine solution used for lens defogging when it contacts the Intra-abdominal [19].

Some researchers have addressed these issues by providing in-vivo cleaning. EndoClear is a device that can be attached to the internal abdominal wall in the beginning of surgery and be used as a cleaning station during surgery [16]. Disadvantages of this system are: 1) it needs fixation inside the cavity which probably done by suturing which is harmful; 2) the EndoClear itself can get dirty during surgery due to the probable bleeding and fluids inside the abdominal cavity.

An Irrigation system has been developed to wash the lens during surgery [14]. The drawback of this system is that it needs a fluid tube to be inserted along the trocar or an overtube which influences the single port dexterity by increasing port conflict.

Floshield is a product which uses a plastic overtube that fits over conventional laparoscopes and blows CO_2 and fluid solution over the lens of the laparoscope [20]. Floshield itself increases the trocar outer diameter through the entry port which reduces the dexterity, also it needs external fluid pumping trough tubes.

A mechanical wiper has been implemented to clear the lens for *in-vivo* visual robot systemwith digital defogging by Feng et al [21]. The drawback of this design is the complexity of mechanisms, transfered from motor to actuate the wiper.

In this paper, a novel camera robot system is developed to provide a high quality video feedback by considering proper local lighting, lens dirt prevention and lens cleaning. The system consists of an *ex-vivo* holder and *in-vivo* robot. The holder can manipulate the rotor by magnetic force and provide motion against the abdominal wall as shown in Fig.1. The robot consists of 2 motors, enable it to provide tilt motion and spread the LED wings. The LED wings provide a local lighting which can boost the video quality by reducing the shadows inside the abdominal cavity. A thorough study of lens cleaning mechanisms provides the idea of designing a simultaneously in-vivo debris-prevention and debris-cleaner system. This has been achieved by implementing a piezoelectric micro-pump and a mechanical wiper mechanism over a hydrophobic lens cover.

The contributions of this paper are: 1) A novel camera robot has been designed to provide a wide covered field of view for camera with lighting system which can improve the video feedback; 2) A totally *in-vivo* debris prevention system has been designed to deviate the debris and streams coming toward lens; 3) A mechanical wiping system is designed to clean the lens in case of dirt.

II. MAGNETIC HOLDER SYSTEM

The robot system is designed to enable fixation and translation by using magnetic coupling. The *ex-vivo* magnetic holder can be manipulated by human hand or robotic arm while the *in-vivo* rotor moves against the abdominal wall to reach the proper area and there it can illuminate the surgical area and provide video. A set of Nedymium permanent magnets with grade $N42$ were used to compensate the gravity force over the camera robot. Diametrical magnetization of both External Permanent Magnet (EPM), 25.4 mm in diameter and 25.4 mm in height, and Internal Permanent Magnet (IPM), 15.875 mm in outer-diameter and 6.35 mm in inner-diameter and 15.875 mm in height, provides a proper magnetic coupling for linear motion and pan rotation of robot over the tissue. Fig.2(a) shows the degrees of freedom (DoF) provided by magnetic actuation. The magnets provide proper normal force along Z_S to anchor the rotor and Fig.2(b) shows the magnet-magnet pull force graph.

A. Magnet Holder

The Holder is a 60 mm × 60 mm × 55 mm cube, designed to hold the EPM and motor driver circuits as shown in Fig.3(a). The EPM is fixed to the base of holder to maintain the magnet orientation. STMicroelectronics DC motor drivers are used to actuate and control the DC motors. The holder itself can be manipulated by human or robotic arm to control the rotor.

III. INSERTABLE LAPAROSCOPY CAMERA ROBOT

A novel camera robot is designed to move inside the abdominal cavity by magnetic manipulation, which consists of six modules as: 1) anchoring module; 2) actuation module; 3) video capturing module; 4) illumination module; 5) dirt and debris prevention module; 6) lens cleaning module, as shown in Fig.3(b). Total length of the camera robot is 96 mm in retracted mode and 60 mm in spread mode. Considering the tilt ability of camera robot and wing spread, it can be fitted in the 100 mm to 150 mm in depth workspace provided inside the abdominal cavity after insufflation. In this section design details of each module will be discussed.

A. Anchoring Module

The anchoring module includes a permanent magnet (IPM) as discussed in section II and a magnet holder. The holder is a 20 mm in diameter cylinder with 17 mm height and 0.7 mm wall thickness manufactured by CNC machine out of an aluminum bar. The top part is in direct contact with abdomen internal tissue and the edges are curved to prevent damaging. Two hinges are designed at the bottom of holder for tilt mechanism's shaft. Hinges plate is connected to cylinder by a 12 mm in diameter screw. Fig.3(c) shows the details of this module.

B. Actuation Module

The insertable camera robot has two actuation mechanisms for tilt motion and wing spreading. The tilt DoF provides a rotation of camera robot around the tilt shaft from 0 to 45 degrees. The wing spread mechanism enables the three LED wings of the camera robot to spread from 0 to 70 degrees and provide the proper illumination. The zero degrees represents the closed wings which protects the video modules during robot entry through incision.

The required torque for tilt motion of the camera robot, based on part wights, was calculated as $23 mN.m$. A 6 mm outer diameter DC brushless motor, with gear box of ratio 136 : 1 and 18.7 mm total length was chosen for this purpose (Shenzhen ZhaoWei Machinery & Electronics Co. Ltd.). The motor provides 12.2 mN m torque at its maximum efficiency so a worm and gear set were designed to improve the generated torque. The tilt worm has 5.5 mm outer diameter with one thread and 20 degrees pressure angle. The plastic tilt gear has 10 teeth with 6 mm outer diameter with same pressure angle as tilt worm. This set can increase the motor generated torque ten times which is sufficient for robot tilting motion. The power and control signals are sent through the wire from magnetic holder.

Each LED wing is consisted of wing structure, circuits and LEDs with the total mass of 40 g for three wings. Required torque for spreading all three wings together is calculated as $8 mN.m$. The same DC motor as tilt motor is used for wing spread mechanism. As shown in Fig.4(a), the spread worm attached to the motor drives three spur spread gears simultaneously. The wings can be controlled to open from 0 to 70 degrees together and stay fixed at proper angle. This feature provides a controllable illumination inside the abdominal cavity over the surgical area. spread gears are fixed to the wings by 1 mm diameter shafts and all moves synced together.

The motors are encapsulated in an aluminum cylinder of 20 mm diameter and 23 mm height. The actuation module is connected to anchoring module by two hinges aligned with tilt hinges and a 1 mm shaft. Other modules are connected through the wing spread mechanism to the actuation module.

C. Video Capturing Module

The video capturing module consists of a monitor, imaging board and focal lens as shown in Fig4 (b). The focal lens is a 6.28 mm format, all plastic with a total track length of 4.98 mm. This camera is designed for compact camera applications and the lens has 60 degrees diagonal field of view. The module sends the video signal through the wires to monitor.

D. Illumination Module

The mechanical design of wing parts is not only used for actuating the lens cleaning module, but also can carry

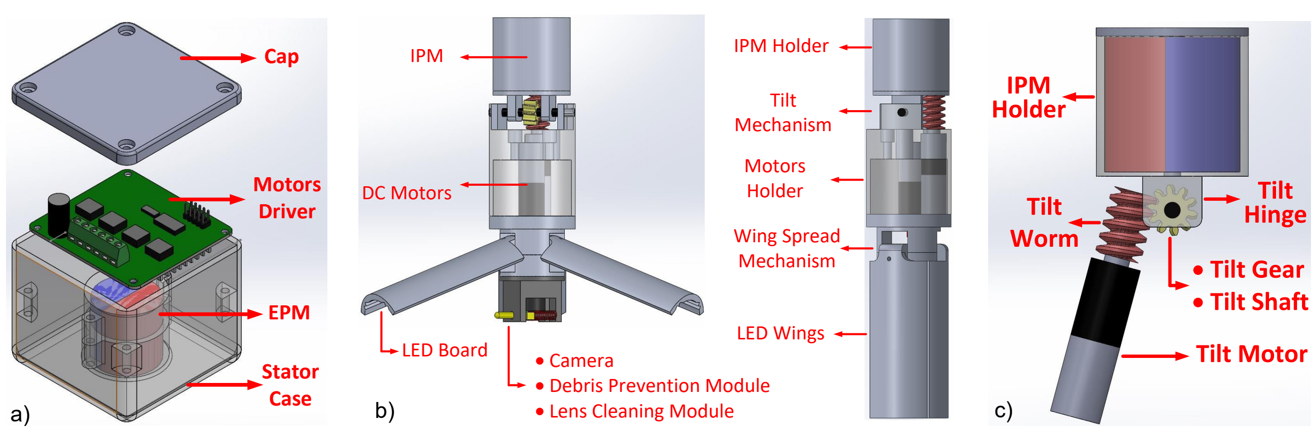

Fig. 3. Design details: (a) Magnetic holder; (b) Rotor; (c) Tilt mechanism.

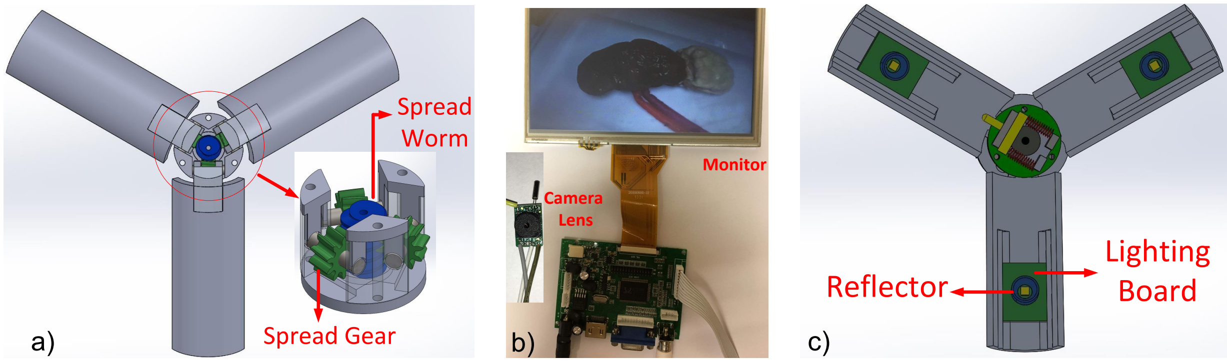

Fig. 4. Modules design details: (a) Wing spread mechanism; (b) Video capturing module; (c) Illumination module design.

illumination system, as shown in Fig. 4(c). The illumination system consists of a LED circuit board and a reflector attached on each wing. The reflectors are used to improve the optical efficiency. Compared with the illumination systems developed for the state-of-the-art designs, which are arranged around the imaging sensor in a fixed pattern, our design can adjust the focus of light beams according to different target area by changing the wings' angles. The three LED wings can be adjusted to the desired angle by the wing spread mechanism to provide proper illumination requirements.

E. Dirt and Debris Prevention Module

surgical video systems encounter with image blurring frequently during operation. As mentioned in section I-A only around 50% of surgery time is done by clear imaging. The main sources of blurring inside the abdominal cavity are water vapor, fog, smoke, blood and peritoneum fluid. To address this issue, a prevention system is proposed in this section to deviate the debris and dirt sources from contacting the lens.

The Dirt prevention module shown in Fig.5(a) consists of a micro-pump which inlets the CO_2 gas from the insufflated abdominal cavity and blow it through the designed channel toward the camera lens.

This system makes a gas barrier in front of the camera lens and the air flow is able to prevent the smoke stream, water vapor stream and low pressure blood stream from contacting the lens. It also removes the fog over the lens which is created due to the temperature difference during camera insertion.

This novel in-vivo debris prevention module can decrease the surgery time by decreasing the required lens cleaning

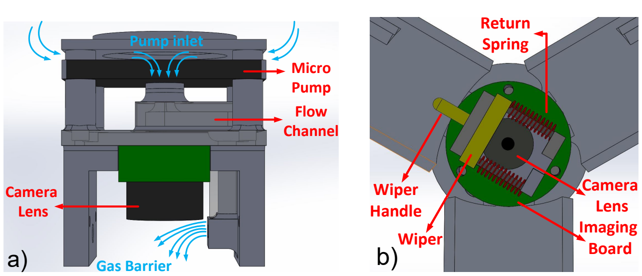

Fig. 5. Design details: (a) Dirt and debris prevention module; (b) Lens cleaning system.

during MIS. Different channel outlet profiles can be designed to improve the gas barrier around the lens.

F. Lens Cleaning Module

Besides the gas streams which causes image impairment, blood drops, peritoneum fluid and water vapor can decrease video quality which causes delay in surgery. In this section a novel lens cleaning mechanism has been designed to wipe the dirt off the camera lens during surgery. This systems can solve the frequent removal of laparoscopic cameras during MIS by cleaning the lens *in-vivo*.

In this design, a simple effective mechanism has been used to avoid extra motor requirement or complicated mechanisms. The LED wings are used to move a wiper over the camera lens to clean the debris as shown in Fig.5 (b). While an impairment due to lens dirt happens, the LED wings spread and retract repeatedly to push the wiper handle and as a result wipe the lens. two mini compression springs return the wiper to its initial place after each push. Hydrophobic covers and solutions also ease the debris removal by decreasing the surface tension, so a layer of thin hydrophobic cover has been implemented over the camera lens.

IV. EXPERIMENTS

In this section, we will discuss the performance of manufactured camera robot and proposed cleaning and prevention systems. Experiments have been designed to replicate the *in-vivo* dirt sources to prove the proposed concepts.

A. Camera Robot Manufacturing

The robot structure has been manufactured by CNC machine by 6061 Aluminum and machined finish and 0.127 mm tolerance. Two brushless DC motors were implemented to actuate the tilt mechanism, spread mechanism and cleaning mechanism as well. Two worm-gear sets were designed to enhance the generated torque. The spread mechanism uses one worm to spread three wings simultaneously. The Fig.6(a) shows manufactured modules and assembled mechanisms.

B. Magnetic Coupling

In this section the magnetic coupling of EPM and IPM is tested. The total camera robot with all the modules weigh $58.320g$. As shown in Fig.6 (b) the EPM is able to anchor

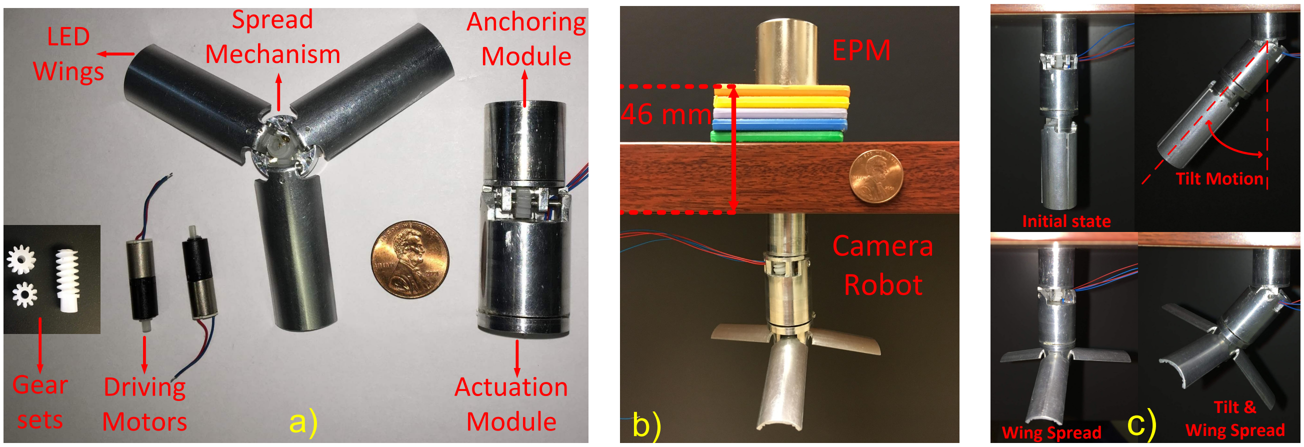

Fig. 6. (a) Manufactured camera robot parts; (b) Magnetic coupling test; (c) Tilt and wing spread mechanisms performance.

the camera robot from the distance more than 46*mm* which proves the ability of using this system over the abdominal cavity with average thickness of 25*mm* to 45*mm*. The camera robot can be manipulated for X_I and Y_I motion as well as pan rotation around Z_I. (See Fig.2)

C. Pan, Tilt and Spread Mechanism

Pan mechanism is actuated by magnetic coupling of EPM in holder and IPM in robot. Diametrical magnetization of magnets enables a smooth controllable 360 degrees pan motion. Tilt mechanism is designed to provide proper view angle for camera and illumination modules to improve the video quality. This mechanism is able to tilt to 45 degrees in maximum and stall the camera in proper angle. Considering the 60 degrees lens's field of view, the camera robot is able to cover -75 to $+75$ degrees inside the abdominal cavity as shown in Fig.7.

The wing spread mechanism is able to spread and hold the LED wings up to maximum 70 degrees to provide proper illumination. Also, it spreads and retracts repeatedly and fast to actuate the lens cleaning module. The performance of these mechanisms is shown in Fig.6 (c).

D. Debris Prevention Test

The prevention module provides a gas barrier in front of the camera lens to repel the gas streams and debris coming toward the lens during surgery. A Low profile, high speed and high pressure air pump were used for this purpose. This pump weighs 1.4 g with 1.85 mm thickness and 20 mm in diameter core part. Murata piezoelectric pump uses 15 Vp – p driving voltage and a very low current square signal output of signal generator with 25 kHz frequency. This pump provides more than 1.42 kPa static pressure with more than 0.70 L/min flow rate. The operating temperature is also 0 to 70 Celsius which make it a proper choice for in-vivo use.

The pump outlet is connected to camera through a designed flow channel inside the structure. For this experiment a stream of smoke, generated by smoke machine, was blown toward the camera lens as shown in Fig.8(a) when the pump is off. after turning on the pump, the stream was deviated from the camera lens and eddy current were created far from the lens as shown in Fig.8(b).

Prevention module also can remove the fog created over the lens by constant flow over it. The channel were designed to blow the lens as well. The results proves that in-vivo prevention module can help deviating the streams and debris to contact the camera lens.

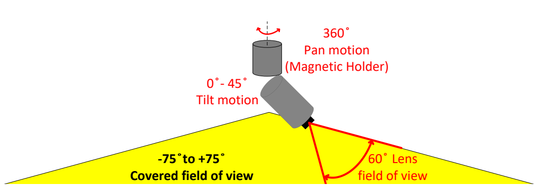

Fig. 7. covered view angle of camera robot inside the abdominal cavity.

E. Lens Cleaning Test

Cleaning system was manufactured by 3D-printing and it holds video capturing module inside it as shown in Fig.8(c). Only one wing is attached to show the mechanism clearly. Two compression spring with 1.4 mm outer diameter and 0.2 mm wire size were used to return the wiper to its initial position after each wing retraction. Springs are mounted over 0.7 mm circular tracks to make the procedure smooth.

The camera lens is covered with a clear thin cover treated with nano-tech hydrophobic solution to reduce the surface tension and ease the cleaning procedure. Standard gauze was used as wiper tissue to clean the lens ty using the wing spread

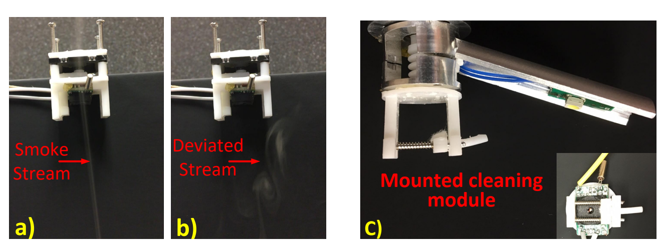

Fig. 8. (a) Debris prevention system test on smoke stream; (b) deviated smoke stream prevents the image blurring; (c) Mounted cleaning module on the camera robot.

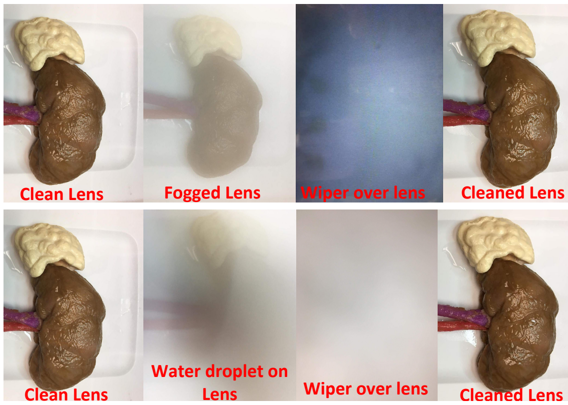

Fig. 9. Cleaning module test for impaired image with vapor and water.

mechanism. SynDaver kidney model is used to capture the video. By using humidifier, the lens was covered with fog to replicate the abdominal avity fogging situation. Fig.9 shows the images before and after the wiping mechanism for fogged lens. Another experiment were conducted for water droplets over the lens. This system is able to clean the lens off the fluid droplets as well. The results of experiment clearly shows that the cleaning module is able to remove contamination over the camera lens by wiper.

V. CONCLUSION AND FUTURE WORK

In this paper a camera robot system with the aim of in-vivo cleaning and debris prevention has been designed and manufactured. This robot can provide debris-safe video feedback for the surgeons which will result in decreasing the surgery time and cost, will enhance the surgery work flow and reduces anxiety of surgical team. The camera robot is able to adjust the illumination of surgery area by changing the wing spread angles and can provide higher quality illumination compared to fixed, near camera LEDs.

In our future work, a smaller version of this camera system will be provided which can reduce the size and weight of the robot. Illumination system will be improved to provide shadow-less surgical area which can be am improvement for surgical videos. The camera robot system will be used for laparoscopy surgery on alive pigs.

VI. ACKNOWLEDGMENT

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