Design for a Self-Contained, Maneuverable Endoscopic Camera System

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Abstract

A self-contained, maneuverable endoscopic video camera system is crucial for the enhancement of laparoscopic surgery procedures. This camera will be set in place by a magnetic couple through insertion via a trocar into a laparoscopic port. The magnetic couple will then maneuver the device internally to view any area of interest. By means of developing such a device, periodic post-operative viewing may be facilitated for a veterinarian (or doctor) with the benefit of fewer invasive procedures. Considerations that are essential to the performance and reliability of such a device include visual quality, maneuverability, power sources, and consistency of the magnetic couple installation. The goal for this semester was to build the prototype of a large scale model for a self-contained, maneuverable endoscopic camera that includes a light source and power source with uncompromised visual quality and feedback.

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Problem Statement

Design a self-contained, maneuverable endoscopic video camera system for laparoscopic procedures at the Small Animal Clinic within the UW-Veterinary Hospital. This device will be used during laparoscopic procedures and will have the ability to be maintained internally for periodic post-operative viewing. In addition, the device will allow for deft orientation of the video camera system without compromising its visual capacity, and will have all electrical components sealed off from the body cavity environment. This device will be easy to insert and remove from the patient as well as reduce the invasiveness of laparoscopic procedures by requiring fewer ports.

Background Information

Endoscopic surgery is a minimally invasive form of surgery which is performed using a rigid endoscope and long-handled instruments through small incisions in the body (see Figure 1). Trocars, or port-like instruments, are placed through the body wall for easy exchange of endoscopic instruments. When the surgery is being performed in the thoracic or abdominal cavity, a needle is inserted through one of these ports to insufflate the cavity and give the surgeon a better view of the area. There are many benefits to this type of surgery

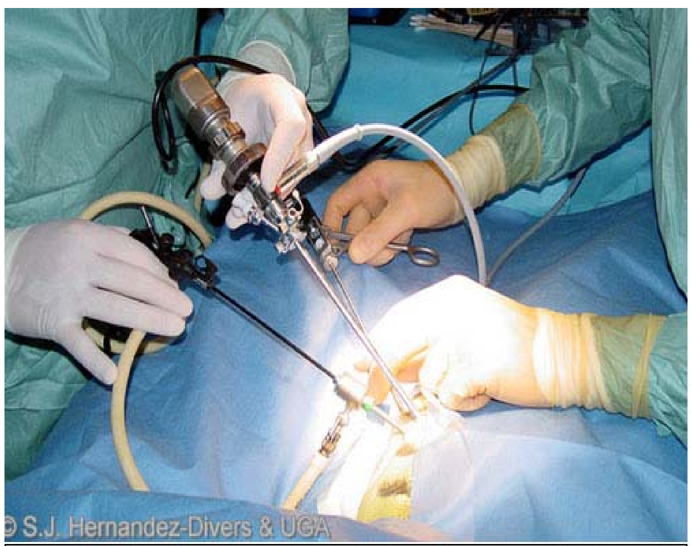

Figure 1: Endoscopic Surgery with (from left to right) grasper, rigid endoscopic camera and gas insufflator.

including faster patient recovery time, less tissue damage and scarring, fewer complications, and less patient discomfort following surgery (Hardie, 2008).

Rigid endoscopes are small tubular telescopes which contain a series of stacked lenses to greatly magnify an image (see **Figure 2**). They are often used in conjunction with a camera system which allows a surgeon to see the magnified image on a computer or television screen. While the rigid endoscope is a very useful instrument, the current rigidity and fixed position of the design limits the field of view and the ability to examine organs and tissues from a variety of angles. In addition, rigid endoscopes cannot easily be used for periodic or long-term post-operative viewing due to the need for anesthesia during insertion and manipulation of the instruments.

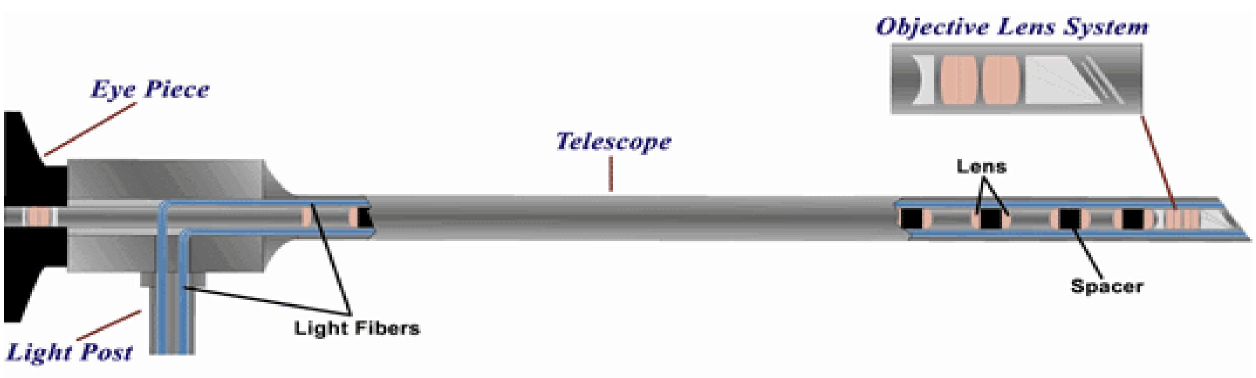

Figure 2: Current rigid endoscopic camera scope for endoscopic surgery.

Our client, Dr. Hardie, is a small animal general surgeon at the UW Veterinary Hospital. He often performs endoscopic surgeries on the thorax or abdomens of small animals such as dogs and cats. Due to the limitations of the current rigid endoscope design, Dr. Hardie desires a self-contained, maneuverable endoscopic camera system which can be placed within the thorax or abdomen for a prolonged period of time post-surgery. A device like this would help in early diagnosis of surgical complications or other disease conditions which may require repeated or real-time evaluations for accurate diagnosis.

Current Devices

Currently, few devices which allow for non-invasive post-operative viewing of the abdominal cavity exist on the market. The most pertinent design available for post-operative viewing is capsule endoscopy. The Pill Cam™ is a capsule equipped with miniature cameras on both ends (see **Figure 3**). A patient swallows the Pill Cam™ and it is transported through the GI tract by the body's own natural peristalsis. The cameras capture images of the inner lining of the GI tract, and these images are transmitted to sensor arrays and then finally to a portable data recorder which downloads the images.

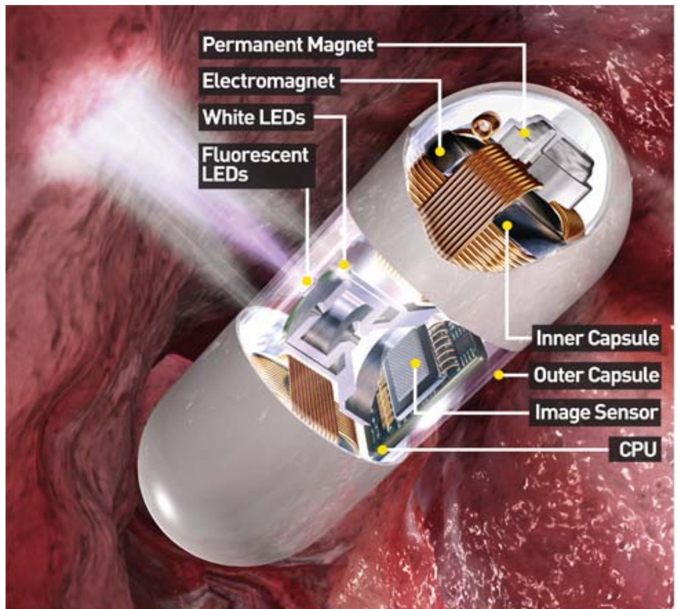

Figure 3: The Pill Camera, a self-contained camera system that is in use today.

One problem with the Pill Cam™ is a lack of control over camera angles and direction since the camera is tumbling through the intestines. Another issue is pinpointing exactly where in the body the image from the camera was taken. Likewise, the quality of the images taken by the Pill Cam™ may be decreased due to tumbling and a build-up of body fluids on the capsule. The Pill Cam™ generally passes from the mouth to the stomach in about 20 minutes, so it is not very useful for prolonged post-operative viewing. Additionally, the Pill Cam^{TM} is designed to take images of the inner linings of organs, and not in the thoracic or abdominal cavity outside of the organs.

Design Constraints

In order to design a self-contained, maneuverable endoscopic video camera system, certain design constraints need to be met. This device must have the ability to be utilized during minimally invasive surgeries as well as post-operatively for periodic viewing of the thoracic or abdominal cavity. Since the device is being implanted into the patient, the camera system must be completely gas sterilizable in order to prevent infection and other potentially hazardous problems. The device must be easy to remove from the patient once the viewing period has concluded. The camera should be completely self-contained with its own light and power sources, and should have the ability to transmit data wirelessly to a receiver which will display the streaming video on a television or computer screen. This device must capture images of equal or greater quality than current rigid endoscopes must be built with a budget of $500.

Important design requirements for the workings of the device must also be met. These include powering the video camera and LEDs with two 9-Volt batteries and not exceeding a current of 10 mA per LED. Additionally, the magnetic coupling system needs to be able to support the weight of the camera and maneuver it around a target area. Finally, the device must not contain any sharp edges since it will be maneuvered throughout the body cavity.

Design Alternatives

All three design alternatives considered share basic features which allow them to be used as visual guidance systems for laparoscopic surgery. More specifically, they all contain cameras and light sources that are inserted into a patient's abdominal cavity through a small incision. Also, each design alternative can be steered or oriented to some degree within a patient's body via controls that remain outside the body. All video images captured can be displayed on a monitor so the surgeon can clearly see what they are doing inside of the patient.

Design 1: Motorized Head

Overview

The structure of this design is very similar to that of a basic rigid endoscope: it has an eyepiece that can be hooked up to a monitor to display the camera image; it has a long, slender, rigid body; and it has a lens and light source on the end that is inserted into the patient. The aspect of this design which sets it apart from a rigid endoscope is the flexible tip that houses the camera and light source. This flexible tip would be anywhere from one to three inches long and contain several small motors that are capable of moving the camera lens over a large range of degrees (approximately 90 degrees or more as seen in **Figure 4**).

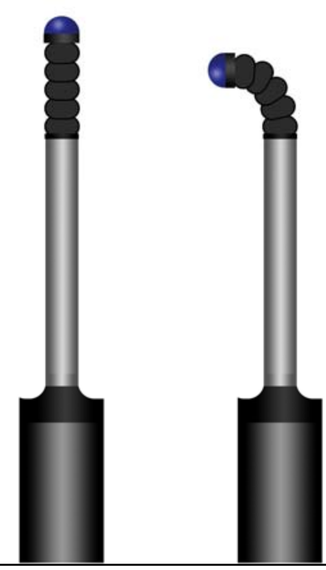

Figure 4: Motorized head with flexible tip at rest (left) and with flexible tip bent (right).

Advantages and Disadvantages

Preserving the basic structure of a rigid endoscope plays a significant role in the advantages of this design. First of all, no laparoscopic tools or imaging monitors would have to be modified to accompany this new design. Any equipment used to position and hold the device would work with little or no adjustment. Furthermore, the familiar size and shape could make it easier for a surgeon to get used to. Just like basic rigid endoscopes, however, this design would have to be re-inserted each time for post-operative monitoring of the internal surgical site.

The flexible head of this design makes it more functional than a standard rigid endoscope. Because of this design's rigid body, it can be held in place while the flexible head is easily moved via external controls. Also, the large viewing angle range of this design means a wider field of view for the surgeon as well as the option to orient the rigid body to a position that is convenient while keeping the camera focused on the area of interest.

Design 2: Puppeteer

Overview

This design alternative is much more flexible than the previous design. The entire construct consists of a hollow, segmented cylinder in which each solid, non-flexible segment can pivot with two degrees of freedom about a fixed point located within an adjacent segment (similar to the cars of a train: a car in the middle cannot pivot unless the cars ahead of it have been directed to turn). The amount each segment is allowed to pivot is limited in order to maintain a waterproof seal. The entire body of this design is kept straight by taught cables held close to the lumens of the cylinder segments. In order to move the camera head, which is located at the tip of the cylinder, one of the cables is pulled to move each segment in the desired direction (see **Figure 5**). As an added feature, extra cables that attach at different lengths along the cylinder can be used to curve the endoscope in complex configurations, as depicted in the far right image of **Figure 5**.

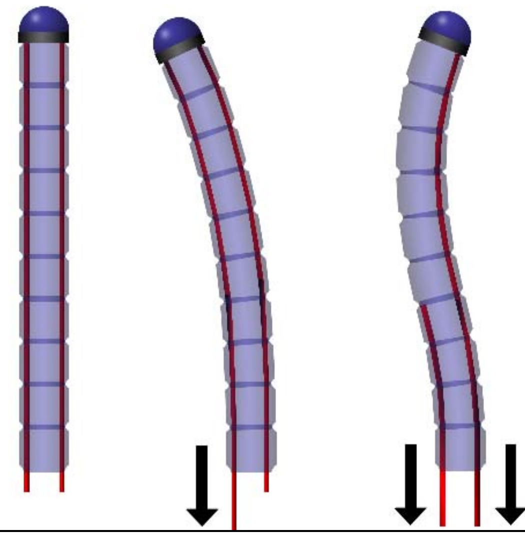

Figure 5: Puppeteer with taught cables (left), after pulling one cable (middle), and pulling two different-sized cables (right).

Advantages and Disadvantages

By controlling the curvature of this design at the end which remains on the outside of a patient's body, simple cable tension controls can be used to make it easy for the surgeon to adjust the camera angle. Also, because of the complex curvatures made possible, this design has the capacity to navigate around certain objects. This could be useful since there is not much workspace made available during laparoscopic surgery, and anything obstructing the camera could have costly repercussions.

There are a couple disadvantages to using this particular design. Similar to the previous design and other endoscopes currently used for laparoscopic surgery, this device must be re-inserted each time for post-operative viewing. Furthermore, one of the biggest problems with this device is the large displacement of the camera head associated with trying to use larger viewing angles. Not only does the camera head rotate when a cable is pulled, but the entire head of the camera displaces a significant amount. This could become a difficult endoscope to work with, especially if the surgeon is not used to how the camera moves.

Design 3: Magnetic Couple System

Overview

The third design that was considered this semester was the magnetic coupling device as seen in **Figure 6**. The concept of this design evolved from a dome security camera that hangs from the ceiling. In this design, a much smaller dome camera system would be developed. In addition to a camera, the dome would also need to contain a light source to illuminate *in vivo*, a power source for the camera and light source as well as some small magnets. The reason that magnets are placed in the dome is so when the device is *in vivo*, it can be magnetically coupled to the internal body wall by magnets placed *ex vivo* on the dermal surface. By coupling the device in this fashion, the *ex vivo* magnets can be moved and rotated, thereby causing the *in vivo* portion of the device to also be moved. In this fashion, real-time images can be captured *in vivo* without any additional incisions or trauma to the patient.

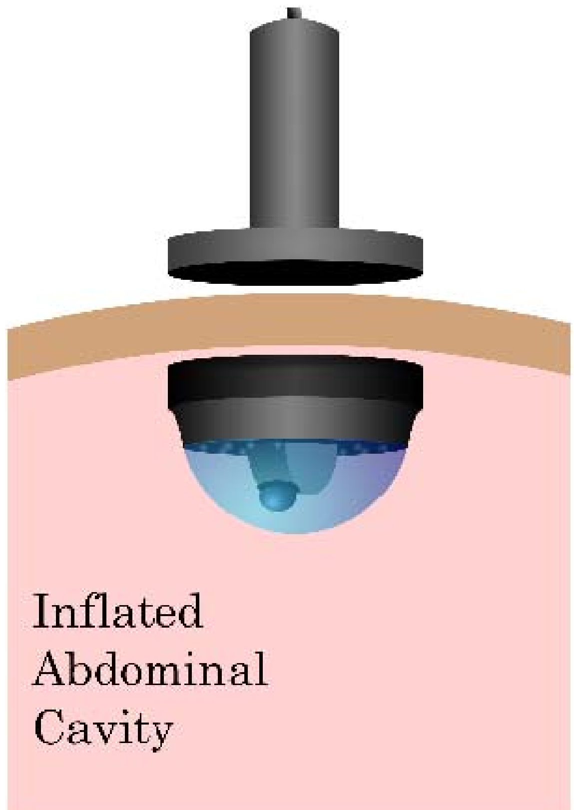

Figure 6 : Magnetic Couple System for a fully self-contained, maneuverable endoscopic camera system

Advantages and Disadvantages

The main advantage of this design is the ease in which it is maneuverable. Not only does the device have the ability to be translated easily, but the ability to be rotated with a zero degree turning radius means that images can be captured from a wide area.

The main disadvantage of this design is that it is not known if the coupling device may cause additional trauma to the patient. Due to the fact that high powered magnets will be in place for a length of time, it is unknown whether this will cause bruising, pinching etc. of the patient. As a result of this, an additional level of support may be necessary to supplement the magnets, to allow for the magnets to be removed when the device is not being used.

Design Matrix

With the three proposed designs in mind, each design idea was evaluated against several design criteria with the respective results summed together and tabulated to form the design matrix (**Table 1**) in order to determine which design undertaking was the most feasible given the limitations of time, budget and available materials. Each design criteria was weighted differently according to order of importance and adherence to our client's specifications in order to devise a successful and meaningful prototype.

The design criteria used for the design matrix below were established to rate each design idea in terms of how capable the device would be able to accomplish the function of self-contained, post-operative viewing and how feasible the design proof of concept would be for fabrication given a single semester. The ability for the designed construct to be properly maintained and sterilized were crucial components to determining the choice of design because this device would be used multiple times and would be expected to remain inside a patient's body over a period of 3-4 days. Deliverability was a measure imposed to determine whether the design could be successfully constructed, function, satisfy the client requirements and be sufficiently tested given the semester long constraint and budget limit. The cost criterion was an evaluation method by which each design was rated on cost-efficiency of design incorporation into a working model.

	Post-Operative Viewing Ability (*30pts*)	Feasibility of Construction (*25pts*)	Sterilization and Maintenance (*25pts*)	Deliverability (*10pts*)	Cost (*10pts*)	Total (*100pts*)
Mechanical Head System	20	22	17	6	8	73
Puppeteer System	3	15	13	2	8	41
Magnetic Couple System	28	19	24	10	4	85

Table 1: Design Matrix of the three design alternatives

Upon completion of design idea evaluations, it turned out that the magnetic couple system was the ideal design idea to be incorporated for this project due to the fact that its ratings for all criteria excelled all across the board. Moreover, this design idea was the only fully self-contained alternative that could enable a great range of mobility for the surgeon to view a patient's abdominal cavity without having to make further surgical incisions.

Final Design

For our final design, we chose to first develop a large scale prototype, to prove the proof of concept for this design. As a result, we used a 3 ½" plastic dome purchased from a craft/hobby website. Our LED's were purchased from RadioShack, and the camera for our system was purchased from Brickhouse Electronics, and was a 5/8" cube wireless 'spy-cam.' Two 9V batteries were used to power the device; one for the camera, and the other for the LEDs. Originally, reed switches were going to be used to control the on/off function of the device. However, in order to use these reed switches, we would not have been able to place any magnets inside of the dome portion of the device, as they would have most likely caused the switches to always closed. To compensate for this, we initially tried to use a metal plate on the base of the dome for the *ex vivo* magnets to couple to, but found that the device was not able to rotate and had great difficulty being translated on any sort of frictional surface. As a result, we chose to place magnets in the base of the dome, and devised a mechanical switch to power the device on and off. The neodymium magnets were placed in a triangular array in both the base of the dome and also in the *ex vivo* handle.

Figure 7: Magnetically-induced Pressure Switch System (left) coupled with magnetic scope (right).

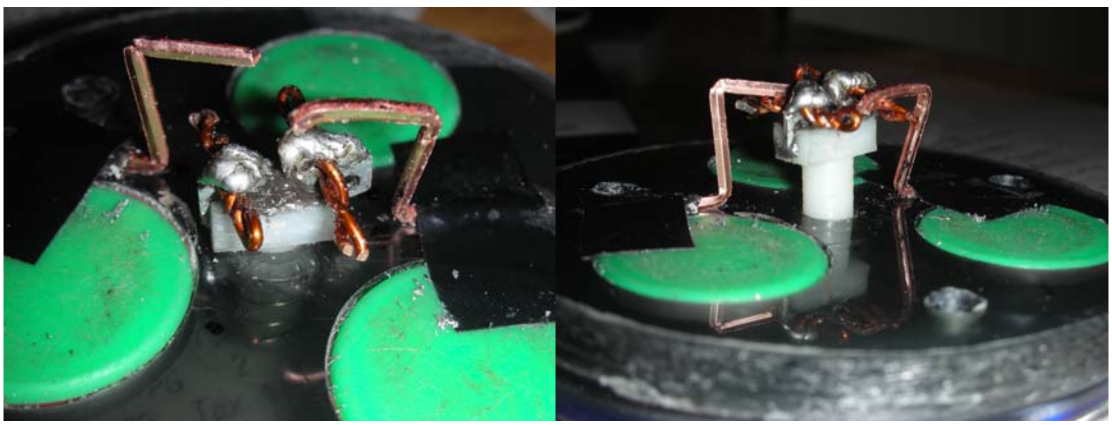

Figure 8: Photos of the pressure switch system are shown in greater detail.

The photo on the left shows the switches (each consists of a copper crossbar and copper overhang) in the ‘off’ position, as the leads are not touching. Using this design, the wire connecting the LED or camera circuit to the negative terminal on the battery would be separated. This wire would run through the switch, with current flowing in to one lead (eg the copper overhang) and out the other (the copper crossbar). One switch was placed in series with the LED circuit, and other placed in series with the camera. When the switch (shown in the

Figure 9: Spring-Loaded Pressure Switch to couple with scope.

Figure 9) is depressed by means of the magnetic coupling device, the leads are brought together, thereby closing the circuit. The closed switch can be seen in the figure above, on the right.

Finally, the camera was fixed at an angle relative to horizontal to allow for a better viewing capability of the device. The finished device is shown in **Figure 10** below.

Figure 10: Photos of the finished prototype; the dome camera with illuminated LEDs (top left); the 9V power source held down to the base of the camera (bottom left) and the final magnetic couple system held between sheets of notebook paper (right).

Future Work

This final design idea would allow for the construction of a fully self-contained and maneuverable endoscopic video camera system that could be reliably operated *in vivo* and kept within the body over an extended period of time. The current prototype is still a proof of concept and would require improvements to ensure seamless function and operation of the device while being reliable, safe for the patient and able to withstand internal biological functions.

In order to improve our current design prototype such that it would meet the aforementioned standards, we would need to install both a wireless self-focusing camera system that may be controlled by knobs on a magnetic scope and a wireless, mechanical self-cleansing system that will be used to clear buildup of biological material when the camera is *in vivo*. On the scale of physical proportion, we would ultimately wish to reduce the dimensions of our current prototype to about a 1/3 of its original size however our priority should be to accomplish the complete incorporation of all desired functions into the camera system prior to downscaling the device.

In the light of this, we will be taking measures nonetheless to slowly reduce the internal bulk by changing the batteries from rectangular 9V to flat circular Lithium batteries. In order for us to accomplish this task, we would need to first rate the voltage per unit time for the camera and LEDs in order to obtain an idea of our target battery life and performance. The camera will be maintained within a patient for several days and all functions contained within the dome camera will be battery powered, therefore it is imperative for successful performance to ensure that sufficient power will be delivered to all components when post-operative viewing has commenced.

Further developments that would definitely need to be made are improvements in the maneuverability of the device over surfaces of higher friction and lower stiffness constants. To date, the device has been maneuvered along rather low friction and stiff surfaces such as waxed tables, plastic boards and cardboard. This aspect of the prototype's performance will need to be tested and improved if mobility is insufficient. Ideally, this device should work between the layer of skin, fat, flesh and sinews reminiscent of the abdominal region of a patient.

Last but not least, we need to settle on a decision for a gas-sealing system for the dome camera that would both effectively seal the internal components from the environment and be easily removed when batteries or other components need to be changed or replaced. We are currently using black foam that is press fitted between the clear plastic dome and an acrylic circular plate, held down with electrical tape. Needless to say, this should be improved upon for next semester.

Usability Testing

To ensure the quality of the designed mechanism, a proposed list of tests should be conducted such that an end product functions properly and its function is convenient, ergonomic and meets the client requirements. Among these tests, an *in vivo* 'maneuverability' test should be performed along with 'insertion and extraction' trials to evaluate the capability of the designed device to function in a surgical setting. The ability of the device to act as an asset to the operating surgeon is crucial to the development of this device, therefore seamless maneuverability and ease of use would not only satisfy the client expectations but lead to repeated use for other surgical procedures as well.

In addition, ‘electronics’ testing would need to be conducted on a regular basis in order to guarantee the performance expectations of the designed mechanism such that clear, colored video images are obtained and other camera functions are kept sufficiently powered throughout the duration of use and implantation within a patient. Successful ‘sterilization’ tests would also need to be conducted so that the device may adhere to surgical safety protocols and therefore be approved for surgical procedures. The device must be kept sterile prior to insertion into body, such that it is safe to use during surgery and implanted in a patient’s body with minimal chance of introducing pathogens that may cause complications when contained over an intended 3-4 day span.

Conclusion

Several design objectives have been accomplished this semester with regards to the design prototype. These objectives included the construction of a working model and proof of concept for the magnetic couple system. Light source, power source, pressure switch system and camera installation were the main achievements this semester, however there is still a lot more work to be done regarding the refinement of this product. One objective that was not sufficiently addressed this semester was a self-cleansing system to remove the buildup of biological material when the device is maintained in the body over extended periods of time. This objective will be highest on the priority list of goals to accomplish for the following semester, along with the installation of an automatic lens focusing system for the camera. Size and weight of the device will be slowly reduced as progression of the design continues, however it is not expected that the device will be constructed within the parameters of having the diameter of a quarter dollar coin. This would not be feasible as the costs incurred would break the budget and machining the components for this device at this size would require skills beyond our current expertise. The next semester will be filled with fabrication ideas and implementation of improvements to the current prototype. More tests will be carried out and data recorded for design development purposes. A busy but fruitful semester lies ahead with the advent of the new year.

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Dr. Robert J. Hardie, DVM

Appendix A - PDS

Product Design Specifications

Design for a Self-contained, Maneuverable Endoscopic Video Camera

Matthew Kudek, Chelsea Wanta, Dustin Gardner, Richard Bamberg

October 13, 2008

Function: Design a self-contained, maneuverable endoscopic video camera system that can be set in place and be maintained internally for post-operative viewing. This device would allow a veterinarian to periodically monitor a patient, thus reducing the number of invasive procedures. The client works with small animals at the UW Veterinary Hospital where he currently uses a rigid scope with an attached camera head and a Xenon light source to conduct surgery. At the present time, no device allows for non-invasive post-operative viewing of the abdominal cavity. We are interested in exploring the possibilities of designing an endoscopic camera that can be deftly orientated without compromising the visual capacity of the video camera.

Client requirements: The device must:

- be able to be completely gas sterilized.
- be able to be used both during and following a surgical procedure.
- be built within a $500 budget.
- be able to capture images comparable to current laparoscopes.
- contain its own light and power sources.
- be able to store data internally, or transmit the data wirelessly.
- be easily removable from the patient.

Design requirements:

1. Physical and Operational Characteristics
    a. Performance Requirements
        i. Must be able to function within a biological environment
        ii. Camera's viewing field must be able to be clear during imaging
        iii. Must maintain its position in the body for multiple days
        iv. Must be an improvement to the current operative viewing procedures
        v. Must be able to transmit data from camera to an outside storage device
        vi. Must possess the ability to illuminate the abdominal cavity during imaging
    b. Safety
        i. No sharp edges or protrusions that may cause abrasions to surrounding tissue
        ii. Maintain its location throughout its entire stay in the body
        iii. Efficient and practical method of insertion and extraction

iv. Mechanically and biochemically resistant materials to minimize debris *in vivo*
v. Must be easy to sterilize prior to insertion into body

c. Accuracy and Reliability
i. Visual information must be transmitted post-operatively when camera activated
ii. Visual resolution must be on par or exceed that of current endoscopic cameras
iii. Method of maintaining a clear viewing field is imperative
iv. Stable construct that can remain intact and functional throughout duration *in vivo*

d. Life in Service
i. Camera must be used multiple times post-operatively
ii. Battery must last for at least one week before recharging
iii. Camera navigation system must be continuously operable

e. Operating Environment
i. *In vivo* conditions apply within abdominal cavity
ii. Constant temperature, pressure and humidity maintained
iii. Biochemical interactions make for hostile environment conditions
iv. Compression force on camera by organs when patient is mobile, post-surgery

f. Ergonomics
i. Must be easy for doctor to place camera in patient's body before viewing period
ii. Must be able to be positioned in the patient's body securely so that it will not be errantly moved from its initial location (i.e. without the assistance of the veterinarian)
iii. Must be easy for doctor to locate the device and remove from the patient's body following the viewing period

g. Size
i. Maximum size for the portion of the device located inside the patient's body is 10-25 mm in diameter
ii. Once placed in the patient's body, the device cannot cause damage to any of the patient's surrounding organs or tissues

h. Weight
i. Must weigh enough to be able to be securely fastened to the patient's body
ii. Also must not weigh too much to cause pain to patient after placement, or have the potential to disconnect from the coupling device used to secure the device in place
iii. ***Maximum weight***: 1-2 lbs

j. Materials
i. Must be able to remain within the body for several days
ii. Must be completely waterproof to protect patients from electrical components
iii. Electrical components must be tolerant of large magnetic fields

k. Aesthetics, Appearance, and Finish

i. Final unit must be small enough to fit through a standard surgical trocar

ii. Outer cover must not have any sharp edges that could puncture or otherwise damage the patient

iii. The outer cover portion that the lens faces must be transparent enough to obtain a clear picture under a low-light setting

iv. The magnetic control device that is utilized outside of the patient must be easy to use and adjust during viewing sessions

v. Camera unit should be easy to insert, fix into place, and remove with little complication

2. Miscellaneous:

a. Standards and Specifications:

The device must:

i. Be approved for experimental animal surgery

ii. Undergo several tests and clinical trials before being approved by the FDA for human use

b. Customer (Doctor):

i. Would like a device that is easy to insert, use, and remove

ii. Wants a device capable of maintaining a clean lens

iii. Wants the device to provide sufficient light for optimum viewing

iv. Wants the device to improve both surgical and post-operative viewing procedures

c. Patient-Related Concerns:

The device must:

i. Be able to be gas-sterilized between patients

ii. Limit patient discomfort while *in vivo*

iii. Not hinder the patient's daily activities

iv. Remain attached to patient during observation period

v. Be easy to remove from patient post-observation

d. Competition:

i. Pill Cam™ (ESO, SB, COLON)

ii. Steerable segmented endoscope (US Patent 7087013)

iii. Rigid endoscope

iv. Wireless endoscopic camera (WO/2008/063565)

v. Fiber optic endoscope

vi. Deflectable endoscope (US Patent 5168864)

vii. HeartLander (A Miniature Cable-Driven Robot for Crawling on the Heart) - CMU