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MARVEL IN VIVO WIRELESS VIDEO SYSTEM

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This article describes the design, optimization, and prototype testing of a Miniature Anchored Robotic Videoscope for networked Expedited Laparoscopy (MARVEL), which is a camera module (CM) that features wireless communications and control and is designed to decrease the surgical-tool bottleneck experienced by surgeons in state-of-the art Laparoscopic Endoscopic Single-Site (LESS) minimally invasive abdominal surgery. Software simulation is utilized to characterize the internal human body (in vivo) wireless channel to optimize the antenna, transceiver architecture, and communication protocols between multiple CMs. A CM research platform has been realized that includes: a near-zero latency video wireless communications link; a pan/tilt camera platform, actuated by two motors, which provides surgeons a full hemisphere field of view inside the abdominal cavity; a small wireless camera; an illumination control system; wireless controlled focus; digital zoom; and a wireless human–machine interface (HMI) to control the CM. An in vivo experiment on a porcine subject has been carried out to test the performance of the system and features, with the exception of recently added autofocus and digital zoom. MARVEL is a research platform for a broad range of experiments for faculty and students in the Colleges of Engineering and Medicine at USF and at Tampa General Hospital.

Key words: Minimally invasive surgery; In vivo wireless networking; In vivo channel modeling

INTRODUCTION

Minimally invasive surgery (MIS) is an alternative to conventional “open” surgery. MIS minimizes trauma and metabolic disruption to patients by minimizing incisions and points of access to patients’ body cavities. Laparo-Endoscopic Single Site (LESS) surgery is an advance in MIS for digestive disorders and is performed through the umbilicus, which provides access to the abdominal and pelvic cavities, and through multiple small incisions distant to the umbilicus through which trocars (i.e., small hollow valved tubes) are placed to provide access for operating instruments.

Current “state-of-the-art” commercial videoscopes (i.e., laparoscopes, endoscopes) for MIS are encumbered by cabling for power, video, and a xenon light source inside a semiflexible or rigid mechanical rod. Though these videoscopes are quite good in image quality, they are cumbersome and require a point of access into the patient, either through a separate incision or through a port in a multiport access trocar. The light, video image, and power cables of the videoscope clutter and consume space in the operative field, which is sometimes referred to by surgeons as “dueling swords.” A conventional videoscope also requires an assistant in the operating room to hold the scope and redirect it to maintain consistent and stable views of the ongoing operation. Some developing approaches to intracavity visualization bypass the rod–lens

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approach of conventional videoscopes, but the resulting video platforms still maintain a significant spatial presence within the operating cavity and require multiple points of access (e.g., incisions and/or trocars).

There is significant interest in developing advanced endoscopes for MIS (5). Research at the University of California at Los Angeles (UCLA) (2) includes a surgical "polyvisiometric" camera. This device provides a multiview video platform with simultaneous views of the surgical sites and surrounding anatomy from multiple camera angles. It attaches to the abdominal wall by pressure arms with four cameras at 90°. Other research on endoscopic cameras by Columbia University (6,9) includes two distinct prototypes, one with a single camera and another with a stereoscopic camera, allowing for the possibility of depth perception, but resulting in an increased diameter. The Columbia cameras feature a low-power, high-efficiency pan/tilt mechanism and have pinhole lenses. At the University of Nebraska, Lincoln (4,10) work has been done on a robotic camera system that moves through the abdominal cavity while tethered to a supporting cable for power and video interfacing. UNL has also performed work on cameras attached to the abdominal wall and manipulated via magnetic fields. Recent work at The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy (11) resulted in the design of three 12-mm-diameter modular robotic units: a camera, a retractor, and a manipulator unit, and the assembly and testing of the camera unit.

There is great benefit in developing wirelessly networked systems of embedded endoscopic, and other, units that are able to communicate and transmit data in real time. These devices could also eventually be designed to communicate with other embedded sensors and actuators to enable rapid, correct, and cost-conscious responses in chronic and emergency circumstances and are expected to become part of our future healthcare system, as illustrated in Figure 1. Therefore, it is essential that the efficiency of the internal human body (in vivo) environment as a transmission medium for radio frequency (RF) and microwave communication signals be characterized as thoroughly as possible. Characterization of the in vivo channel is still in its infancy, but the importance of obtaining accurate channel models is instrumental to the design of optimum communication systems and protocols for such advanced biomedical applications. In this article we describe advanced software simulation techniques that will provide complete in vivo channel characteristics to model how electromagnetic signal propagate through the human body. A significant amount of work has already been done to characterize the performance of communications and channel models for on body communications; however, the study of in vivo wireless transmission, from inside of the body to external transceivers, is just starting to get traction. In this study, we use ANSYS HFSS high-frequency electromagnetic fields simulation software (1) and a complete human body model with geometric accuracy down to 1 mm that completely characterizes the electrical properties of over 300 organs, bones, and tissues. One application where the use of software tools is especially helpful is in the design of wirelessly capable high-definition (HD) video transmitters. Wireless HD data require more bandwidth than its standard definition (SD) counterpart and therefore it is essential that the RF transmission medium is thoroughly understood to provide high-quality video imaging to the surgeon.

We also demonstrate the use of a wireless communications and control Miniature Anchored Robotic Videoscope for Expedited Laparoscopy (MARVEL) Research Platform (3) that is self-contained, internalized, and cable free to provide real-world testing capabilities of networked devices and communication protocols developed by researchers and students at the University of South Florida. The camera module (CM) of the MARVEL system includes: a near-zero latency video wireless communications link; a pan/tilt camera platform, actuated by two motors that provides surgeons a full hemisphere field of view inside the abdominal cavity; a small wireless camera; an illumination control system; wireless manually controlled autofocus; postprocessed digital zoom; and a wireless human–machine interface (HMI) to control the CM to meet surgical requirements.

This research is the first step in developing semi-autonomous wirelessly controlled and networked laparoscopic devices to enable a paradigm shift in minimally invasive surgery and other domains such as Wireless Body Area Networks (7).

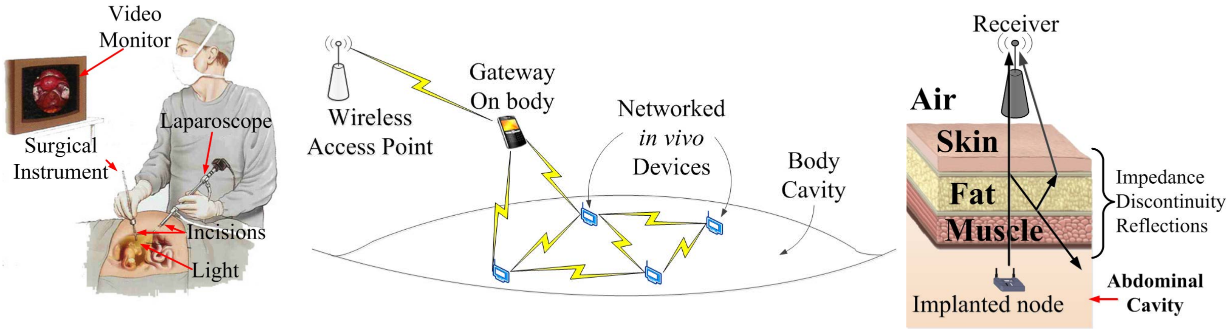

Figure 1. Minimally invasive surger (left), in vivo wireless networking (center), and in vivo multipath (right).

IN VIVO CHANNEL MODEL

Overview

The in vivo channel is very different from the classic multipath communication medium (Fig. 2). Since the electromagnetic wave is passing through different media that have vastly different electrical properties, the wave propagation speed is significantly reduced in some organs and may induce significant time dispersion (propagation delay that varies with frequency) that is different with each organ and body tissue (Fig. 2).

The simulated in vivo channel model was derived using the ANSYS HFSS high-frequency electromagnetic field simulator. This software calculates the total RF fields in 3D that are generated from arbitrarily designed and placed radiating antennas in the simulated environment over a wide frequency range. ANSYS also provides a physically and electrically accurate human body model that can be used to model the RF field interactions with human body tissues in HFSS. The model includes over 300 muscles, organs, bones, and other tissues with a geometrical accuracy down to 1 mm. Frequency-dependent material parameters (conductivity and permittivity) for each organ and tissue are included in the model, accurate from 20 Hz to 20 GHz. Figure 3 shows the CAD drawing of the HFSS human body model used to derive the in vivo channel model; side view of a torso and a cross-sectional top view are shown.

Figure 4 shows the attenuation of an RF signal that is transmitted from an antenna inside the human body to an external antenna. The transmitting antenna is located inside the abdomen of the human body model with a transmission path of 30

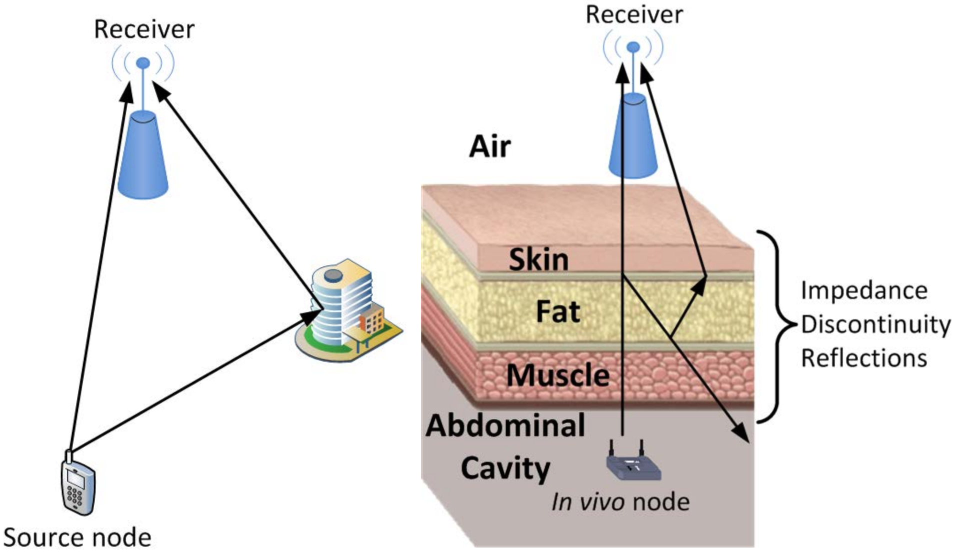

Figure 2. Classical RF channel model (left) and in vivo channel model (right).

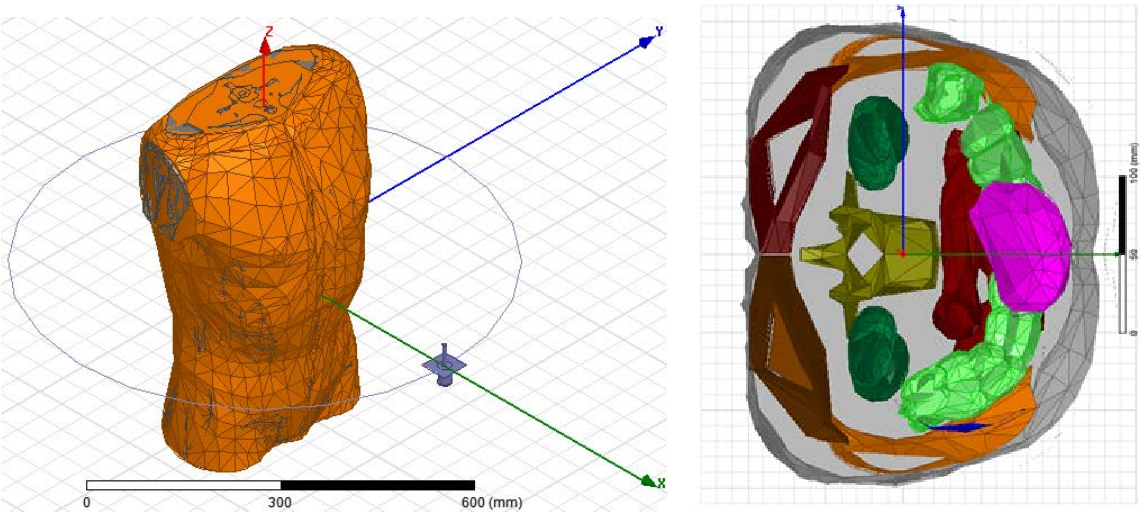

Figure 3. HFSS human body model: (left) torse and external antenna; (right) top view cross cut showing internal organs, muscles, and bones.

cm (9 cm inside of the body) to the external antenna, which is located at the same height in front of the abdomen as the transmitter. The plot of the attenuation of a signal through free space is also shown for comparison. It can be observed that besides a significant increase in attenuation, the attenuation rate is not constant with frequency, as is the case with free-space transmission losses. These results show that signal attenuation through the human body is vastly different form classical models and proves the need for accurate characterization for communication system development.

In Ketterl et al. (8), we presented the impulse channel response (CIR), which was calculated from

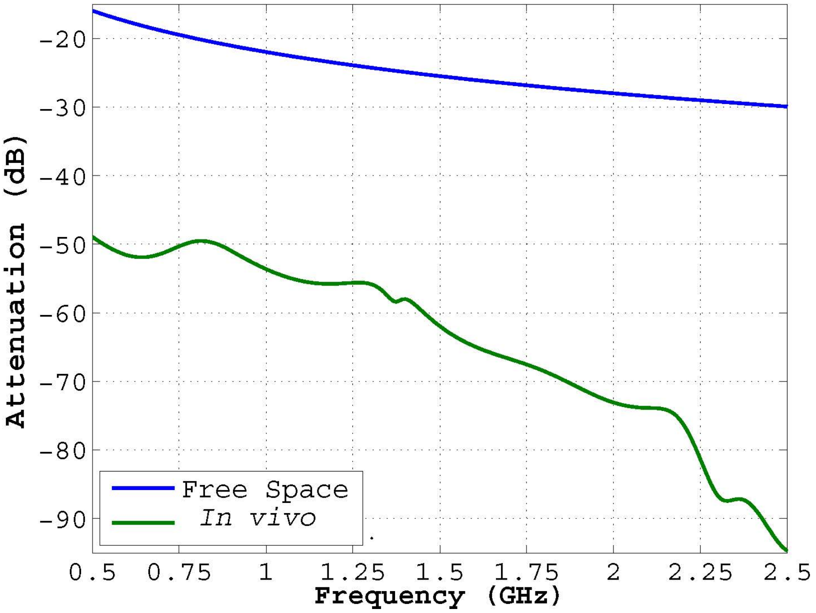

Figure 4. Simulated RF signal loss versus frequency through the human body and in free space.

the attenuation data found in the in vivo simulation experiments. A CIR provides a mathematical description of how a transmitted signal is affected in the time domain as it travels through the channel. The CIR therefore contains all the necessary information to characterize how a communication system will perform when operating in a certain channel. We compared the calculated CIRs of signals traveling through the side, front, and back of the body and found through these channel impulse calculations (Fig. 5), and found that the dispersion through the body is greatest when the signal passes from the inside through the abdomen of the body. The higher dispersion is most likely due to the fact that the RF signal encounters more organs (stomach, intestines, bladder, etc.) as it traverses through the abdomen that present a greater amount of frequency-dependent variations to the signal.

These results show the importance of developing highly accurate channel models for the human body as a RF transmission medium, which will allow us to refine and utilize these channel models so that external receivers can be optimally placed, and optimal radio transmitter and receivers can subsequently be designed. Furthermore, the results obtained will be used to develop reliable communication algorithms and protocols for networked embedded MARVEL units.

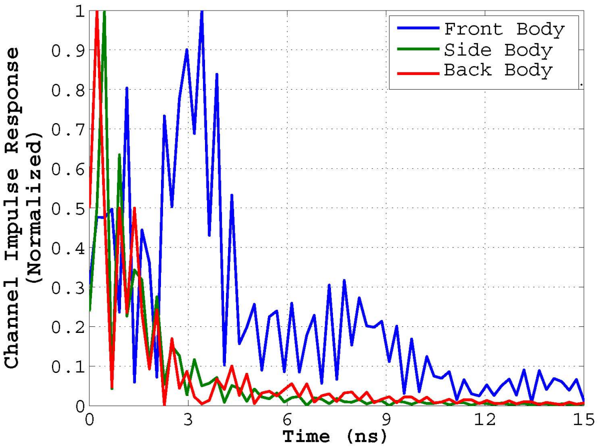

Figure 5. HFSS channel impulse response for the human body for different locations of the receiver.

High-Definition Video Transmission Design and Modeling

An example of how the in vivo channel model can aid in the development of optimized communication devices is the transmission of HD video through the human body. Many challenges arise when attempting to transmit in vivo wireless HD: the output of most HD sensors is digital with data rates above 1 Gbps, which would require large bandwidths to modulate and transmit wirelessly; bit rate reduction through software compression could be utilized to reduce the required transmission bandwidth, but at a cost of introducing undesired video latency; biological tissues are very dispersive to RF signals (dielectric and conductive properties vary with frequency), which can cause signal distortion during HD transmission.Initially, HD video transmission will convert the raw digital HD signal to its three analog components signals (Y, Pb, Pr) and frequency multiplexed onto a single carrier using frequency modulation (FM). The advantage of this approach is that bandwidth requirements are reasonable (<100 MHz), signal processing is simplified, and the complexity of the transmitter and receiver is minimized.

The system block diagram of the proposed HD transmission of the frequency multiplexed analog component signals is shown in Figure 6. Before actual implementation and testing of the proposed concept, software simulations were performed where the drive signals used in the simulation were captured HD analog outputs from a HD video camera with Y, Pb, Pr outputs. The analog components were FM modulated to carrier frequencies of 1.9, 1.03, and 1.06 GHz and transmitted on a single channel in the simulation.

Once a channel model has been derived from simulations, it can be implemented into the system design to model the signal behavior of the multiplexed analog HD signal after it has been transmitted through the body model using the system architecture shown in Figure 5. The input and output signals were compared in the software and it was observed that very little distortion and reduction in signal quality of the received signal occurred after transmission through the human body in simulation. Figure 7 shows a portion of the analog Y component comparing the transmitted

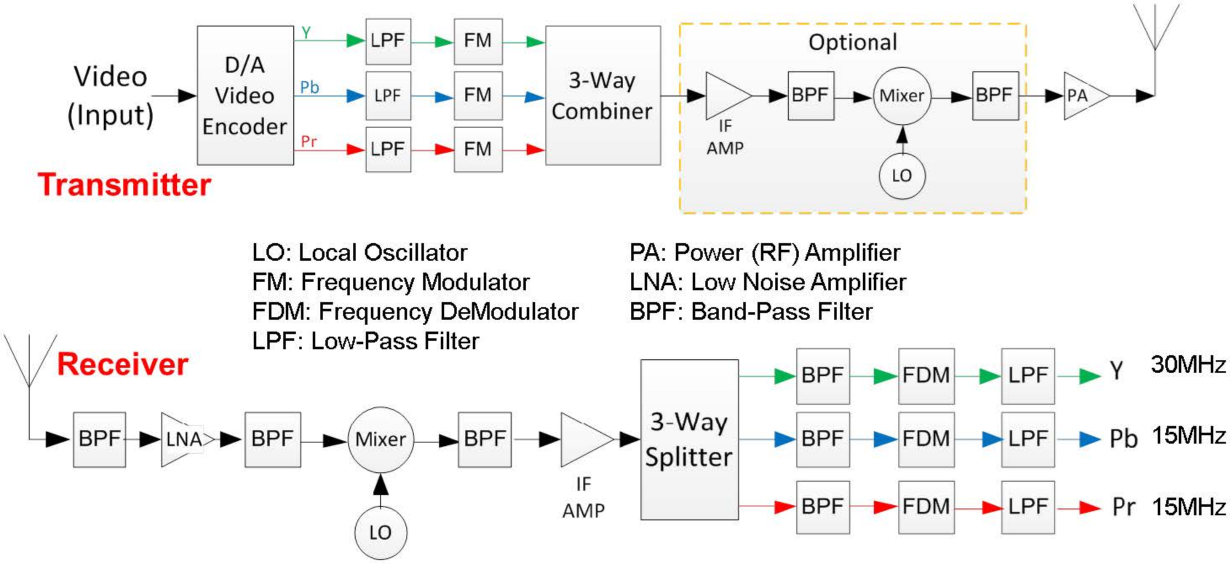

Figure 6. Analog HD video transmitter and receiver architecture.

and the reconstructed received signals. Very little latency (~0.1 µs) can also be seen in the plot.

MARVEL CONCEPT AND DESIGN

MARVEL System Overview

The MARVEL System consists of a wireless HMI and a wireless laparoscopic CM attached to the abdominal wall as shown in Figure 8. An insertion/removal tool (IRT) (not shown) will be used to i) insert the CM through a trocar port, ii) attach the MARVEL CM to the abdominal wall, and iii) remove the CM on completion of the operation. The IRT will i) supply power to the CM during insertion and removal, ii) align the CM so the illumination and video imaging subsystems enter the trocar port first, providing video imaging during the insertion process, iii) secure the needle within the IRT to preclude inadvertent needle contact during insertion and removal, iv) rotate the CM to a

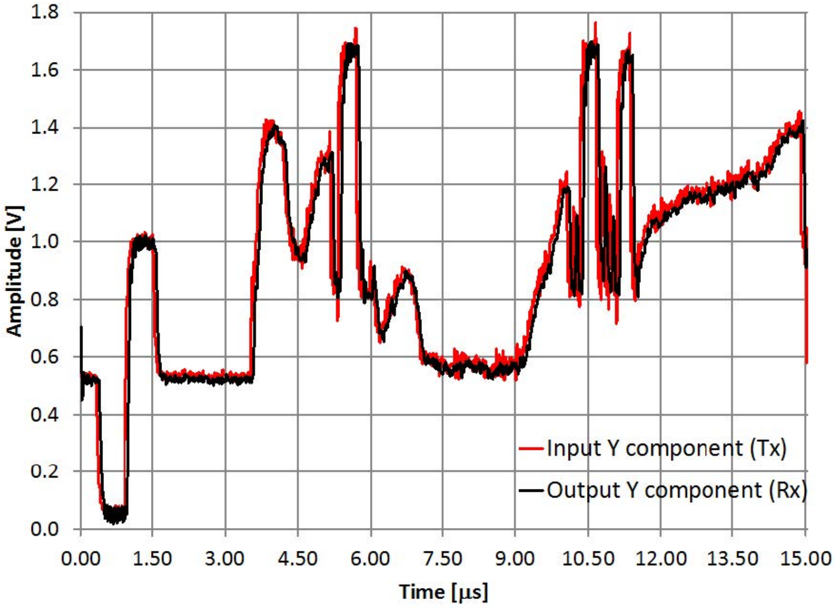

Figure 7. Comparison of the input Y component at the transmitter (Tx) and reconstructed output form simulations performed in ANSYS Designer.

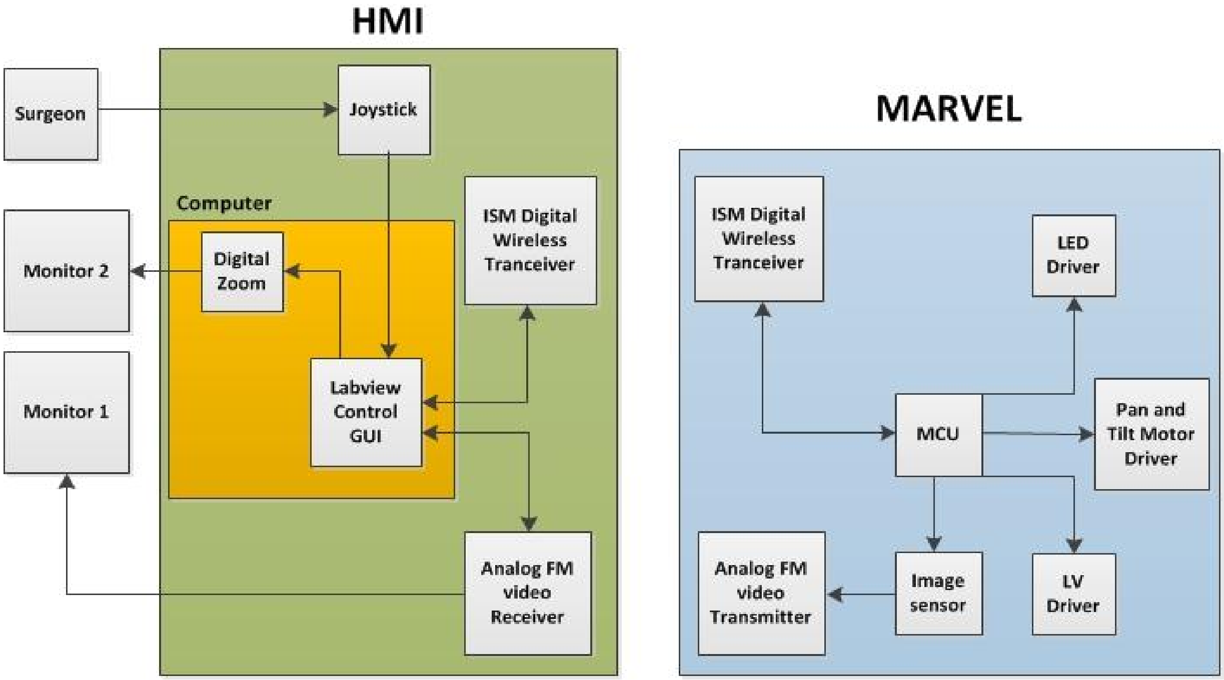

Figure 8. MARVEL camera module after attachment to abdominal wall.

position perpendicular to the abdominal wall, and v) push the needle through the abdominal wall holding the CM in place while the attachment module (AM) secures the CM in place. Power is supplied to the CM by the AM, allowing uninterrupted CM operation.

The surgeon interacts with the system through a standard joystick and a Labview application running on a standard computer. The joystick controls direction of motion of the CM through the available hemisphere of motion, and the velocity of pan and tilt motion. Every command from the joystick is interpreted to specific control instructions that are pushed out into a datagram. The instructions are then relayed to a 900-MHz band ISM digital transceiver where they are wirelessly transmitted to the MARVEL (CM). The wireless datagram is processed by the embedded microcontroller (MCU) in the CM, and divided into pan, tilt, light intensity, and image sensor control commands. For every command, the MCU drives control signals for all of the internal modules. The wireless video from MARVEL is continuously transmitted through an analog wireless interface to the wireless HMI and displayed with near-zero latency on high-resolution monitors. A block diagram of the MARVEL control system is shown in Figure 9.

MARVEL has been designed to address the following functional requirements:

10 × 42-mm camera housing platform
Wireless actuator control
Wireless illumination control
Enhanced view inside abdominal cavity
Needle power and anchor subsystem
Wireless and cable-free videoscope
Wireless HMI
1080 p high-definition video, 30 fps, near-zero (1 ms) latency displayed video

In order to design a reusable modular research platform where new functionality can be added and tested efficiently, a 3× size model was designed, taking care to ensure that the electronics could fit in a 1× (~10 mm) commercialized CM. The 3× MARVEL CM is 105 mm long with a diameter of 30 mm.

A MARVEL CM, as illustrated in Figure 10, is composed of five subsystems: the illumination subsystem provides light inside the abdominal cavity,

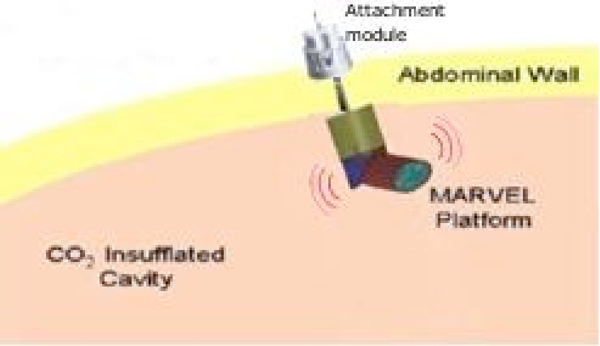

Figure 9. Block diagram of the MARVEL control system.

the vision subsystem provides optimal focus range through the use of a fixed lens with a remote manually controlled auto-focus lens and video resolution, the wireless communication subsystem handles the control commands and video between the device and the HMI, the embedded control subsystem handles the control decision making for the device, and the attachment needle power subsystem secures the CM to the abdominal wall and powers the CM.

The vision subsystem shown in Figure 11 includes the lens, the lens holder, and the video image. Additionally, the system is optimized with a manual auto-focus feature using a voltage controlled variable lens. This liquid lens uses a unique, patented technology to transform a simple liquid crystal (LC) cell into a variable focus lens (9). This device is a replacement for mechanically moving lens solutions. Lens focus is controlled by applying a small control voltage to dynamically change the refractive index of the material that the light passes through. The block diagram of the vision subsystem control feature is shown in Figure 12.

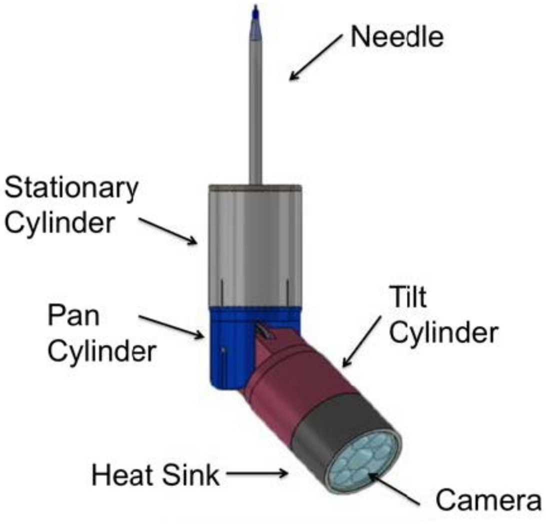

Figure 10. MARVEL: CAD model of the camera module.

The CM vision subsystem also has a digital zoom capability. Zoom is provided through software that postprocesses the transmitted image by expanding the pixel area of view of the original image. This feature will also be remotely controlled by the surgeon using the CM control joystick. Since standard definition quality video is being used in these initial tests, the zooming range will be limited due to losses in picture quality at higher zooms. Therefore, it is critical that high-definition video be implemented in future CM devices.

Interconnection and Wireless Communication Subsystem

The MARVEL CM is comprised of five PCBs in a modular design (Fig. 13). Each PCB has two connectors that allow for easy integration of new and/or additional designs into the system. The interconnection system provides two digital control buses throughout the PCB stack.

MARVEL uses two different links for wireless communications. The first link is for control a second wireless transmitter that provides an analog link between the video image sensor and an external receiver with near-zero latency. Since the PAL video signal requires less than 8 MHz of bandwidth, a frequency modulated (FM) transmitter was designed with a carrier frequency in the 1.1 to 1.3 GHz range and an output power of 10 dBm. The transmit frequency is easily tuned to any point within the chosen frequency range. This ability allows the use of more than one MARVEL CM during a surgical procedure, whereby each CM transmits at a different frequency with enough band separation to avoid interference. A detailed description of the MARVEL research platform can be found in (3).

EXPERIMENT

An in vivo experiment was carried out in the USF Vivarium, and illumination, image quality, wireless communication, CM sealing, and wireless control of the CM was tested. In this initial test, manual auto-focus and digital zoom were not implemented but will be tested in the future. Two

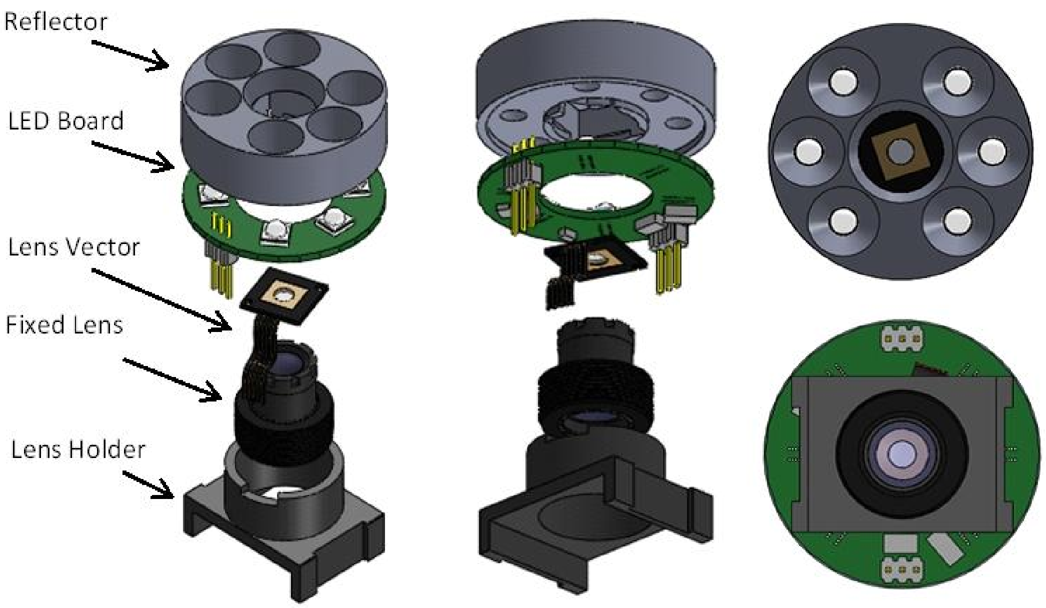

Figure 11. Vision Subsystem CAD model.

CMs (Figure 14) were inserted into a porcine subject and simultaneously tested. A "balloon," shown on the left side, was used to seal the space between the cylinders.

Two CMs were controlled simultaneously by the surgeons and real-time images of internal organs were transmitted and recorded (Fig. 15). The surgeons intuitively adapted to the positions of each CM and effortlessly switched from one CM to the other, demonstrating that a physical alignment of each CM to the viewing perspective of the surgeon, at least in this case, was unnecessary. Future work with multiple CMs in vivo will include a positioning and alignment procedure to enable pixel edge matching of multiple images creating a panoramic video display view of the surgical site.

Normal physiologic motion of the porcine subject did not affect image stability. Future work will integrate motion detection and image stabilization to compensate for patient motion caused by the surgical team.

CONCLUSION

It has been demonstrated that optimization of networked robotic endoscopic systems requires a broad range of methodologies that when integrated together have the potential to significantly advance

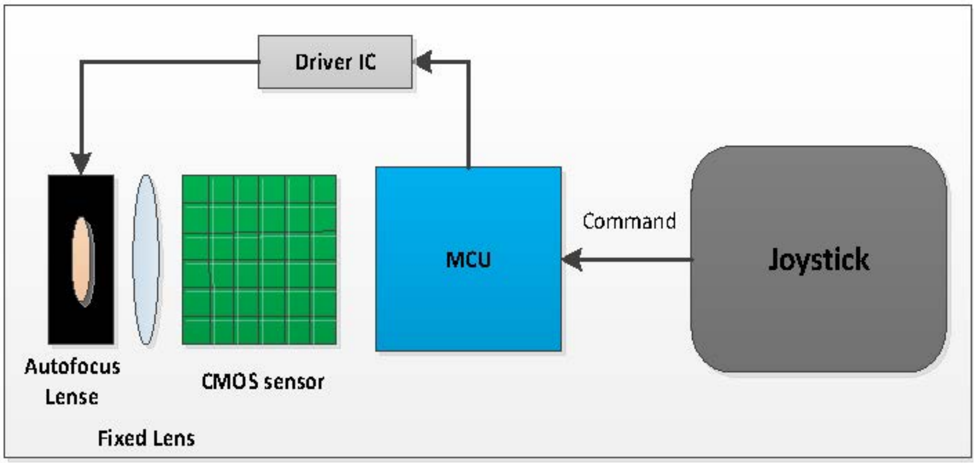

Figure 12. Block diagram of the vision subsystem control.

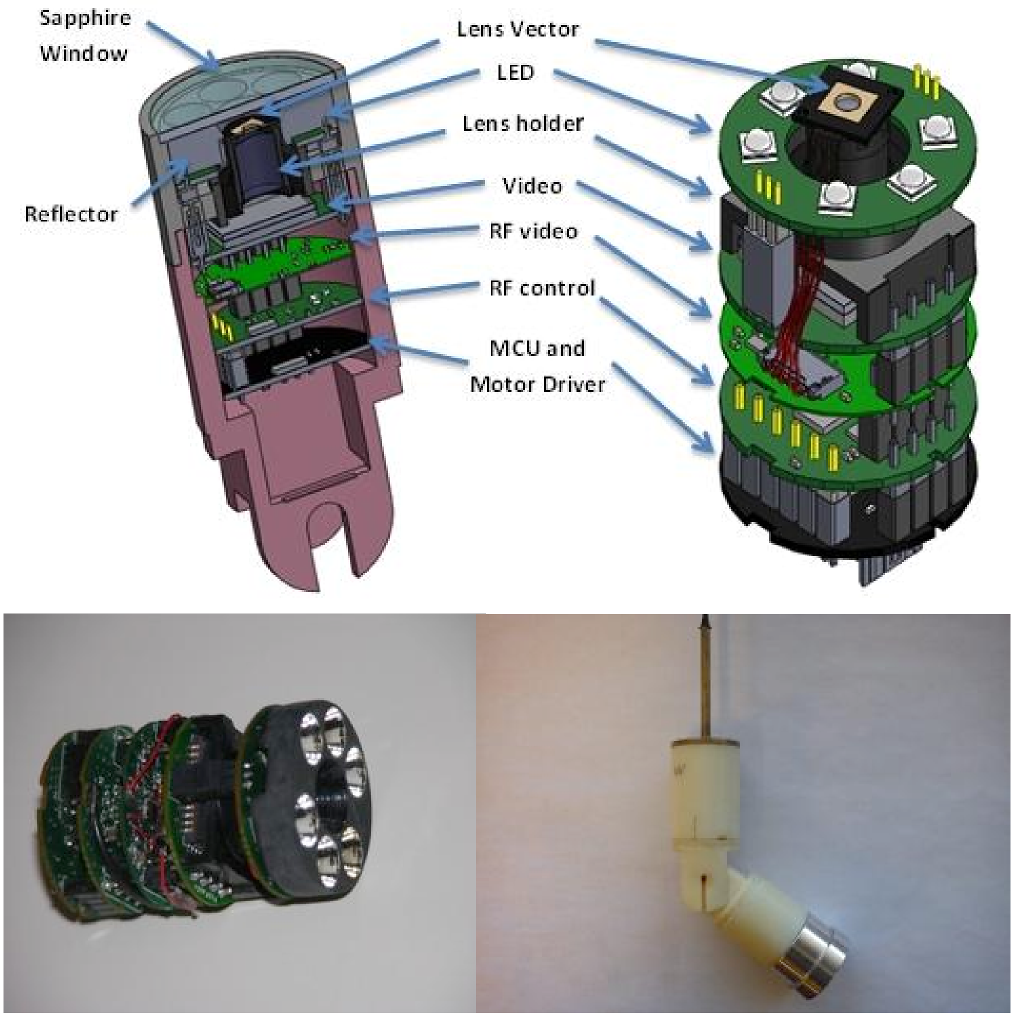

Figure 13. Top: CAD PCB description. Bottom left: MARVEL CM PCB research platform electronics stack. Bottom right: Assembled tilt cylinder.

the field of minimally invasive surgery. The methodologies we demonstrated include software simulation, research platform development, and real-world testing.

Our knowledge of how wireless signals interact with the human body when traveling internally or transmitted from the inside to the outside of the body is still very limited. If reliable communication and data transfer between imbedded medical devices, such as camera units, sensor, and actuators is to be achieved, accurate in vivo channel models will need to be developed. Channel modeling through software simulations is one way of calculating highly accurate channel models; much more accurate than using physical models that do not provide frequency dependent electrical properties.

With the use of the ANSYS HFSS simulation tool and its complete human body model, we showed the simulated dispersion characteristics as a signal travels from an internal transmitter to an external receiver. We also presented how this software tool can be used to simulate the behavior of high-speed signals, such as analog HD video, and can be used in other RF system simulators to further optimize the transceiver architecture. These results show the importance of developing highly accurate channel models for the human body as a RF transmission medium, which will allow us to

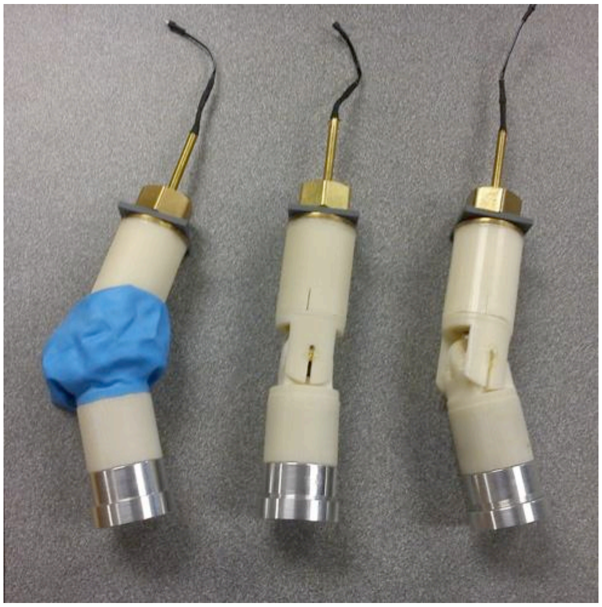

Figure 14. Three MARVEL CMs with their respective attachment modules and power cables.

refine and utilize these channel models so that external receivers can be optimally placed, and optimal radio transmitter and receivers can be subsequently designed.

The research platform we developed, a wireless robotic laparoscopic imaging system (MARVEL), has been implemented with the goal of advancing minimally invasive surgery. The complex system design of the MARVEL platform has involved research in the areas of robotics, wireless communications, heat transfer, image processing, illumination engineering, and embedded systems with the goal of implementing a broad range of functionality required for laparoscopic surgery (remote motion control, wireless video, and illumination) in a single device.

To demonstrate the real-world capabilities of the research platform, two MARVEL CMs were successfully tested simultaneously in vivo in a porcine subject by a team of surgeons. The two CMs were inserted into the abdominal cavity of the porcine test animal, demonstrating individual control of each CM while simultaneously transmitting good quality images from each CM. Future work to improve the capabilities of the MARVEL modules will include wireless HD image transmission (again, with near-zero latency), autofocus, zoom, and image stabilization.

Furthermore, the robotic system described in this article is a proof of concept research platform designed to support a broad range of experiments in a range of domains for faculty and students in the Colleges of Engineering and Medicine and at Tampa General Hospital. This research is the first step in developing semiautonomous wirelessly controlled and networked laparoscopic devices to enable a paradigm shift in minimally invasive surgery and other healthcare domains.

Figure 15. Two MARVEL camera modules are shown (left). Image of porcine intestines taken by a MARVEL CM (right). The surgeons have independent control of each CM.

ACKNOWLEDGMENTS: A color version of the images can be found at http://iwinlab.eng.usf.edu. The authors declare no conflict of interest.

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