

Virtually Transparent Epidermal Imagery for Laparo-Endoscopic Single-Site Surgery

Yu Sun, Adam Anderson, Cristian Castro, Bingxiong Lin, Richard Gitlin, Sharona Ross, and Alexander Rosemurgy

Abstract—This paper presents a novel design, and prototype implementation, of a virtually transparent epidermal imagery (VTEI) system for laparo-endoscopic single-site (LESS) surgery. The system uses a network of multiple, micro wireless cameras and multiview mosaicing technique to obtain a panoramic view of the surgery area. This view provides visual feedback to surgeons with large viewing angles and areas of interest so that the surgeons can improve the safety of surgical procedures by being better aware of where the surgical instruments are relative to tissue and organs. The prototype VTEI system also projects the generated panoramic view on the abdomen area to create a transparent display effect that mimics equivalent, but higher risk, open-cavity surgeries.

I. INTRODUCTION

Minimally invasive surgery (MIS), by utilizing small incisions in the body for placement and manipulation of surgical equipment, has been widely adapted and performed as an alternative to open-cavity surgery because it provides a tremendous public benefit for minimizing trauma, shorter hospitalizations, and faster recoveries; however, these operations often take longer to complete than equivalent open operations, with associated patient risks to contamination. The MIS procedure also poses challenges to surgeons in many aspects: limited view and limited number of view points fixed by the insertion sites, an overhead monitor that displays the video from the videoscope but does not have a consistent and clear indication of orientation of the video, and long-stick surgical tools which transduce less touch sensing and limit hand dexterity. MIS requires significantly more training than regular open surgery, which may discourage surgeons to master the skills for MIS especially in remote and developing regions or less than ideal surgical venues.

MIS has stimulated much interest in Natural Orifice Transluminal Endoscopic Surgery (NOTES) or Laparo-Endoscopic Single Site (LESS) surgery - recently developed MIS techniques - whereby "scarless" abdominal operations can be performed with multiple endoscopic tools passing through a

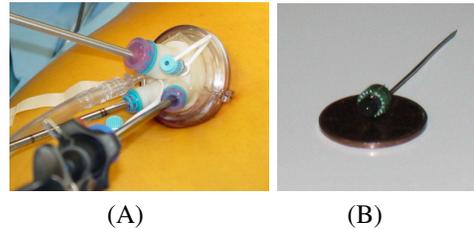


Fig. 1. (A) A multiport trocar placed through the umbilicus during a LESS surgery. (B) A prototype wireless endoscope.

natural body orifice, such as the umbilicus, as the insertion point. Each year thousands of patients enjoy the benefits of these types of non-open surgeries; however, LESS surgery poses even more challenges than traditional MIS. First, there is only a single insertion site with usually a 12-15mm multiport trocar that has up to four insertion ports (Figure 1). This creates a bottleneck for surgical tools through the natural orifice where graspers, cutters, videoscopes, and insufflation tubes all compete for limited available space. Second, since the videoscope can only be inserted through one site, the viewpoint is fixed and it is difficult to maneuver the videoscope to provide a good view of the entire area. Though there are advances in MIS equipment, such as flexible tip endoscopes or robotic surgical platforms [1][2], surgeons often have to rely heavily on their experience to sense the locations of tools relative to the internal surgical area.

Either in traditional MIS surgery or robotic aided MIS surgery (e.g. the da Vinci system), the images displayed to the surgeons are all done via endoscopes. The state of the art commercial videoscopes (i.e. laparoscopes, endoscopes) for MIS have, and are encumbered by, cabling for power, video, and a xenon light source inside a semi-flexible or rigid mechanical rod. Many surgeons have expressed their disappointment with the fundamental limitations of these scopes based on their experience with hundreds of MIS operations. The limitation of the viewpoint and view angle of the rigid endoscope requires the surgeons to be aware of where the surgical tools are relative to tissue and organs without seeing them, which pose a significant safety hazard for patients. The misinterpretation of the image orientation on the overhead monitor also poses a significant problem to the hand-eye coordination for the surgeons and requires great skill and training to master and compensate. Our work is to limit the impediments of MIS surgery while making it more similar to open surgeries.

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Y. Sun and B. Lin are with the Department of Computer Science and Engineering, C. Castro and R. Gitlin are with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 U.S.A. yusun@cse.usf.edu, bingxiong,cacastr3@mail.usf.edu, richgitlin@usf.edu

A. Anderson is with the Department of Electrical Engineering, Brigham Young University, Provo, UT 84602 U.S.A. ala28@byu.net

S. Ross and A. Rosemurgy are with the Tampa General Hospital, Tampa, FL 33606 U.S.A.

Various approaches [3][4][5][6] for visualization in image-guided interventions have been proposed to achieve a "see through" effect by applying the concept of augmented reality. The benefits of such an approach include enabling the surgeons to focus on the surgical site without dividing his or her attention between the patient and a separate monitor and providing hand-eye coordination as the surgeon observes the operation room. For example, a CT image of a patient overlaid with the patient and appearing at the location of the actual anatomy was proposed in [7]. Usually the location of the surgery tool is tracked and graphically drawn as a virtual tool and displays on the CT or other images based on the tracking to guide surgeons to operate [8][9]. If the mapping does not align correctly with the patient and the surgical tool, the visualization could be dangerous. It is very challenging to achieve satisfactory, accurate alignment between the tracking data and the image since it requires precise models of the patient and models of instruments.

We present a VTEI approach that composites the videos from several micro wireless cameras where it is not necessary to track the surgical instruments or align them with the mapping image since the proposed system captures the surgical anatomy and the surgical instruments at the same time and in the same frame. This approach does not encounter the difficult instrument mapping and alignment problem seen by other advanced augmented reality approaches. The long-term goal of our work is two-fold: 1) we develop an image-based rendering approach to mosaic the videos from wireless scopes to form a panoramic view of the surgical area and then project this panoramic video onto the outside abdominal wall and 2) we plan to evaluate and iterate this approach in a surgical training environment at Tampa General Hospital.

II. SYSTEM CONFIGURATION

The goal of the system is to provide visual feedback to the surgeons about where the surgical instruments are relative to the in vivo organs. A network of wireless cameras are placed inside the abdominal wall via serial insertion through the trocar. Since the cameras are anchored on the abdomen with a thin needle ($< 1mm$), they leave no scar. With CO₂ inflation, the abdominal wall changes to a dome shape. The inflated abdominal cavity provides a free space for surgical instrument to be operated in. For example, Song et al. [10] founded that with 12 mmHg pressure the volume of abdominal cavity is $1.27 \times 10^{-3}m^3$ on average. In our current system, three cameras are attached on the abdominal wall to monitor the activities in the whole working space.

The panoramic video merged from the wireless cameras are then processed to have the correct orientation so that abdomen projection provides a correct hand-eye correlation for surgeons. Figure 2(A) shows a graphic demonstrating VTEI in action.

Figure 2(B) is a test platform setup with a surgical simulator, which has a simulated inflated abdomen, plastic internal organs, a LESS multi-port trocar with a couple of laparoscopic surgical instrument. Three wireless cameras are anchored on the abdomen with a LED light source. The

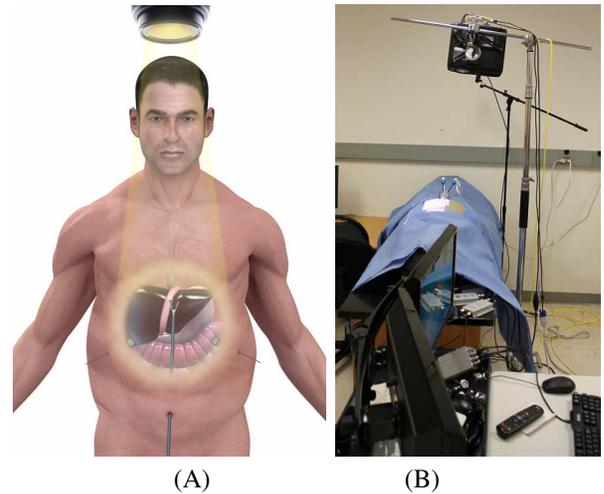


Fig. 2. (A) shows a graphical representation of VTEI as "see-through" imaging while (B) shows the prototype setup housed at the University of South Florida campus.

wireless video signals are collected with three receivers and a 4-channel USB Sensoray 2255S frame grabber. The images are processed with a Core i7-950 Quad-Core 3.06GHz PC with three Nvidia GeForce GTX 470 video cards and then projected on the abdomen with a BenQ MX761 XGA 3D DLP Projector projector with a Point Grey Flea video camera as distortion feedback.

A. Wireless Endoscope

The key sensor interface between surgeons and the operating environment is the endoscope which, traditionally, is held by an operative assistant and manipulated as dictated by the surgeon. This traditional method requires access through one of the rare commodities of NOTES/LESS surgery - trocar space. The proposed VTEI work takes a different approach to these surgeries by the design, fabrication, and implementation of wireless endoscopes that leave the trocar commodity open for other surgical equipment while still providing the necessary images for VTEI vision. Multiple versions of the wireless endoscope have been developed based on need and size requirements and also the basic parameters of the sensor: resolution, illumination, and modulation. Contrary to popular design problems, power is less of an issue since the backing needle used to attach the tools within the abdominal wall can double as a power interface.

1) *Resolution*: Resolution is the first quantity most think of when discussing video sensors. It is important that the resolution be sufficient to provide the fine tissue details necessary for surgeries. The sensors used in this work were provided by OmniVision Technologies, Inc and then integrated into custom-built PCBs:

- OV6920 is a 320x240 pixel analog NTSC video sensor with a 2.1mm \times 2.2mm footprint. A picture of this camera is shown in Figure 1(B) with a backing needle that is pushed through the abdomen wall for attachment purposes.

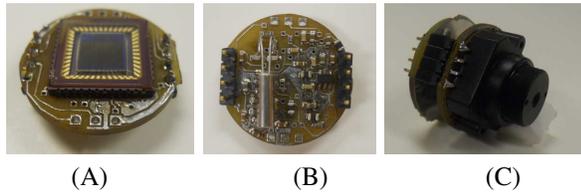


Fig. 3. (A)(B) The image sensor board of the custom-built wireless endoscope front and back. (C) The assembled wireless endoscope with a RF transmission board and a camera lens.

- OV7949 is a higher resolution 628x586 NTSC/PAL analog sensor with a 14.22mm × 14.22mm footprint. This sensor is larger but facilitates wireless transmission as a good resolution with its tv-standard output. The custom-built wireless scope is shown in Figure 3. This resolution of camera was used to provide images for Figures 5.

Each of these image sensors was integrated into a prototype endoscope that was built at USF. The ideal wireless endoscope for VTEI surgeries will have 1080p resolution and fit on a round 5mm board.

2) *Illumination*: Any equipment that illuminates the surgical cavity of interest falls under the same requirements as the wireless endoscope - it must not occupy any of the precious trocar space. This is a huge challenge for VTEI since traditional wired endoscopes often have a powerful fiber-optic light source that completely illuminates the cavity. We have experimented with the following components in determining the necessary lighting for the sensors:

- UT-692NW a 250mcd (milli-candela) LED with 0603 footprint (1.6 x .8 x .6mm) built by LC-LED. Though weak illumination the small footprint allows for many LEDs to be scattered around the printed-circuit boards. These were also used for the proof-of-concept wireless endoscope in Figure 1(B).
- XLamp XM-L LED from Cree with a footprint of 5mm x 5mm. This single LED can deliver up to 1000 lumens! The size precludes integration directly with the video sensor but can easily be inserted through the trocar and attached as a separate “wireless” tool.

Additional work is being done on creating optical light-pipes that funnel the light in an optimal manner with minimal power requirements.

3) *Modulation*: While the video sensor gathers data in the form of images, the wireless portion of the endoscope must be able to transmit these images to some receiver outside the body but inside the operating room. Though details on wireless modulation methods are well beyond the scope of this paper, a key consideration of data comes down to whether to transmit digital or analog data:

- Analog transmission is far simpler to implement, requires less circuitry, and benefits from zero latency; however, analog data can also suffer from interference that may not be tolerable to surgeons.
- Digital data is the format of almost all HD video sensors. Wireless HD video is the focus of several

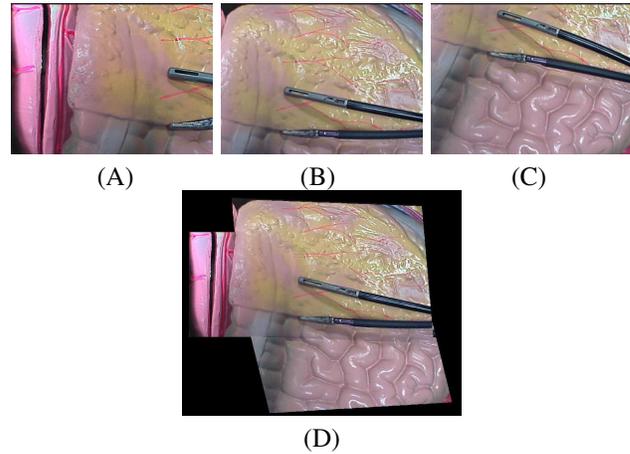


Fig. 4. (A) Image from the camera focusing on the area of interest. (B, C) Images from the cameras monitoring the pathway of the surgery tools and their surrounding organs. (D) The merged view of the whole surgical related regions from all three wireless cameras.

commercial companies (e.g. Amimon and SiBeam).

Next-generation surgeons will demand HD video for almost all surgical procedures. Commercial solutions to digital wireless HD are not yet small enough to fit within the footprint of the wireless endoscope. A possible alternative solution being explored is to use another third-party IC to convert the digital HD data to analog prior to wireless transmission. This expands the required bandwidth but can still be done to remain within the ISM bands.

III. PANORAMIC VIRTUAL VIEW GENERATION AND DISPLAY

Videos from three wireless cameras looking at the region of interest from different viewing points are stitched together with partial overlapping areas to create a seamless panoramic video with high resolution. We use scale invariant feature transform (SIFT) [11] and random sample consensus (RANSAC) [12] based matching techniques to automatically compute optimal global alignment for the mosaicing of videos from different cameras with Levenberg-Marquardt nonlinear minimization algorithm [13].

As shown in Figure 4, the video from the wireless camera focusing on the area of surgery and the videos from the cameras monitoring the surgery instrument pathway and surround organs are merged together to generate a panoramic view of the surgical related regions. The computed mapping relationship for the mosaic remains the same during a surgery if the abdomen is stationary. Otherwise, the mapping has to be recomputed when there is any motion for the abdomen (e.g. induced breathing). However, the computation can use the computed mapping result as initial point for more efficient optimization and surgical motion is relatively slow.

Before the panoramic video is fed into the projector, it is processed to prevent color or geometrical distortion for the convex abdomen surface with the feedback from the Point Grey Flea camera. The camera provides a visual feedback for projection distortion compensation and orientation

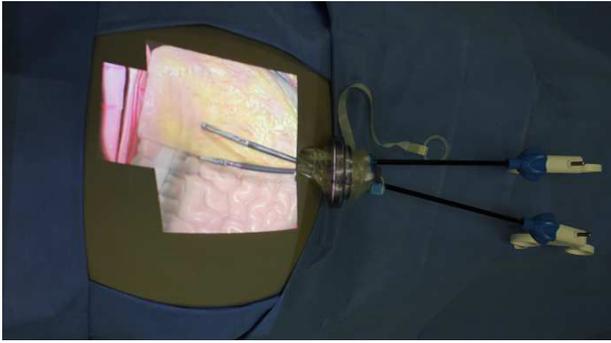


Fig. 5. The surgical area video is projected on the abdomen right above the surgical region to provide a natural hand-eye correlation.

alignment. For distortion calibration, the computer sends a checkerboard image to the projector and the camera captures the projected checkerboard image as part of surgery preparation. The locations of the checker corners in both images are automatically detected, and then a mapping between the source image and the projected image is built for future use of distortion compensation [14].

Figure 5 shows the projection result on the inflated abdomen of our surgical simulation setup with distortion compensation for the merged video. The image was taken with a natural indoor lighting condition from surgeon's point of view.

IV. RESULTS AND DISCUSSION

Our VTEI work has demonstrated a new method of perceiving the surgical area, which presents an easier and safer scar-less minimally invasive surgery. VTEI will allow MIS surgeons to benefit from the "feel" of open surgeries while maintaining the safety of LESS. The system is currently being evaluated by two MIS surgeons on our research team for surgical training.

There are many open problems to resolve before surgeons can benefit from our system on real patients. The current wireless endoscope design will be improved in terms of size and resolution while not sacrificing video delay which is unacceptable for surgeons. The geographical locations of the wireless endoscopes need to be carefully planned before surgery to provide an optimal view of the surgical regions, instrument pathway, and other related regions. State-of-the-art wired endoscopes have irreplicable functionalities, compared with fixed wireless endoscopes, with large motion range that is important for surgeons to see behind organs. How to use both an imaging system and efficient display of videos will be explored in our future work. We also plan to improve our current image-based rendering approach to generate more reliable mapping with less distortion - the current approach is very sensitive to the accuracy of feature detection. We have not achieved full automatic compensation for the alignment of the projected image with the patient, especially the organ alignment from the displayed organs to the real organs though relative placement between organs and surgical instruments is consistent. Unlike the tracking-based

augmented approaches, as the relative relations between the surgery instruments and organs are preserved in the image after image processing, even with a small level of alignment error, there poses no safety issue. However, we plan to setup a thorough experiment to study the influence of the misalignment error to surgical performance.

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