Uteraug: Augmented Reality in Laparoscopic Surgery of the Uterus

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Abstract

One of the goals of medical Augmented Reality (AR) is to reveal the hidden anatomy, such as a tumour or major blood vessels within an organ. We present Uteraug: a real-time state-of-the-art AR system for locating tumours within the human uterus in gynaecological laparosurgery. The system works by registering a preoperative volume, such as MRI and fusing it in real-time with the laparoscopic video. Several related AR systems exist for AR guidance with other organs such as the liver or kidney, however ours is the first to achieve automatic, robust and markerless registration in real-time and the first to be validated in live use in the operating room (OR). Our system is based on [3] with some important improvements to allow it to be used by the medical staff, which is essential for its wide-spread adoption. It has been improved to both reduce the time requirement for system initialization and to overcome ergonomic limitations, allowing its use by a clinician operator.

Keywords: Augmented Reality, Laparoscopic Surgery, Registration, Medical Imaging.

1 Introduction

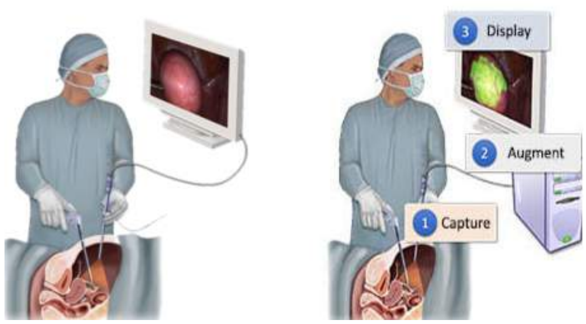

Figure 1: Laparoscopic surgery (left) and augmented laparosurgery with Uteraug (right).

Nowadays numerous diseases are treated using minimal invasive surgery to access the internal anatomy of the patient. Contrary to open surgery which requires a large incision of the abdominal wall to gain direct access to a lesion, laparoscopic surgery requires smaller incisions and is less traumatizing. The abdomen is inflated to create a working space and a laparoscopic camera is inserted so the surgeon can observe the abdominal and pelvic cavities. Compared to open surgery however, which allows the surgeon to palpate the tissues, helping them to localize tumours, locating the hidden tumours in laparoscopy can be challenging.

Our system Uteraug has been designed to assist myomectomy, which is a procedure for removing benign tumours of the uterus causing pain and potential fertility problems. Small tumours detected in a preoperative scan are often missed during the operation, as being nearly impossible to localize. These tumours will grow, possibly leading to a new surgical procedure. Using Uteraug, the surgeon is able to localize them and remove them safely in the same procedure. It has been recently shown that AR guidance using our system can significantly improve the localization and resection of tumours in an ex-vivo pig kidney study [1]. Such results suggest that the same system would also be beneficial for patients.

Uteraug has been contributed by computer vision experts and gynaecologists of the EnCoV research group who worked together to create a research prototype [3]. This first prototype correctly augments the uterus, but requires a computer vision expert to be present to manage various sub-tasks such as running the 3D interventional reconstruction, initialization and camera calibration. A new streamlined prototype was then developed that eliminates the need for a computer vision expert to be present.

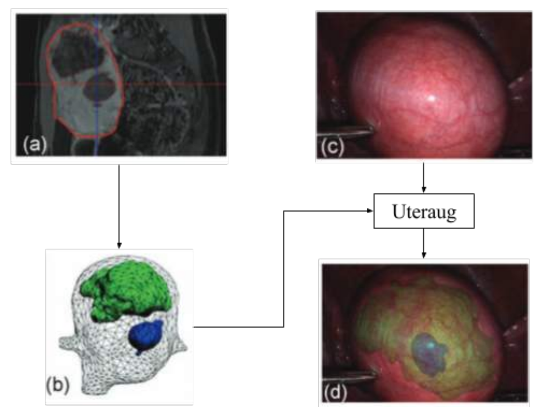

Figure 2: Overview of the Uteraug system: (a) Preoperative MRI data are segmented to obtain the organ, intra-organ tumours and external surfaces (b). Uteraug superimposes the video frame (c) with the 3D registered models (b) to obtain the augmented image showing virtual transparency (d).

Currently, Uteraug is the only AR guidance system in laparosurgery working live on a non-stationary organ. It requires no artificial markers and its robustness has been validated through several live tests in the OR. We propose to demonstrate Uteraug live at ISMAR 2017 using a realistic latex surgical training unit (see Figure 4). We believe this demonstration will showcase a very important AR application, and will open discussions for other potential medical applications.

2 System Overview

The system is divided into two main phases: a *preoperative* and an *intraoperative* phases. In the preoperative phase, the external surface of the uterus and tumours are segmented from an MRI into a 3D model (see Figure 2, (a-b)) from which a deformable biomechanical model is derived. The intraoperative phase consists of four parts:

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(a) camera calibration, (b) 3D interventional reconstruction, (c) biomechanical registration and (d) live tracking/AR guidance. All these steps are performed in the OR as soon as the surgeon finishes instrument insertion, using a streamlined Graphical User Interface developed in QT.

Camera calibration and 3D interventional reconstruction

The laparoscopic camera is calibrated using standard methods from OPENCV with views of a calibration chessboard. This is performed after tools have been inserted and immediately before AR guidance is required. We assume the laparoscope operator does not change the camera's focus during the AR guidance. Camera calibration can thus be performed once and the intrinsics kept fixed. During the 3D interventional reconstruction step, the external surface of the uterus is reconstructed from a set of keyframe laparoscopic images, extracted from a short *exploratory video* lasting approximately 30 seconds. During this video the uterus and the laparoscope are moved to acquire a range of images from different viewing angles. The movement of the uterus is performed using a standard instrument called a cannula, which does not induce significant deformation. It is therefore possible to reconstruct the surface using rigid Structure-from-Motion (SFM) techniques. Because the uterus moves relative to background structures, we perform a very coarse manual segmentation using a small number of keyframes (no more than 12). Here a user draws a circular mask to surround the organ, and also marks out any visible occluding contours. These contours are used later in part (c). The use of a tactile screen eases the annotation process, which can be done in under two minutes. Once completed off-the-shelf SfM techniques are used to create a dense texture-mapped 3D reconstruction using the THEIA and PCL libraries.

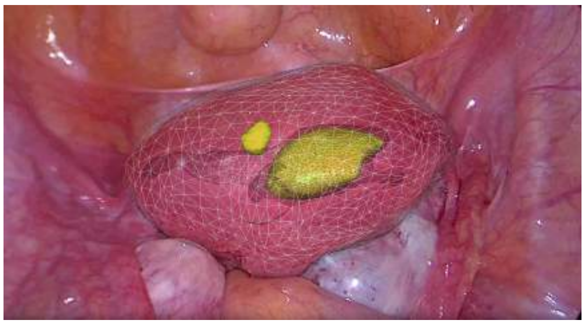

Figure 3: Final Augmented Reality of the uterus: external surface is covered with a white mesh, the two internal tumours are showed in yellow and the uterine cavity is showed by a black mesh.

Biomechanical registration

Once the intraoperative model of the uterus is computed, the 3D preoperative organ model is non-rigidly registered to the 3D interventional reconstruction. Resolving this registration is challenging because the shape of the organ can significantly change between its preoperative and intraoperative states, mostly due to posture and pressure change inside the abdominal cavity. We solve this with a new robust method based on deformable Iterative Closest Point (ICP), which we described in [2]. Once solved, the location of all the internal structures (tumours, vessels, and uterine cavity) are predicted by the registered biomechanical model.

Final Augmented Reality results

After the biomechanical registration (c), the uterus remains approximately rigid. Thus, we can decompose the registration problem into an initial non-rigid *reference* registration, which is done *once* in part (c), and a rigid *update* registration. The update registration is performed in real-time [3] using a feature-based RANSAC approach. To achieve high robustness to viewpoint change, we efficiently register each new frame against features from *all* images used as input for the SfM reconstruction. We use SURF features because they balance performance and speed. RANSAC eliminates false matches and after completion the pose is estimated using a *Perspective-n-Points* method. We use a small amount of temporal averaging to eliminate perceivable jitter.

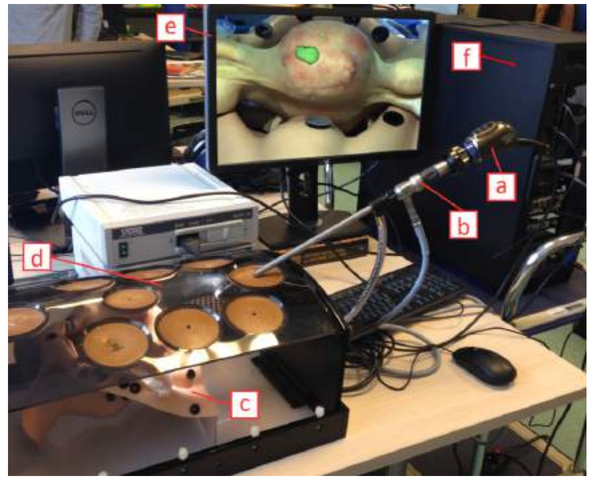

Figure 4: Presentation of the demo set-up: (a) laparoscopic camera, (b) optical fiber, (c) phantom of the uterus, (d) pelvic trainer, (e) display screen, (f) desktop computer.

Once the pose is estimated, we transform the organ's internal structures to camera coordinates and render them using OpenGL (Figure 3). When AR is active, the surgeon can visualise the internal structures and plan the best access path. Once the surgeon is ready to start resection, the AR system is deactivated because the nearly rigid hypothesis is no longer valid. This is nevertheless not a major problem because at this point the job of AR guidance is essentially finished. Currently, the system requires 5 to 8 minutes to complete parts (a-c), then part (d) runs at 10-15 fps with GPU implementation. We have found this is sufficiently high for real usage [1].

3 CONCLUSION

We have outlined a complete markerless AR-guidance system for improving laparoscopic gynaecological surgery. The system has been used in the OR and is sufficiently advanced to be demonstrated live. This system will draw interest in this important application of AR and will spur discussions about the future use of AR in minimal invasive surgery.

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