Trends in AR and Medicine

John P Cavalieri
Umass Lowell
John_Cavalieri@student.uml.edu

ABSTRACT
This article presents an investigation into trends in augmented and virtual reality and medicine--specifically neurosurgery and heart surgery. Applications in AR assisted surgery and VR surgical training are examined from the current literature. The mathematics of marker-based tracking in AR assisted surgery is reviewed.

Author Keywords
Augmented Reality; Neuroscience; Medicine; Surgery

INTRODUCTION
It is expected that AR/VR technologies will easily generate $80 billion in revenue in the coming years [7]. Leading the way in AR/VR development are game developers, the military, and medical researchers. Medical researchers have envisioned AR/VR applications that will reshape patient experience, improve clinical outcomes, deliver new therapies and provide better surgical training [7]. Surgical procedures are often difficult to master, and the primary form of practice is on a living human patient—not necessarily an optimal process. To improve this process, medical researchers developed surgical simulators ranging from relatively simple SIM-K for knee replacements to extremely complex NeuroVR for brain surgery [8]. These simulators are giving medical students more opportunity to practice procedures and allows physicians to rehearse complicated procedures. In addition to simulation, AR/VR provides novel visualizations of medical data. At the Mayo Clinic, researchers wear Occulus Rift headset to explore 3D models from MRI and CT scans.

Researchers are also examining how AR/VR can improve patient experience. Boston's Tufts Medical Center is developing VR application for patients during pre-surgery to detail the surgical process and explore the operating room [9]. The idea is to reduce anxiety associated with these procedures and improve patient care. Further uses of AR/VR on the patient side include novel treatments and therapies for a range of mental health conditions including depression and addiction. Treatments for fear-of-height use a VR environment showing seven story building with glass floors and no guard rails.

Figure **0** shows a fascinating application of AR during surgery. The AR system is accurately registering virtual models of the patient's bone structure and organs over the patients body. This is an example of providing physicians with "X-ray" vision and is expected to improve clinical outcomes.

Fig 0

AR ASSISTED SURGERY
Countless papers in current literature describe applications for AR assisted surgery. These examples display a range of current AR technologies including 3D model reconstruction and feature-based tracking. In particular [2] constructed a virtual 3D model of a skull for assisting brain lesion surgery. The AR system registers the patient's skull with the virtual skull and highlights position of the lesion. The scalpel's position is tracked and updated on the AR display allowing the physician to make an accurate incision without damaging surrounding tissue and blood vessels. Similarly, [4] describes AR assisted heart surgery for coronary artery bypass. A virtual 3D model of the patient's heart is constructed including the location of the clogged vessel. The AR system accurately overlays the heart model onto the patient during surgery to assist the physician.

The key AR technologies used in [2] and [4] are 3D model reconstruction to build virtual models of a patient's organs for AR applications and the tracking systems that accurately register virtual models over the patient. The tracking systems must be extremely precise so that, for example, the virtual heart model is accurately registered with the patient's heart during surgery and correctly identifies the location of the clogged artery.

Virtual 3D Model Construction

Several techniques are available to map 2D CT scans to 3D models for use in AR. This process is known as volume rendering and it creates voxels (3D pixels) out of the stacked 2D cross sections [3]. Visualizing 3D reconstructions of CT images provides more objective, realistic tissue and organ morphology to aide diagnoses [2].

The volume rendering algorithm employed in [2] is the classical Marching Cube (MC) algorithm. The MC algorithm, first published in 1987 SIGGRAPH, takes eight neighboring points in a scalar field and determines polygons needed to represent the part of an isosurface passing through the cube formed by the eight points [10]. The gradient of scalar field yields the normal vector of the isosurface which is critical for shading the resulting polygonal mesh [10]. Figure **1** shows a MC volumetric rendering from 150 MRI image slices.

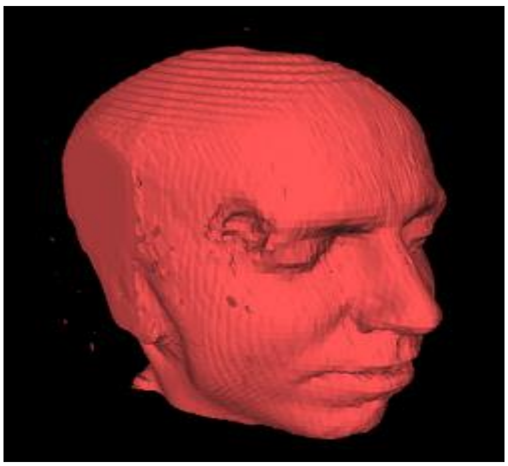

Fig 1

Tracking and Registration

The AR registration technology in [2] is marker-based tracking. This tracking technology requires a fiducial marker on the patient's skull; typically, a washable tattoo. The marker-based tracking system first detects and extracts the marker from the scene camera feed. The position of the marker is used to determine the position of the camera relative to some starting position. The relationship between marker and camera can be represented as a transformation matrix in homogenous coordinates. This is in contrast with [4] where the authors describe a marker-less tracking system for AR assisted heart surgery. The marker-less system determines camera pose using existing objects in scene. In [4], the primary object in the scene in the patient's heart and so the AR system identifies visual features of the heart and tracks those features over each frame.

Marker-less based Tracking

The first step in the marker-less based tracking system defined in [4] is feature extraction. These are the visual features that are identified, extracted and matched in each video frame—occurring at 20-30 times per second to achieve smooth overlay. A computationally effective method for this process is known as SURF (speed-up robust features) [4]. SURF is algorithm for extracting features from image frames that are invariant to rotation, scale and illumination. These invariances are critical otherwise a shadow could disrupt tracking and that could be devastating during heart surgery. Figure **2** visualizes the SURF features extracted and matched from two images of the same heart at different angles.

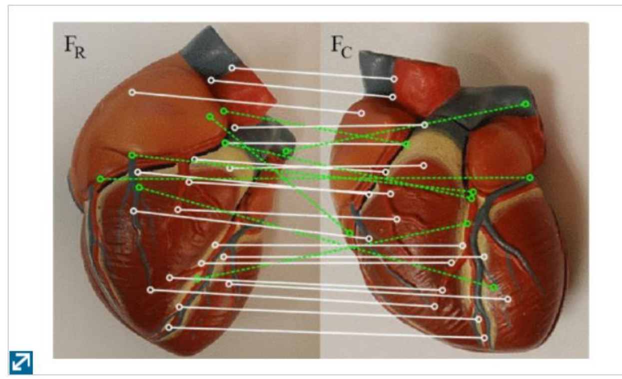

Fig 2

Given a set of extracted features from an incoming video frame, the next step is to use the features to calculate the heart's orientation relative to a reference frame. The system in [4] assumes the feature points are co-planar—obviously an approximation given that the heart is a 3D structure, but necessary to cope with the computational demands of real-time feature tracking. Tracking the visual features from frame-to-frame allows the AR system to update the virtual heart model overlay to be consistent with the movement of the heart—or equivalently the movement of the physician wearing a head-mounted-display.

Marker-based Tracking

The 3D registration problem for marker-based tracking comes down to finding the transformation matrix between marker's coordinate system and camera's coordinate system [2] then using that matrix to position the virtual skull in the AR display. An examination of the mathematics of this process is instructive to understand how the marker's pose in the scene camera's view determines how the scene camera must have moved relative to the marker. Consider figure **3** showing the marker tracking process. Two coordinate systems are shown: marker system (X_m, Y_m, Z_m) and camera system (X_c, Y_c, Z_c), and the points (x_c, y_c), (x_d, y_d) are in screen coordinate system (pixel coordinates).

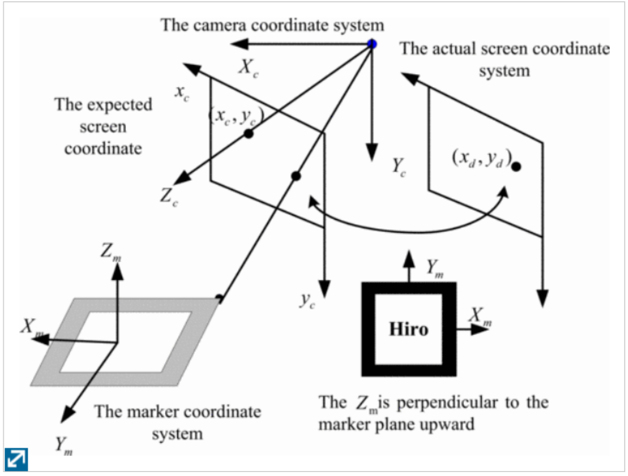

Fig 3

The first step in the process is converting from marker coordinates to camera coordinates via transform matrix. Then the 3D camera coordinates are mapped to expected screen coordinates via camera matrix (intrinsic matrix). The final step is comparing actual screen coordinates with expected screen coordinates to determine camera pose.

The conversion from marker to camera coordinates is via a transformation matrix. Let $\boldsymbol{T_{cm}}$ denote the transformation matrix between camera and marker coordinate systems. Then,

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \boldsymbol{T_{cm}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

Since we know that $\boldsymbol{T_{cm}}$ is a homogenous transformation matrix, we can further define its structure as

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \boldsymbol{T_{cm}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}_{\text{cm}} & \boldsymbol{T}_{\text{cm}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

where $\boldsymbol{T_{cm}}$ is now a block matrix with $3x3$ rotation matrix $\boldsymbol{R}_{\text{cm}}$ and $3x1$ translation vector $\boldsymbol{T}_{\text{cm}}$. Next, the mapping from camera coordinates to expected screen coordinates is via the intrinsic camera matrix $\boldsymbol{S}$.

$$\boldsymbol{S} = \begin{bmatrix} \alpha f & s & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

With focal length f, pixel aspect ratio α, the skew coefficient s (taken to be 0 typically), and c_x, c_y represent the ideal image center.

$$\begin{bmatrix} w \cdot x_c \\ w \cdot y_c \\ w \end{bmatrix} = \boldsymbol{S} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix}$$

Now that we are in expected screen coordinates after applying $\boldsymbol{S}$, the only task remaining is to detect the marker in the scene camera and measure its actual pixel position on the screen and compare with expected screen coordinates. Nonlinear optimization algorithms exist to solve for the transformation between expected and actual coordinates.

AR/VR SURGICAL TRAINING

Surgical procedures are extremely complicated processes that include surgical operations and overlapping surgical tasks [5]. Deliberate training of surgical procedures is necessary minimize risk of complications and this training is moving towards virtual simulations [5]. A particularly valuable use-case for virtual simulated surgical training is the placement of an external ventricular drain—this is a neurosurgical procedure to relieve elevated intracranial pressures. Several complications can arise in EVD surgery including preventable complications from mal-placement of the drain. It should be clear from figure **4** that the trajectory of the scalpel is a critical to prevent complications from mal-placement.

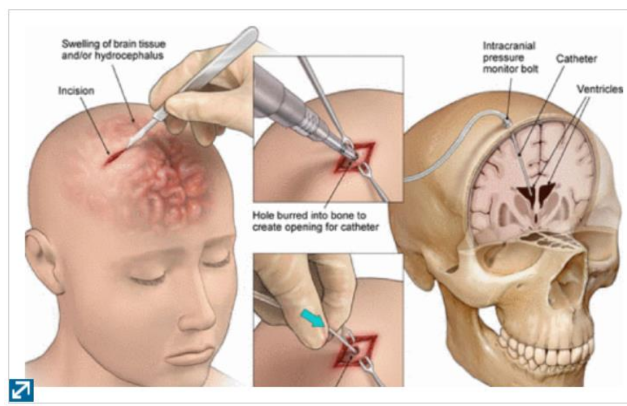

Fig 4

Imaging for the EVD procedure is collected via axial CT scan of the head and this imaging is used by the physician to form a mental plan for the trajectory; this process results in 14-20% of drains misplaced leading to multiple attempts, increased risk of hemorrhage, and infection. The authors in [5] recognized the sub-optimal nature of this process and developed AR/VR simulations to train physicians to guide scalpel with correct trajectory and reduce complications from mal-placement.

VR Training

The field of virtual reality neurosurgical training is dominated by NeuroVR simulator [5] [6]. The idea for NeuroVR came from an examination of the advancements made in aviation safety, “Every pilot that gets in a plane has trained in a simulator and therefore it doesn’t matter what country you’re in, everybody has trained in that simulator. You have to be up to a certain level of efficiency before you ever get in a plane. Everybody who is training in neurosurgery throughout the world could be trained on simulators and everybody could get the exact same level of training” [6]. NeuroVR is capable of modelling brain tissue so that a simulated tumor feels like a real tumor. This was achieved by taking removing tumors for patients and measuring the stiffness and other physical properties then feeding that information into the simulator [6]. Figure **5** shows the NeuroVR simulator.

Fig 5

The authors in [5] developed VR neurosurgical training application by extending NeuroVR. To provide users with meaningful feedback on their trajectory for EVD placement, [5] developed custom feedback module using output of NeuroVR to render current trajectory and display ideal target. A series of experiments were carried out where medical students and physicians practiced placing EVD and results show a correlation between years of experience and performance score—indicating the AR/VR system is a valid training tool for EVD placement. Figure **6** shows several EVD placement trajectories with the ideal trajectory in blue and the user’s trajectory in green in addition to the AR system in use with the user guiding scalpel towards NeuroVR’s skull model.

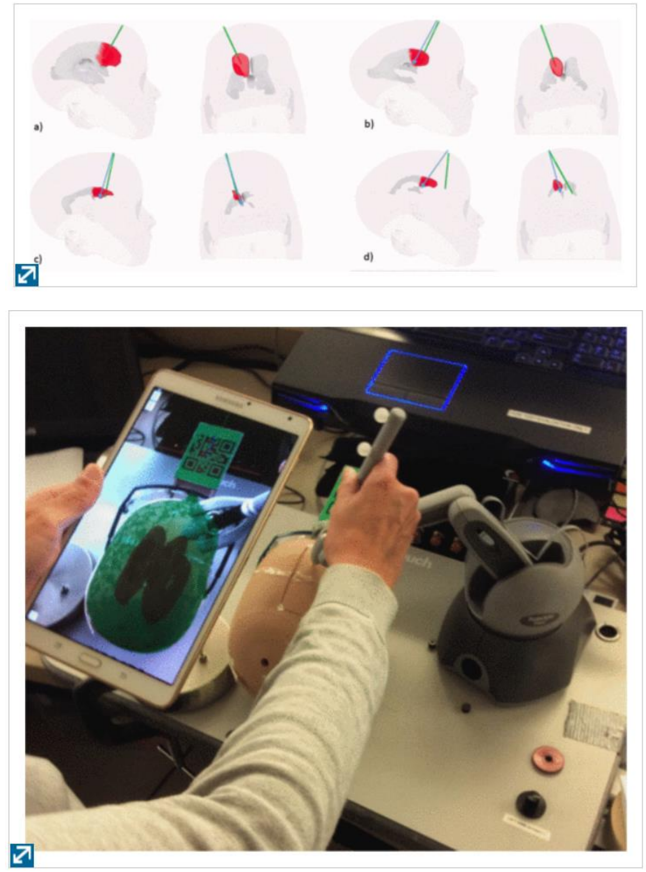

Fig 6

CONCLUSION

This paper presented an investigation of state-of-the-art applications of AR/VR in medicine. Each topic presented here was published in 2016-2017 period and represents the current state of knowledge. The AR/VR applications in the field of medicine are particularly important because they can help save lives and opens radical new methods for physicians to rehearse surgical procedures and offers new visualization techniques to aide in diagnoses. Aside from the topics presented here, many other applications of AR/VR in medicine exist including tele-mentoring where surgeons can follow along with cutting edge surgeries and procedures taking place in any part of the world.

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