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Medical Augmented Reality based on Commercial Image Guided Surgery

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Abstract

Utilizing augmented reality for applications in medicine has been a topic of intense research for several years. A number of challenging tasks need to be addressed when designing a medical AR system. These include the import and management of medical datasets and preoperatively created planning data, the registration of the patient with respect to a global coordinate system, and accurate tracking of the camera used in the AR setup as well as the respective surgical instruments. Most research systems rely on specialized hardware or algorithms for realizing augmented reality in medicine. Such base technologies can be expensive or very time-consuming to implement. In this paper, we propose an alternative approach of building a surgical AR system by harnessing existing, commercially available equipment for image guided surgery (IGS). We describe the prototype of an augmented reality application, which receives all necessary information from a device for intraoperative navigation.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Artificial, augmented, and virtual realities, J.3 [Life and Medical Sciences]: Medical information systems

1. Introduction

Augmented reality (AR) denotes a set of techniques aimed at combining real and virtual image elements in real-time. One particular aspect of AR is the requirement of correct three-dimensional placement and orientation of virtual graphical objects. Two main types of augmented reality can be distinguished. Whereas optical see-through systems use special translucent display devices, video see-through AR is based on mixing a live video stream from a camera with the graphical scene elements (see [Azu97]). The support of medical treatment has always been among the most important applications of augmented reality. Modern methods of surgery, like minimally-invasive procedures, can gain significantly from added information visualization and augmented views to balance the increased difficulty of these interventions. A complete AR application for ultrasound-guided needle biopsies has been described by State et al. [SLH*96]. The system offers stereoscopic rendering and accurate tracking of the user, but relies on a number of proprietary technologies like a hybrid optical-magnetic tracker and a mechanical arm for probe registration. More recently, several research groups have worked on developing augmented reality support for various medical application scenarios. Examples include the Medarpa project [SS04], which uses a special translucent display device mounted on a swivel arm. Here tracking is performed using a hybrid scheme based on active infrared and electromagnetic components. A semi-transparent mirror display mounted directly over the patient is used for reality augmentation in the ARSys-Tricorder described by Goebbels [Goe03]. An application to liver surgery has been examined by Bornik et al. [BBR*03]. Their system uses head-mounted displays for visualization and relies on a specialized optical camera system for tracking.

One significant drawback of many existing methods for medical AR is their reliance on specific hardware. Such devices, like magnetic tracking systems or specialized displays, often are expensive and can require tedious setup procedures. Many of them have originally been designed for applications in industry or virtual reality and may not be optimally suitable for medical scenarios. In particular head mounted displays are often considered to be too bulky, and they may deteriorate the user's perception of the surroundings. They are thus not well accepted for medical applications. Magnetic tracking devices can be disturbed by metallic objects like surgical instruments, and they can also possibly interfere with other sensitive equipment in the operation room.

2. Components of a Medical AR System

- **Camera/Instrument Tracking:** Any AR application has to measure in real-time the spatial pose of the camera or the user's head. Marker tracking is a video-based method which approximates this pose by analyzing artifical fiducials in the video stream [KB99]. Whereas marker tracking is a software-only solution, magnetic and external optical tracking systems consist of additional hardware. However their accuracy and trackable volumes usually surpass the capabilities of marker tracking. In most medical AR systems, it is also necessary to track surgical instruments.
- **Patient Registration:** In order to correctly overlay virtual elements for the display of medical information, the patient needs to be registered with respect to a global coordinate system.
- **Creation of Preoperative Planning Data:** Image data in medicine usually originates from 3D scanning devices like CT or MRI and is stored according to the DICOM standard, which can be notoriously complex. For many applications it is useful to additionally provide preoperative planning data. Such information can consist of trajectories and target points for an intervention, or specifically generated 3d models.

3. The VectorVision IGS system

VectorVision® (see Figure 1) is the current passive, optical-tracking IGS platform of *BrainLAB* consisting of a PC, a touchscreen display and two infrared cameras. Special marker spheres that are rigidly attached to every object to be tracked reflect infrared light. The position of each marker sphere is calculated via triangulation, which allows the touchscreen to display the 3D model of the surgical tool at the correct location in the 3D dataset. Disregarding the fact that soft tissue can slightly modify shape and position over time, the technically possible accuracy achievable today is in the order of magnitude of 1 mm.

To enable the interaction of research systems with an existing IGS product, developers are provided with a specific, well-suited interface: *VectorVision Link (VVL)* [ND03] is an easy-to-use TCP/IP-based interface integrated into the BrainLAB *VectorVision*® *Cranial* system. The API is based on the Visualization Toolkit (VTK) and can be accessed through various programming languages. Among other information, the 3D medical image sets of the patient and the positions of the currently tracked tools can be downloaded for processing by an external system. In return, new image sets and 2D bitmaps can be uploaded and used by the surgeon during the intervention.

Figure 1: *VectorVision IGS system.*

4. The New Augmented Reality System

In this paper, we describe a novel video see-through system for medical AR, which is based on a VectorVision image guided surgery device. We show that all of the tasks described in Section 2 can be performed by this system.

4.1. Camera Tracking

A standard webcam is used for the acquisition of video images. It is necessary to find a method for tracking the webcam using the given equipment. The VectorVision system is capable of tracking several surgical instruments using its infrared camera system. Thus one infrared marker instrument clamp is attached to the webcam (see Figure 2). The pose of the instrument clamp measured by the IGS system is received using the VectorVision Link interface.

Figure 2: *Webcam with one passive infrared marker instrument clamp attached.*

The major difficulty of using tracked instrument data for tracking the webcam is the fact that the pose information delivered by the IGS system does not directly correspond to that of the camera. Only pose information in relation to a hypothetical surgical instrument is available, as shown in Figure 3. Here, **pos** denotes the position of the instrument's tip. The direction of the instrument is given as vector **dir**, with **norm** being a plane normal perpendicular to it. It is then necessary to transform this pose into the camera pose using an additional one-time calibration step, which we have devised.

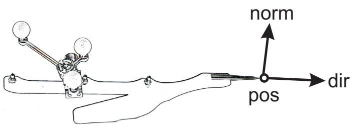

Figure 3: *6-DOF instrument data delivered by image guided surgery.*

4.1.1. One-time Calibration

A common reference coordinate system for the instrument clamp and the webcam is established at a given point of time using conventional marker tracking based on the ARToolKit by Kato et al. [KB99]. An ARToolKit marker is placed in the trackable volume of the infrared cameras. The user then defines the positions of the marker corners in the coordinate system of the infrared camera using a standard pre-calibrated pointer tool (see Figure 4). Since the the corners are defined in clockwise order, the marker coordinate system is the same one as used in the ARToolKit: Vectors **u** and **v** correspond to the x and y axes. The z axis points upward towards the viewer, creating a right-handed coordinate system. The transformation matrix from the VectorVision to the marker coordinate system, $A_{vvctomarker}$, is shown in Equation 1.

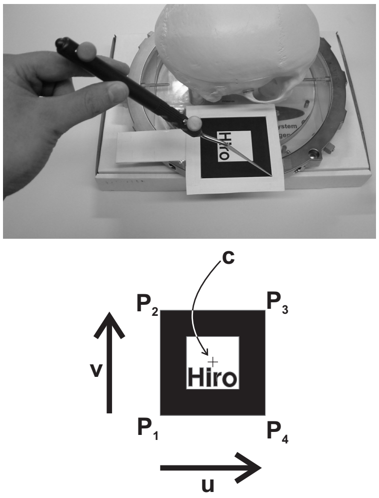

Figure 4: *Marker corners are defined in a clockwise order from P_1 to P_4.*

$$\mathbf{u} := \frac{P_4 - P_1}{\|P_4 - P_1\|} \quad \mathbf{v} := \frac{P_2 - P_1}{\|P_2 - P_1\|} \quad \mathbf{c} := \frac{P_1 + P_2 + P_3 + P_4}{4}$$

$$A_{vvctomarker} := \left(\mathbf{u} \,\middle|\, \mathbf{v} \,\middle|\, \mathbf{u} \times \mathbf{v} \,\middle|\, \mathbf{c} \right)^{-1} \tag{1}$$

The next step is the actual one-time calibration procedure. At one point of time, the webcam has to be positioned so that the optical marker can be recognized by the ARToolKit, while the infrared markers are seen by the VectorVision cameras simultaneously. When the calibration is performed, the current tracked instrument data is recorded. This pose information directly leads to the construction of matrix $A_{vvctoinsm}$ (see Equation 2), which describes a right-handed coordinate system with the (imaginary) instrument tip at its origin.

$$A_{vvctoinsm} := \left(\mathbf{dir} \,\middle|\, \mathbf{norm} \,\middle|\, \mathbf{dir} \times \mathbf{norm} \,\middle|\, \mathbf{pos} \right)^{-1} \tag{2}$$

Finally the marker transformation matrix is retrieved from the ARToolKit. It is then inverted, yielding the transformation $A_{camtomarker}$ from the coordinate system of the webcam to the marker coordinate system. Using the ARToolKit marker as the common point of reference, the transformation from the instrument clamp to the webcam coordinate system is computed. Figure 5 illustrates the relations between the transformation matrices involved in the calibration procedure.

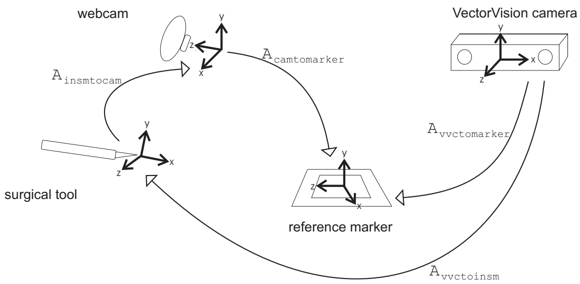

Figure 5: *Overview of the transformation matrices involved in the calibration and tracking process.*

$$A_{insmtocam} = A_{camtomarker}^{-1} \cdot A_{vvctomarker} \cdot A_{vvctoinsm}^{-1} \tag{3}$$

Equation 3 shows how the result of the calibration, matrix $A_{insmtocam}$, is computed. This transformation only needs to be computed once. As long as the physical relation between the instrument marker clamp and the webcam remains unaltered, the matrix remains valid.

4.1.2. Operation of the IGS-based AR System

After the one-time calibration step, only the data from the VectorVision infrared camera is required for tracking the webcam. For every frame that is generated by the AR system, the current tracked tool data is retrieved using the VectorVision Link. An $A_{vvctoinsm}$ matrix is computed (see Equation 2), and the final transformation matrix used for OpenGL camera setup is the result of the simple multiplication $A_{vvctocam} = A_{insmtocam} \cdot A_{vvctoinsm}$. The image guided surgery system also provides support for the remaining tasks of medical AR. Several surgical tools can be tracked simultaneously in addition to the webcam. Methods for patient registration are available, e.g. the matching of anatomical landmarks, artifical fiducials attached to the patient, or 3d surface point clouds from a handheld laser device. It is possible to import DICOM datasets and to define target points or trajectories for interventions.

5. Results and Discussion

We have implemented an application demonstrating the feasibility of IGS-based medical AR. Several images generated by the software are shown in Figure 6. Our tests showed that the system is capable of generating an augmented video stream at average frame rates of more than 10 fps using a webcam resolution of 640x480 pixels. We have measured an average latency of approximately 80 ms for receiving the tracked instrument data from the VectorVision system. Our camera tracking method delivers good accuracy, but sporadic visual mismatches result from the time lag between IGS marker registration and the generation of the augmented video. The range of our tracking method is limited to the viewing volume of the infrared cameras, and it is sensitive to occlusion of the marker clamps from their viewpoint. This makes our augmented reality application ill-suited for the use of head-mounted displays.

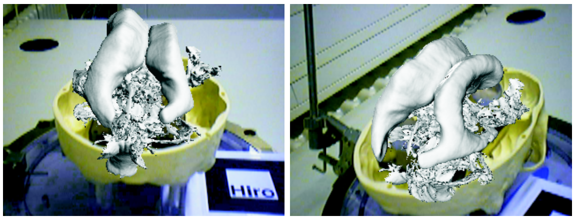

Figure 6: *Several views generated by the AR system using a ventricle model generated from a MRI scan.*

6. Conclusion

We have presented a novel approach of realizing AR for medical applications. Unlike other research systems, our solution is based on existing medical equipment. The transition of AR into the clinical practice can be facilitated by the fact that IGS systems are ubiquitous, well tested, certified for medical settings, and easy to use. Since the VectorVision image guided surgery devices have been designed specifically for medicine, many practical problems like possible magnetic interference or working in a sterile environment have already been taken care of. An IGS-based augmented reality system benefits from these qualities. Utilizing image guided surgery for medical AR also reduces the costs and shortens the required setup procedures. Assuming that IGS equipment exists for a certain medical application, additionally only a standard computer system and webcam are necessary for building a basic AR system.

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