Implementation and Evaluation of an Augmented Reality System Supporting Minimal Invasive Interventions

Bernd Schwald[1], Helmut Seibert[1], Michael Schnaider[1], Stefan Wesarg[2], Sandra Röddiger[3], and Selami Dogan[4]

[1] ZGDV - Computer Graphics Center, Dept. Visual Computing, Fraunhoferstr. 5, 64283 Darmstadt,Germany
[2] Fraunhofer IGD, Dept. Cognitive Computing & Medical Imaging, Fraunhoferstr. 5, 64283 Darmstadt, Germany
[3] Klinikum Offenbach, Strahlenklinik, Starkenburgring 66, 63069 Offenbach, Germany
[4] J. W. Goethe-Universität, Klinik für Herz- Thorax- und thorakale Gefäßchirurgie, Theodor Stern Kai 7, 60590 Frankfurt, Germany

Abstract. Minimal invasive surgery and interventions promise a number of advantages for the patient. The biggest one is a reduced trauma for the patient, at the cost of a limited view for the physician. The project MEDARPA offers Augmented Reality (AR) technology to enhance the real view of the surgeon with pre-operatively acquired medical data from 3D imaging modalities.
During the last three years, a group of clinical, medical engineering and research partners has designed and implemented a prototype of an AR-enhanced navigation support system for minimal invasive interventions. It comprises of a transparent display device 'AR window', a hybrid tracking system, navigation support and a volume rendering system for medical 3D images.
The system has been designed for a variety of medical applications. For the proof of concept cardio-surgery, radio oncology and pneumology scenarios have been considered. This paper gives an overview of the system design and its evaluation.

1 Introduction

Minimal invasive operation techniques have become more important and more accepted in the last 15 years. While offering obvious advantages for the patient such as reduced access trauma, faster postoperative recovery and better cosmetic result, these techniques confront the surgeon with a restricted view of the region of intervention. The application of Augmented Reality (AR) techniques is most promising and it offers a solution to minimise or even overcome the problem of the physician's limited visual perception.

However, many AR approaches are using Head Mounted Displays (HMD) for the fusion of the real and the virtual scene, either as variants with video see-through or as optical see-through. Although HMDs can be an appropriate choice as a display system in many application areas like maintenance, training etc., most surgeons tend not to accept these devices. A likely cause is correlated to the reduced flexibility in movements and to ergonomic constraints. The project MEDARPA (Medical Augmented Reality for Patients) described here addresses these issues by assembling a novel HMD-less AR System using a transparent display, here called an AR window, for Computer Aided Surgery (CAS) and minimal invasive interventions in general.

As a major field of activity for AR applications, a lot of work has been invested in the medical domain already. Early approaches that provided an 'x-ray view' to the physician can be found among others in [1], [2], [3], [4]. Some of the early applications date back until fifteen years ago, but a number of new AR navigation prototypes for CAS have been developed in the recent years. The tracking systems used for these applications cover electromagnetic as well as optical devices [5], [6], [7]. Trials similar to our AR window approach were made using a half-silvered mirror, which is both transparent and reflective [8], [9], [10], the later providing the user with a stereoscopic view using shutter glasses.

An alternative technique for the generation of stereoscopic displays has been proposed in [11] but this auto stereoscopic technique is not applicable for transparent displays. Other approaches such as proposed in [12] use a surgical microscope for augmentation or make investigations to integrate a holographic screen [13], [14].

2 System and Components

This section describes the hardware set-up of the AR system and its integration into the clinical environment. Figure 1 depicts different aspects of the system. Its usage requires preparation in the image data acquisition

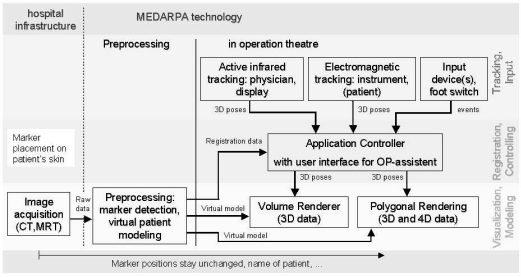

Fig. 1. System overview including components (boxes), work flow (horizontal) and technical layers (vertical).

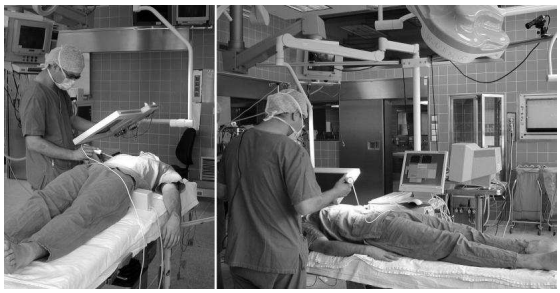

Fig. 2. Set-up of the AR system in an operation theatre.

phase. In order to allow a patient registration in the operational phase, small spherical markers visible in the image data have to be attached to the patient. Following the data acquisition phase, the pre-processing of the image data is performed. This includes detection and identification of the markers in the computer tomography (CT) Image, definition of the area of treatment and/or target regions and the creation of the 3D patient model that is used for the augmentation. The third and final step is the operational use of the system's functionality for the treatment, including patient registration, augmentation and navigation support.

The technological layers of the system are also shown in figure 1. The tracking and input layer contains the components for the determination of poses of the instruments, the physician, the display and the patient, i.e. the two different tracking systems, as well as the input device controller for the supported types of interaction. In the layer called 'registration' and 'controlling' the functionality to process all 3D data and provide the registration procedures are enclosed. The visualisation and modelling layer includes components for the pre-processing of the acquired medical image data and for their visualisation in the correct perspective for the physician performing the medical treatment.

3 Hardware Set-up

All components of the AR system are embedded in or attached to a trolley. On top of the trolley a swivel arm holds the transparent display, the main component of the system. Figure 2 shows a test set-up of the system in an operation theatre. The swivel arm enables the physician to easily move the transparent display to the desired place such that the patient can be observed in the usual manner. The physician's view to the patient is

enhanced with the superimposed virtual information prepared during the pre-processing phase. The positions and orientations of the patient, the instrument, the display and the surgeon's viewpoint are continuously determined in order to provide the correct virtual overlay. This is performed by a hybrid tracking system combining an optical and an electromagnetic tracking system. This approach allows the utilisation of the specific strengths of the different tracking systems with respect to the task that needs to be performed.

For the optical tracking, the EOS system [15], developed at the ZGDV, is used. It consists of a stereo camera system equipped with infrared filters. Similar video-based tracking systems have been introduced in [16], [17], [18] and few are also available on the market [19], [20]. These two cameras are mounted on a stand attached to the trolley. Due to EOS' flexibility in camera placement, an optimised placement was determined to minimise the amount of occlusions while tracking display and surgeon. Tests of the optical tracking system showed a statistical position accuracy of approx. $1mm$ for this set-up, covering an interaction volume of $1.5m$ by $0.8m$ by $1m$ (width, depth, height). EOS simultaneously tracks several six degrees of freedom sensors in form of rigid bodies based on infrared markers. Active infrared landmarks are attached to the display and the physician's glasses. They build up the sensors for the optical position and orientation tracking. In favour of the optical solution, an electromagnetic (EM) tracking system [21] has been chosen to track the medical instrument used for the intervention. This approach avoids any problems with potential occlusions when used below the display.

Fig. 3. AR window, the user navigates inside an anthropomorphic phantom to the red target region. The instrument has a green overlay.

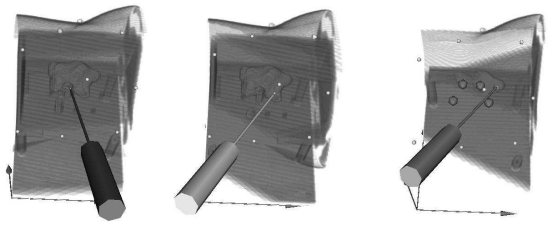

Fig. 4. The virtual overlay of the instrument changes colours: red for non-correct direction to target region, yellow for correct direction to target region and green, if the instrument's tip hits the target region.

The transparent display has been designed and implemented in the MEDARPA project. It is based on a modified TFT screen. Due to the currently available display technology the transparency is limited. The transparency can be improved by supplying sufficient illumination to the observed scene. The display can be moved freely within a working volume of at least $2m^3$.

4 Typical Scenario

The AR system is intended for three clinical scenarios. The first is a cardio-surgical scenario, in which the system helps to find the optimal position for ports needed for totally endoscopic coronary artery bypass(TECAB) grafting. In the second scenario, the system is used for bronchoscopic puncture of suspicious regions. In the last scenario, the system offers assistance for the navigation of brachytherapy catheters within the patient's body. Brachytherapy means radiotherapy very close to a tumour area or inside a tumour. For the latter, catheters, e.g. metal needles or plastic tubes have to be implanted. Prior to this procedure, some (e.g. nine) computer tomography (CT)-markers are fixed on the patient's skin and a CT scan of the region of interest is done. During the preplanning process, organs at risk are defined as well as the tumour area. Target regions within the tumour can be defined for optimal catheter navigation. As soon as the patient is in place and sedated, the system's set-up can be started. The patient is registered to the system using the CT-markers. After dis-infection of the skin, the display can be placed above the region of interest. The catheter is fixed on the handle with the electromagnetic (EM) tracker. The display and the physician are tracked by the optical tracking system, while the patient and the handle are tracked by the EM system. Guided by the AR view through the display, the physician starts the needle implantation.

5 Navigation support

Due to the lack of available display technology, the transparent display does not offer a stereoscopic view for the surgeon. However, to compensate this lack of stereoscopic depth perception head movement and principles like occlusion or collision between virtual objects are utilised. To ease up the task of navigation, a special colour feedback is provided; the colour of the virtual instrument changes depending on its position and direction to the target regions. Figure 4 shows three steps of navigation in the volume data set of a virtual patient. Small blue spheres are the virtual image of the markers, needed for registration, larger red spheres, only visible in the third step, are the defined target regions. In the first step the instrument is pointing into an arbitrary direction and therefore coloured in red. The instrument changes colour to yellow, when it is pointing into one of the target directions. This allows moving the instrument straight into the direction of target region by taking care, that the instrument is always displayed in yellow. If the target region is reached, the virtual instrument changes its colour to green.

An additional optional navigation support is a triangle that is spanned between the virtual instrument's tip, the target region and a point on the virtual elongation of the instrument. If the instrument is pointing in direction of the target region, the triangle is reduced to a line and barely visible, the more it is pointing into a wrong direction, the larger the triangle gets.

6 Evaluation and Test Reports

Among other properties, the achievable overall accuracy is one of the most important ones for a medical system. In fact, specifying an overall accuracy value for the complete system is not an easy task, but accuracies can be given for special aspects of the system as for navigation or the quality of the overlay in the view of the surgeon.

As mentioned in section 2, a hybrid tracking system combining an optical and an electromagnetic system determines poses of the display, the physician's glasses, instruments and the patient. Figure 5 gives an overview how the accuracies depend on the tracking systems and registration procedures. When an object is tracked, normally offsets between sensors and e.g. the tip of an instrument need to be calculated, inducing a

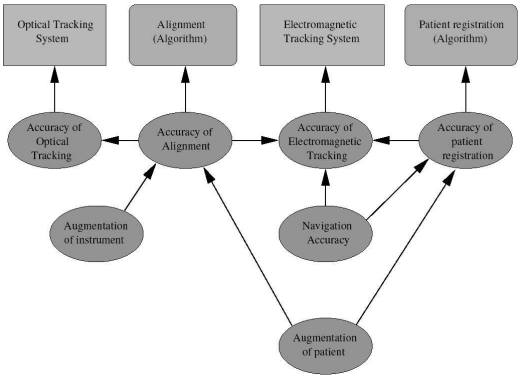

Fig. 5. Errors, induced by the different tracking systems and registration procedures. Arrow direction means 'depends on'.

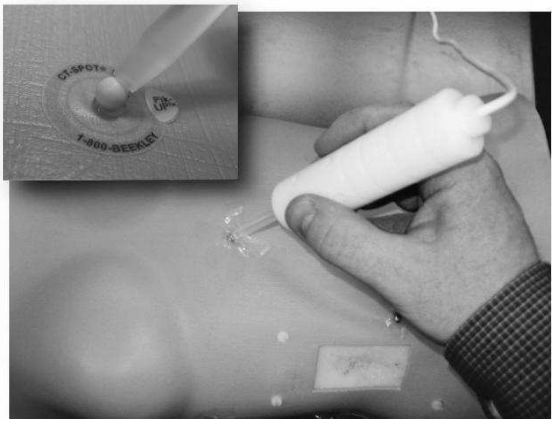

Fig. 6. Patient registration by moving the concave tip of the registration device to spherical markers on the patient's body.

new source of errors. In addition, the rotation error of the tracking system increases. Practically speaking, the larger the distance between an instrument's sensor and the instrument's tip is, the larger will be the position error at the tip of the instrument. In figure 5 this additional error is included in 'Accuracy of Electromagnetic Tracking'.

In the following, we focus on giving a value for the navigation accuracy, depending on the patient registration and the accuracy of the instrument, as introduced above. The accuracy or quality of the overlays is difficult to measure in an objective way and differs for every person. However, our case, the overlay quality is a less critical issue in contrast to the navigation accuracy. A first evaluation of the system in the brachytherapy scenario was published in [22].

6.1 Registration and Positioning of the Patient

Before the AR system is ready to be used in the medical treatment procedure, the patient is registered by moving the registration device to the spherical markers attached to the patient's body. These markers were attached before the patient is scanned and their position in the virtual patient model is identified in the pre-processing step (see [23]). Figure 6 depicts the registration of one marker with the registration device.

After all marker positions are recorded, the virtual patient can be registered to the physical patient by registering two 3D point sets. This procedure is described in more detail in [24]. Table 1 shows representative results from this registration procedure under laboratory conditions.

In this test series nine markers were attached to an anthropomorphic phantom, which was placed in a distance of approximately 300*mm* from the electromagnetic emitter. Ten registrations were performed. The mean and max errors are results, calculated after each test as quality value. The translation and the rotation (not shown here) results are used for the alignment of the virtual patient model in the AR system.

The mean error of the ten tests is with 1.21*mm* very close to the standard deviation of the translations with 1.17*mm*, such that the mean error is seen as a reliable quality value. Furthermore, this error corresponds to the accuracy of the electromagnetic tracking system and is therefore within our expectations of a good patient registration.

From a practical point of view, the number of the spherical markers should be minimised in order to make the registration as comfortable as possible for the surgeon. Several test in the clinical environment showed, that the accuracy of the registration decreases strongly, if less than six markers are used. In general eight to ten markers are a good basis for the registration procedure.

6.2 Navigation Error

To evaluate the accuracy of the navigation several needles are inserted into a patient under AR navigation support and their positions are stored by the system. After the insertion, a second control CT scan is recorded. Registering the two CT scans to each other now allows a very precise evaluation, how close the needles were inserted to the defined target regions. Table 2 shows the results of such tests, performed in two different hospitals. The distance between instrument's sensor and its needle's tip was in the first test approx. 150*mm* and in the second test approx. 225*mm*. The mean error of the measurements is 6.3*mm*, respectively 9.8*mm*, which we denote the overall navigation error.

test	mean error [*mm*]	max error [*mm*]	translation [*mm*]		
1	1.72	3.3	277.8	190.4	497.8
2	0.86	1.97	276.7	189.8	499.0
3	0.86	1.61	276.7	189.4	499.8
4	1.42	2.65	277.5	190.2	497.5
5	0.76	1.34	277.3	189.0	499.4
6	1.51	3.18	276.9	190.6	497.2
7	1.46	3.04	277.8	190.1	497.8
8	0.88	1.32	276.7	189.3	499.0
9	1.48	2.58	277.4	190.1	497.7
10	1.11	1.90	277.0	189.2	498.3
mean	1.21	2.29	277.18	189.81	498.3
stddev	0.349	0.756	1.174		
max	1.72	3.3	1.505		

Table 1. Results from ten alignments in the same setup with an anthropomorphic phantom with nine markers.

	Frankfurt hospital	Offenbach hospital
needle length[*mm*]	≈ 150	≈ 225
number of meas.	15	16
mean error at tip[*mm*]	6.3	8.9
minimal error[*mm*]	4.7	3.4
maximal error[*mm*]	9.3	12.8
stddev of errors[*mm*]	1.3	2.5

Table 2. Results from ten alignments in the same setup with an anthropomorphic phantom with nine markers.

Ignoring the major disturbances (see e.g. section 6.3) of the EM tracking system, the navigation error is basically influenced by the accuracy of the registration, the accuracy of the calibration of the instrument (distance sensor to needle's tip), the position accuracy of the sensor and the rotation accuracy of the sensor. The registration accuracy and the position accuracy of the sensor are both independent of the type of instrument and we expect approx. 1.5*mm* for both (see section 6.1). In contrast, the error induced by the rotation accuracy of the sensor and the accuracy of the calibration of the instrument both depend on the length of the needle to be used. An increasing length of the needle causes a higher loss of accuracy. The rotation error of the EM tracking system is specified with 0.5°. Therefore the position error at the tip of a needle, which is 150*mm* remote from the sensor, is increased by approx. 1.3*mm*, for a needle with 225*mm* by approx. 2.0*mm*. Similar values are supposed for the accuracy of the calibration of the instrument. Additional problems arise, if the instrument is very flexible.

Summing up these theoretical values the navigation error at the tip of a 150*mm* instrument would be 5.6*mm* and at the tip of a 225*mm* instrument 7.0*mm*.

6.3 General Experiences in Hospital

Major disturbances of the EM tracking system could be observed when using the MEDARPA system next to a computer tomography device or close to high voltage cables. Minor disturbances were seen in the operation room. These findings led to a modification of the brachytherapy scenario. Initially, it was planned to use the system and the CT in parallel during the implantation procedure for the verification of the catheter positions.

In an undisturbed environment the systems is easy to handle and needs - after installation - 6 minutes (3.5-10.0) for the set-up (calibration of tracking systems and registration of the phantom/patient). The prototype enables the physician to implant brachytherapy-catheters guided by the AR view. Target regions can be reached either freehand or guided by the navigation support tools. The puncture of organs at risk can be avoided. The system is furthermore useful for the training of unexperienced physicians.

7 Realization Potential, Outlook

The first tests show that the concept of the system is useful to support planning of interventions and training purposes. The AR system itself is not only designed for the planning of minimal invasive cardiac interventions or needle implantation in brachytherapy, but as a generic system for several medical domains, including navigation support.

Upcoming display technologies should allow improving the display quality in the near future. Alternatives like projecting the virtual augmentations directly on the skin of a patient is one of the visions for a future system, making AR even more user friendly and seamlessly integrated into the real environment.

The accuracy of the navigation of about 6.3*mm* for a needle with length of approx. 150*mm* is not fully satisfying yet, but has already been considered a useful 'add-on' for existing interventional procedures. We expect to be able to reduce the navigation error to around 4*mm* within the existing set-up and a needle of approx. 150*mm* length. Furthermore the flexible software architecture of our system allows an easy integration of new tracking technologies, as soon as they are available. Given a higher accuracy of the tracking systems, we expect increased accuracy of the overall system.

8 Acknowledgements

The project MEDARPA [25] has been funded by research grants of the German Federal Ministry of Education and Research (BMBF), research grant 01IRA09A. We want to thank all our project partners for their cooperation and encouraging input.

References

1. Mellor, J.P.: Enhanced Reality Visualization in a Surgical Environment. AI Lab . Cambridge, MA, Massachusetts Institute of Technology (1995) 102
2. Lorensen, W., Cline, H., et al.: Enhancing Reality in the Operating Room. Proceedings of the 1993 IEEE Visualization Conference (1993) 410–415
3. Grimson, W.E.L., Ettinger, G.J., et al.: Evaluating and validating an automated registration system for enhanced reality visualization in surgery. Proceedings of Computer Vision, Virtual Reality, and Robotics in Medicine '95 (1995) 3–12

4. Betting, F., Feldmar, J., et al.: A New Framework for Fusing Stereo Images with Volumetric Medical Images. Proceedings IEEE Conference on Computer Vision and Pattern Recognition (1995) 30–39
5. Seibert, F.: Stereo-based Augmented Reality in Medicine. 3. German-Korea Joint Conference on Advanced Medical Image Processing, EWHA University, Seoul, Korea (1998)
6. Tonet, O., Megali, G., D'Attanasio, S., P.Dario, Carrozza, M., Maracci, M., Martelli, S., Palombara, P.L.: An Augmented Reality Navigation System for Computer Assisted Arthroscopic Surgery of the Knee. Lecture Notes in Computer Science, S.L. Delp, A.M. DiGioia and B. Jaramaz Eds., Springer **1935** (2000) 1158–1162 (MICCAI 2000)
7. Birkfellner, W., Huber, K., Watzinger, F., Figl, M., Wanschitz, F., Hanel, R., Rafolt, D., Ewers, R., Bergmann, H.: Development of the Varioscope AR: A See-through HMD for Computer-Aided Surgery. In Proceedings International Symposium Augmented Reality - ISAR (2000) 47–53
8. Blackwell, M., DiGioia, A., Nikou, C.: Image Overlay Techniques for Surgery. Transactions on Medical Image Analysis (1998)
9. Blackwell, M., Nikou, C., DiGioia, A., Kanade, T.: An Image Overlay system for medical visualization. Transactions on Medical Image Analysis **4** (2000) 67–72
10. Nakajima, S., Nakamura, K., Masamune, K., Sakuma, I., T.Dohi: Three-dimensional medical imaging display with computer-generated integral photography. Comput Med Imaging Graph (2001) 235–241
11. Sandin, D., Margolis, T., Dawe, G., Leigh, J., DeFanti, T.: The Varrier Auto-Stereographic Display. SPIE, San Jose, California, 01/20/01-01/26/01 **4297** (2001)
12. King, A.P., Edwards, P., Maurer, C., de Cunha, D., Gaston, R.P., Clarkson, M., Hill, D., Hawkes, D., Fenlon, M., Strong, A., Cox, T., Gleeson, M.: Stereo Augmented Reality in the Surgical Microscope. Presence: Teleoperators and Virtual Environments **9(4)** (2000)
13. Dohi, T.: Surgical Robotics and Three Dimensional Display for Computer Aided Surgery. in Proc. of Computer Aided Radiology and Surgery, CARS 2000, San Francisco, U.S.A. (2000) 715–719
14. Lievin, M., Keeve, E.: Stereoscopic Augmented Reality System for Computer Assisted Surgery. In: Proceedings Computer Assisted Radiology and Surgery, CARS'01 (2001) 27–30
15. ZGDV: EOS optical tracking system. http://www.zgdv.de/zgdv/departments/z2/z2projects/eos (2004)
16. Madritsch, F., Gervautz, M.: CCD-Camera Based Optical Beacon Tracking for Virtual and Augmented Reality. Eurographics **3** (1996)
17. Dorfmüller, K.: An Optical Tracking System for VR/AR-Applications. In M. Gervautz, A.H., Schmalstieg, D., eds.: Virtual Environments 99, Proceedings of the Eurographics Workshop, Springer ComputerScience, Vienna, Austria (1999)
18. Ribo, M., Prinz, A., Fuhrmann, A.L.: A new Optical Tracking System for Virtual and Augmented Reality. IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary (2001)
19. ARTtrack: Optical tracking systems. http://www.ar-tracking.de (2003)
20. Northern Digital: Tracking systems. http://www.ndigital.com/products.html (2003)
21. Ascension Technology Corporation: Tracking systems. http://www.ascension-tech.com (2004)
22. Wesarg, S., Firle, E.A., Schwald, B., Seibert, H., Zogal, P., Roeddiger, S.: Accuracy of needle implantation in brachytherapy using a medical AR system: a phantom study. In: SPIE Medical Imaging 2004. (2004)
23. Wesarg, S., Lauer, T.H., Firle, E.A., Dold, C.: Several marker segmentation techniques for use with a medical ar system - a comparison. In: Proceedings of the 17th CARS 2003, Elsevier. (2003) 1303
24. Schwald, B., Seibert, H.: Registration Tasks for a Hybrid Tracking System for Medical Augmented Reality. In: accepted for the International Conference on Computer Graphics, Visualization and Computer Vision (WSCG 2004). (2004)
25. Medarpa Consortium: MEDARPA, MEDical Augmented Reality for the PAtient. http://www.medarpa.de (2003)