A CONCEPT WORK FOR AUGMENTED REALITY VISUALISATION BASED ON A MEDICAL APPLICATION IN LIVER SURGERY

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Commission V, WG V/3

KEYWORDS: Augmented Reality, Medicine, Photogrammetry, Visualisation, Close Range

ABSTRACT:

This paper describes a concept of an innovative medical application with augmented-reality support. This work is based on a cooperation between the Div. Medical and Biological Informatics at Deutsches Krebsforschungszentrum (DKFZ), and the Department of Photogrammetry and Cartography of the Technical University Berlin.

Augmented Reality (AR) is a growing area in virtual reality research. An augmented reality system generates a composite view for the user. It is a combination of the real scene viewed by the user and a virtual scene generated by the computer that augments the scene with additional information. The wide scope of application domains reveals that the augmentation can assume a number of different forms. Therefore, we compare different technologies for augmented reality visualisation with the focus on video see-through head-mounted displays, optical see-through head-mounted displays and virtual retinal displays. In a further step, we analyse the state-of-the-art of medical applications in augmented reality visualisation.

New technologies and methods implemented in DKFZ's ARION™ software will enable image-guided liver surgery. It is shown that many tools for preoperative planning of surgical interventions in hepatobiliary and pancreatic (HBP) surgery are available in the clinical environment, while the surgical procedures itself still lack computer assistance. On this basis, Div. Medical and Biological Informatics at DKFZ, the Depts. of Surgery and Radiology at the University Clinics Heidelberg and the research group "AR-work" of Technical University Berlin derived strategies for AR-support of open liver surgery. A technique will be developed in order to superimpose virtual computer-generated information with real patient image data using a see-through technology. The data from the preoperative planning, the clinical and technical requirements for augmented-reality techniques and our concept of the augmented-reality system will be presented in this contribution. The advantages of see-trough technology will be discussed. Our future work will analyse why (nowadays) AR-systems are not available in surgery and which technical and clinical requirements can be fulfilled with currently available display technologies.

1. INTRODUCTION

Because imaging technology is so pervasive throughout the medical field, it is not surprising that this domain is viewed as one of the more important for augmented reality systems. Most of the medical applications deal with image guided surgery. Pre-operative imaging studies of the patient, such as CT or MRI scans, provide the surgeon with the necessary view of the internal anatomy. From these images surgery is planned. Visualisation of the path through the anatomy to the affected area, where, for example, a tumor must be removed is done by first creating a 3D model from multiple views and slices in the preoperative study. This is most often done mentally though some systems create 3D volume visualisations from the image study. Augmented reality can be applied so that the surgical team can see the CT or MRI data correctly registered on the patient in the operating theatre while the procedure is progressing.

AR has some very interesting applications in medicine but most of them are still in the prototype stage. The most important applications will be summarised in the paper.

Our concept relies on the research work of the Div. Medical and Biological Informatics at DKFZ Heidelberg in surgery planning for liver resection:

The planning of surgical interventions of the large inner organs like the liver can be based on a computer supported planning system. The complex anatomical structure of the liver including two venous vessel trees, one arterial vessel tree and the bile duct is hard to understand without three-dimensional reconstruction. Additionally, anatomical information is important during surgery concerning the position of the eight liver segments and in particular the position of their interfaces. The anatomical variation between different patients demands individual operation planning in this field. A software system including the whole planning procedure is developed and is embedded in the radiological workstation CHILI®. The planning procedure starts with the segmentation of important areas (liver, tumor, etc.), the processing of the vessel trees, and it ends with the proposal of an individual surgical strategy. The next mandatory step is the integration into the operation theatre. Here intraoperative visualisation and navigation of the surgical instruments will be used.

Nowadays, augmented reality (AR) allows for enhanced perception of the surgical situs by superimposing stereoscopic projections over the field of operation. But the most AR-applications are used for the preoperative planning and not for the intervention itself. Our future work aims at elaborating the best display-technology for liver surgery (Herfarth, 1998; Hassenpflug, 2001).

2. NAVIGATION IN LIVER SURGERY WITH ARION™

Deutsches Krebsforschungszentrum and University Clinics Heidelberg have developed a prototype of an IGSS for application in oncological liver surgery. This IGSS will enable the surgeon to see her/his instrument in relation to important structures inside the liver. For the successful resection of tumors in oncological liver surgery (R0 resection) the exact knowledge of the localization of the tumorous tissue and the surrounding security margin is necessary [Hassenpflug, 2001; Hassenpflug, 2001b; Vetter, 2001]. The transfer of the preoperatively planned resection margins to the current situs is of interest. The complex structure of the intrahepatic vessels like the liver veins and the portal veins assist the surgeon to orientate inside the liver. Damaging a vessel that has to be preserved is life-threatening and a major intraoperative risk. The transfer of the preoperative anatomy and planning results to the intraoperative situs involves intraoperative image acquisition, registration with the preoperative data, deformation tracking and modeling, and the adequate presentation to the surgeon (cf. Fig. 1).

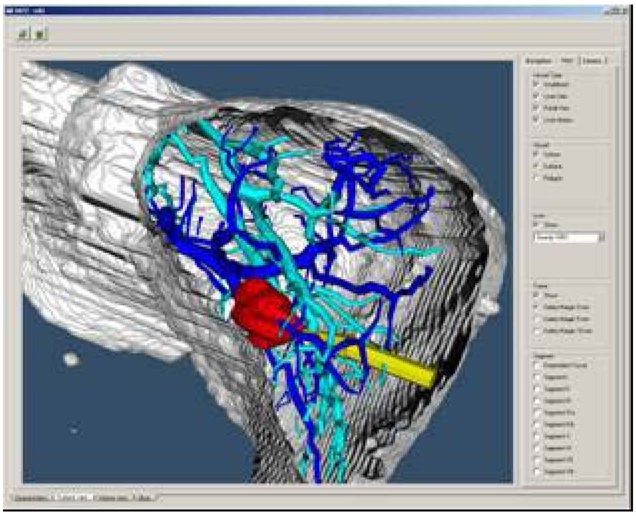

Figure 1. Screenshot of ARION with view on a surface visualisation of a clipped liver with intrahepatic vessels, tumor, and a depiction of the virtual instrument

We are building a prototype named ARION (Augmented Reality for Intra-Operative Navigation) to demonstrate the feasibility of image-guided liver surgery (Meinzer, 2002). It consists of five modules to realize the aforementioned visions:

Module 1:
Contrast agent enhanced images are acquired preoperatively and postprocessed by LENA, DKFZ's already clinically established computer-assisted surgical planning system. This module provides the portal and venous vessel tree in a mathematical graph representation, the tumor with surrounding security margin and calculated resection planes.

Module 2:
Intraoperative vessel trees are reconstructed from three-dimensional freehand Doppler ultrasound-scans and represented in graph representation. The vessel graphs provide all the features necessary for registration. For Module 2 to 4 the liver is kept in position by jet ventilation and stabilised within the surrounding space with sterile cloth. (Glombitza, 2001)

Module 3:
Registration of the vessel trees by rigid pre- and elastic post-registration. The resulting deformation vector field is used to infer the deformation of the parenchyma. Now, the localisation of the virtual planning structures is known via the world coordinate system of the transmitter of the applied electro-magnetic tracking-system. (Vetter, 2001b)

Module 4:
Localisable navigation aids (NSA), consisting of a needle, a tracking sensor, and an anchor, are brought into the liver to keep its registered state after it has been released for parenchyma resection. Therefore, an adaptive transformation correction parameterised by the navigation aids' sensor values are used to update the deformation vector field in a volume of interest in order to sustain the registered state. (Vetter, 2002)

Module 5:
The tracked surgical instruments are visualised in respect to the transparent intrahepatic structures on an auto-stereoscopic flat-panel to achieve an adequate depth perception.

3. AUGMENTED-REALITY TECHNIQUES

The introduction of an augmented-reality technique like see-trough is an important component to find out the best visualisation technology for liver surgery.

3.1 Display technologies

The combination of real and virtual images into a single image could be realised with the following display technologies:

- Head-Mounted Display
    - Optical–See-Trough
    - Video-See-Trough
    - Microscope
- Image Overlay Systems
- Virtual Retinal Systems
- Monitor-AR-Systems
- Direct Projection

In our work we focus on wearable systems that means on head-mounted displays and virtual retinal displays.

Head-mounted displays (HMD) have been widely used in virtual-reality systems. Augmented-reality researchers have been working with two types of HMD. These are called video see-through and optical see-through. The term see-through comes from the need for the user to be able to see the real world view that is immediately in front of him even when wearing the HMD. The HMD approach consists of viewing the outside world via a video camera fixed on a HMD. The video image is combined digitally with the computer generated image and displayed within the HMD.

The virtual retinal display (VRD) is a new technology for creating visual images. It was developed at the Human Interface Technology Laboratory (HIT Lab) by Dr. Thomas A. Furness III. The VRD creates images by scanning low power laser light directly onto the retina (Viirre, 1998).

The other systems came not into the questions because they are not able to serve the requirements of our application (Sect. 3.3).

3.1.1 Head-Mounted Displays

A see-trough HMD is a device used to combine reality and virtuality. Standard closed HMDs do not allow any direct view of the real world. In contrast, a see-trough HMD lets the user see the real world with virtual objects superimposed by optical or video technologies.

Optical see-trough

Optical see-trough HMDs work by placing optical combiners in front of the user's eyes. These combiners are partially transmissive, so that the user can look directly through them to see the real world. The combiners are also partially reflective, so that user sees virtual images bounced off the combiners from head-mounted monitors. Fig. 2 shows a conceptual diagram of an optical see-trough HMD. Fig. 3 shows a optical see-trough HMD made by Kaiser Electro-Optics Inc.

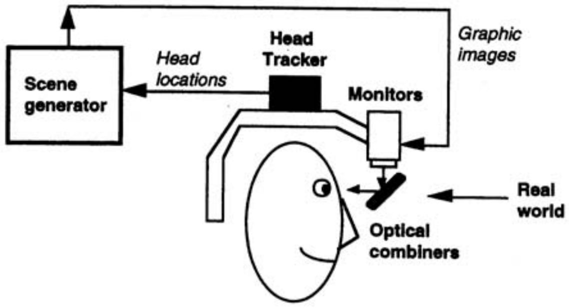

Figure 2. Conceptual diagram of an optical see-trough HMD (Azuma, 2001)

Figure 3. Optical see-trough HMD: ProView XL40/50 STm Kaiser Electro-Optics Inc.

Video see-trough

Video see-trough HMDs work by combining a closed view HMD with one or two head-mounted video cameras. The video cameras provide the users view of the real world. Video from these cameras is combined with the graphic images created by the scene generator, blending the real and virtual images. The result is sent to the monitors in front of the users eyes in the closed-view HMD. Fig. 4 shows a conceptual diagram of a video see-trough HMD. Fig. 5 shows a video see-trough HMD made by 5DT. (Azuma, 2001)

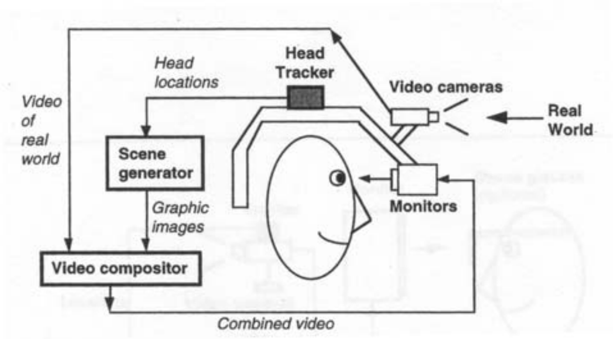

Figure 4. Conceptual diagram of a video see-trough HMD (Azuma, 2001)

Figure 5. Video see-trough HMD: 5DT HMD 800

3.1.2 Virtual Retinal Systems

Virtual Retinal display (VRD) is a visual display device that uses scanned light beams. Instead of viewing a screen, the user gets the image scanned directly into the eye. A very small spot is focused onto the retina and is swept over it in a raster pattern. The VRD uses very low power and yet can be very bright. Fig. 6 shows a block diagram of VRD systems. Fig. 7 shows a VRD made by Microvision (Viirre, 1998).

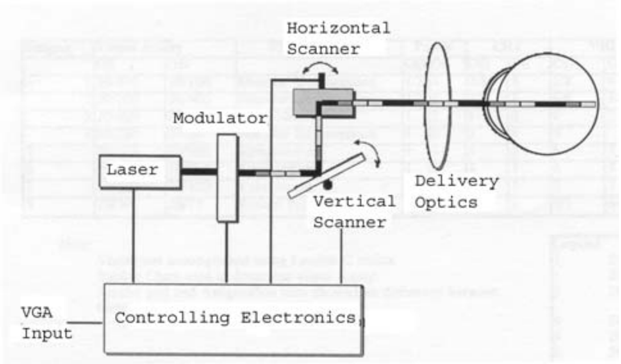

Figure 6. Block diagram of a Virtual Retinal Display

Figure 7. Virtual Retinal Display: Nomad Personal Display System made by MICROVISION

3.2 Applications

Augmented reality has a wide scope of application domains — like medicine, entertainment, military training, engineering, design, robotics and telerobotics, manufacturing, maintenance and repair. A overview is given in Fig. 8.

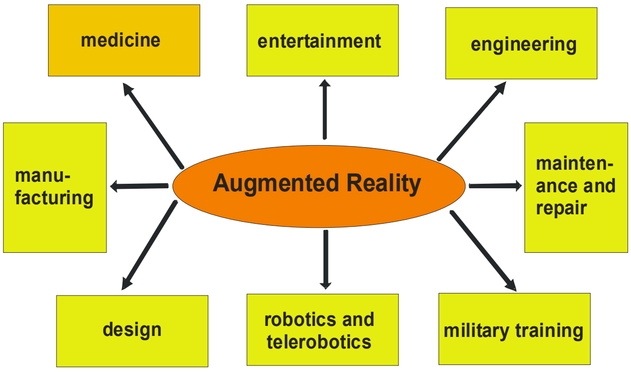

Figure 8. Applications in augmented reality

3.2.1 State of the art — medical applications

For example researchers from the Department of Computer Science at the University of North Carolina, Chapel Hill, investigated the use of three-dimensional medical images superimposed over the patient's body for noninvasive visualisation of internal human anatomy. A physician wearing a HMD viewed a pregnant woman with an ultrasound scan of the fetus overlaid on the women stomach walking around the patient allowed the physician to observe the fetus in 3D perspective and to determine its placement relative to the other internal organs. Other researchers used augmented-reality environments for medical visualisation. In the application of Gleason, three-dimensional images were used to assist preoperative surgical planning and to simulate of neurosurgical and craniofacial interventions (Barfield, 2001).

Further developments are:

- Researchers at the Aachen University of Technology in Germany have developed a "Computer Assisted Surgery" module for use in ENT surgical procedures (Adams, 1990).
- A group at TIMB in Grenoble, France has developed a "Computer Assisted Medical Intervention" module (Lavallee, 1990).
- A group at the University of Chicago has developed a method for "Interactive 3D Patient - Image Registration" (Pelizzari, 1991).
- A group at MIT's Artificial Intelligence Laboratory has developed "An Automatic Registration Method for Frameless Stereotaxy, Image Guided Surgery, and Enhanced Reality Visualization" (Grimson, 1994).
- A group at Stanford University has developed "Treatment Planning for a Radiosurgical System with General Kinematics" (Schweikard, 1994).
- A group at the University of North Carolina has developed a method for "Merging Virtual Objects with the Real World" (Bajura, 1992).

Other work in the area of image-guided surgery using augmented reality can be found in (Betting, 1995; Grimson, 1995; Lorensen, 1993; Mellor, 1995; Uenohara, 1995).

Current research efforts in enhanced-reality visualisation differ in many implementation details. The one thing they all have in common is the requirement to align a model with an image of the real world.

3.3 Augmented reality issues

In the following text we describe the issues for AR approaches. According to (Rolland, 2000) we describe technological issues in a short form and mention human factor and perceptual issues and design issues. From these aspects we derive the clinical and technical requirements for our AR approach in liver surgery. In Fig. 9 the relationship between technological and human factors /perceptual issues are illustrated.

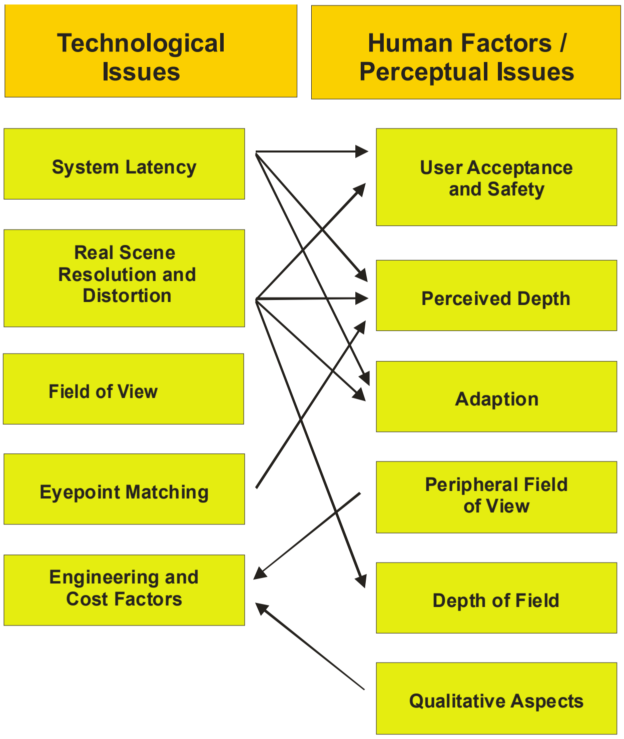

Figure 9. Relationship between technological and human factors / perceptual issues according to (Rolland, 2000)

3.3.1 Technological issues

System Latency
An essential component of see-trough HMDs is the capacity to properly register a users surrounding and the synthetic space. A geometric calibration between the tracking devices and the HMD must be performed. The major impediment to achieving registration is the gap in time, referred as lag, between the moment when the HMD position is measured and the moment when the synthetic image for that position is fully rendered and presented to the user.

Real Scene Resolution and Distortion
The best real-scene resolution that a see-trough device can provide is that perceived with the unarmed eye under unit magnification of the real scene. Optical see-trough HMDs take what might called a "minimal obtrusive approach; that is, they leave the view of the real world nearly intact and attempt to augment it by merging a reflected image of the computer-generated scene into the view of the real world. Video see-trough HMDs are typically more obtrusive in the sense that they block out the real-world view in exchange for the ability to merge the two views more convincingly.

Overlay and Peripheral Field of View
The term overlay FOV is defined as the region of the FOV where graphical information and real information are superimposed. The peripheral FOV is the real-world FOV beyond the overlay FOV. Large FOV is especially important for tasks that require grabbing and moving objects. Most current high-resolution HMDs achieve higher resolution at the expense of a reduced FOV. In surgery the resolution is more important than a large FOV.

Viewpoint Matching
In video see-trough HMDs, the camera viewpoint (the entrance pupil) must be matched to the viewpoint of the observer (the entrance pupil of the eye)

Engineering and Cost Factors
HMD designs often suffer from fairly low resolution, limited FOV, poor ergonomic designs and excessive weight. A good ergonomic design requires an HMD whose weight is similar to a pair of eyeglasses. To our knowledge, at present, no large-FOV stereo see-trough HMDs of any type are comparable in weight to a pair of eyeglasses.

3.3.2 Human Factor / Perceptual issues

The following issues could be discussed from both a technological and human-factors standpoint:

User Acceptance and Safety
Perceived Depth
- Occlusion
- Rendered Locations of Objects in Depth
- FOV and Frame-Buffer Overscan
- Specification of Eyepoint Location
- Residual Optical Distortions
- Perceived Location of Objects in depth

Adaption
Peripheral FOV
Depth of field
Qualitative Aspects

3.3.3 Design issues

The following design issues are important aspects of augmented reality systems and wearable computers:

Display Technology
Input / Output Devices
Power Supplies
Image Registration Techniques
Required Accuracy

3.3.4 Clinical and technical requirements

Our extension is to use augmented reality not only for the preoperative surgical planning. For an intraoperative solution we require a system with very good **real time** quality. In this context we must achieve high **accuracy** in tracking and registration. So we estimate the required accuracy of registration under 1 cm. In optical case of HMD, the virtual image is projected at some **distance** away from the user. This distance should be adjustable, although it is often fixed. Therefore, the virtual objects are all projected to the same distance while the real objects are at varying distances from the user. If the virtual and real distances are not matched for the particular objects that the physician is looking at, it may not be possible to clearly view both simultaneously (Azuma, 2001). In our case, the virtual objects should be projected in the distance of the working hand of the surgeon.

The surgeons expect an improved orientation during the intervention by the three-dimensional visualisation of the complex structure and context of the organ's anatomy. A typical task of an IGSS is the virtual depiction of the surgical instruments in spatial relation to the individual anatomy of the patient. Therefore, preoperative CT- and MRI data are post processed and enhanced with data from interventional planning. These data are then registered with the current situs during an intervention and readapted to the current deformation of the organ. In many cases the mutual depiction of pre and intra interventional data is required, which permits the specific selection of the kind of data that is currently of interest during the intervention. The depiction of the surgical instrument in relation to the anatomy and the chosen data from planning is important for the ability of the surgeon to orientate by means of the virtual visualisations. Therefore, the visual depth perception and a **stereoscopic** AR system are important for intraoperative orientation and navigation. The display devices used in our application may have less stringent requirements than for example accuracy or stereoscopic view. **Monochrome** displays may be adequate for our application. Furthermore, the **resolution** of the monitor in an optical see-trough HMD might be high enough for our three-dimensional virtual data because the low resolution of a see-trough HMD does not reduce the resolution of the real environment. The whole AR systems should be designed in such a quality, that it is well accepted by the surgeons. In order to achieve this requirement, the system should be not only fast and accurate the components should be **easy, robust** and relatively **inexpensive**. Within the operation theatre more than one surgeon might want enhanced reality and observe the operation with AR techniques. All hardware must fulfil the **sterile** conditions in the operation theatre.

3.4 Concept for augmented reality in liver surgery

The prerequisite for augmented reality in liver surgery is given with Module 1 to 4 from our ARION™ System described in chapter 2. The future extension should visualise the data with a see-trough technology. In Fig. 10 is illustrated the current and future use of computer–guided surgery according to (Peuchot, 1993).

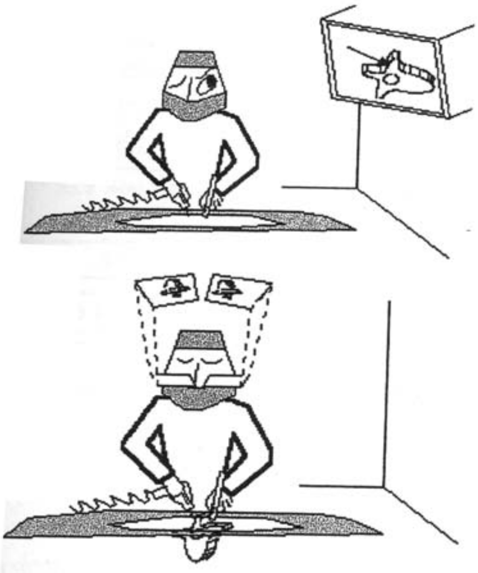

Figure 10. Graphics illustration of current and future use of computer-guided surgery according to (Peuchot 1993)

The task is to fulfil the clinical and technical requirements (Sect. 3.3). Nowadays, we are looking for the best see-trough technology. The displays currently available for enhanced-reality visualisation are less than optimal. Head-mounted displays are still heavy, awkward and have relatively low resolution. Conventional CRTs have better resolution but limit the applications of enhanced-reality visualisation. Our conceptual diagram is shown in Fig. 11.

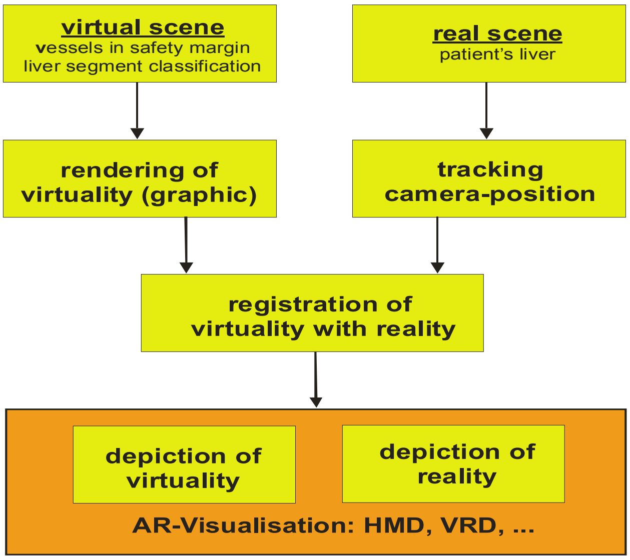

Figure 11. Conceptual diagram for augmented reality in liver surgery

4. CONCLUSIONS

New technologies and methods implemented in DKFZ's ARION™ software will enable image-guided liver surgery. It is shown that many tools for preoperative planning and surgical interventions are available in the clinical environment, while the surgical procedures itself still lack computer assistance. On this basis, the Div. Medical and Biological Informatics, Deutsches Krebsforschungszentrum and the research group "AR-work" of Technical University Berlin derived strategies for an adequate AR-application. A technique will be developed in order to superimpose virtual computer-generated information with real patient image data using a see-through technology.

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