A Tangible Interface for Augmented Reality Visualisation in 4D Echocardiography Imaging of the Left Ventricle of the Heart

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Abstract

In this work we report a Tangible Augmented Reality system that can be applied to interactive visualization scenarios in the cardiology medical field, such as in the teaching of medical techniques or in the recognition of organs. Moreover in can be used for a more detailed and natural interaction with virtual models of organs or other physiological structures of the human body. The system provides the means for a user to naturally interact with an augmented version of the previously referred models. The interaction with this models is made through the use of a totally sensor-less Tangible Interface, designated Magic Examiner, which aids the interaction and visualization tasks in the augmented environment.

Keywords

Augmented Reality, Tangible Interface, AR Toolkit, 4D Echocardiography, LV - Left Ventricle of the Heart

1. INTRODUCTION

In this paper, we aim at introducing the advantages of using augmented reality and tangible interfaces in the medical field. We specifically targeted our project to cardiac research and evaluation. The augmented reality visualization possibility is to us a major complement to the traditional visualization techniques used nowadays. The tangible interface explained in this paper was developed as an integrated module of a larger project, a SAPIENS National project, referred to as DIE-Heart, "Diagnostic Improvement of Echocardiography by Quantitative Assessment of the Heart". The general objective of DIE-HEART is to develop a 3D/4D echocardiography technique (a low cost, non-invasive, non-radioactive video technique) able to describe the Left Ventricle - LV mechanical properties applicable in animal model, clinical diagnosis and research. The specific work reported in this paper, brings the possibility of interacting, in a tangible way, with the virtual models created by other system modules of DIE-HEART (namely the reconstruction of the 3D and 4D deformable model of the LV), giving us a new perspective on what this technology can bring to this specific field of science and medical practice.

In synthesis, in this paper we introduce the usage of previously developed augmented reality technologies to the construction and deployment of tangible interfaces in augmented environments, applicable in the cardiology medical field as well as in other areas.

The paper is organised as follows: in section 2, we provide a background in augmented reality and tangible interfaces and reference some use cases of tangible interfaces in the medicine field. In section 3, we present our system architecture and its modules, give an overview on the operation of the system and describe the system configuration. Section 4 covers the issues of our tangible interface technology. Section 5 discusses clinical use cases. Finally, in section 6, conclusions and future directions of the research are given.

2. BACKGROUND

According to Azuma [Azuma99], Augmented Reality, AR "1) combines real and virtual environments; 2) is interactive in real-time; 3) is registered in 3D. To interact within immersive AR environments, where the user experiences a "visual augmentation" of the reality through, for example, a video see-through head-mounted display, standard input devices such as keyboards or mice are useless, since they distract the user from the task at hand, thus creating a severe cognitive seam within the interaction process. On the other hand, traditional input devices used in virtual environments, such as the data glove or a 3D mouse with 6 degrees of freedom, introduce undesirable complexity in the tracking technology, or add "strange" gadgets, to the user's workspace, with whom he's not daily accustomed.

To face this problem, Kato [Kato01a] proposes Tangible Interfaces, as a new approach for the design of Augmented Reality interactions. According to the author, Tangible Interfaces, "are those in which 1) each virtual object is registered to a (tangible) physical object; and 2) the user interacts with virtual objects by manipulating the corresponding tangible object". Tangible interfaces are described in the literature as being intuitive, since physical object manipulations are mapped to virtual object operations. If the mapping is one-to-one, we classify the interface as a space-multiplexed one.

In an application to the medical field, ARAS (Augmented Reality Aided Surgery) [Rainer], employs mixed reality as a collaborative tool for intra-operative planning of extended liver resections. The most important advantage of real time visualization of intra-hepatic vascular structures using see-through glasses is the improved accuracy of the preparation of liver parenchyma. These authors, not only use AR to augment the surgeons view by pre-operative and live 3D data streams, but also convey these enhancements to an off-site radiologist and implement direct collaboration between the radiologist and the surgeon. The off-site radiologist sees a live video stream from the surgeon's perspective, augmented by overlays displaying pre-operative and intra-operative (US) volumetric data. The surgeon takes advantage of the comprehensive visualization of the organ and additional hints placed by the radiologist, allowing accurate localization of the pathology.

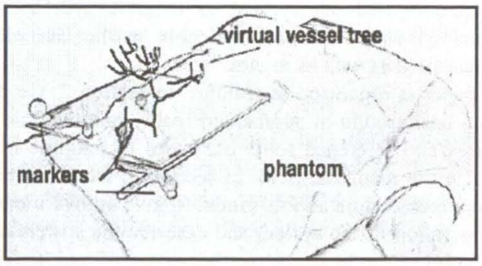

Figure 1 - Phantom with Virtual Vessel Tree Overlay (extract from [Rainer]).

Another work that adopts somehow the concept of Augmented Reality, using an optical effect and no special computing equipment, is the "Sonic Flashlight" project [Stetten02]. The prototype device, known as the "sonic flashlight," merges the visual outer surface of a patient's skin with a live ultrasound scan of what lies beneath. It creates the effect of a translucent ultrasound image floating in its actual 3-D location within the patient, showing blood vessels, muscle tissue, and other internal anatomy. The sonic flashlight displays an image within the natural field of view that can be used to guide invasive procedures, such as taking blood samples without missing the vein, catheterizations, surgery, or numerous other procedures while looking directly at a patient instead of at a monitor.

This work shows mainly the growing interest in the Medical community of modalities of visualisation that are registered in the human body.

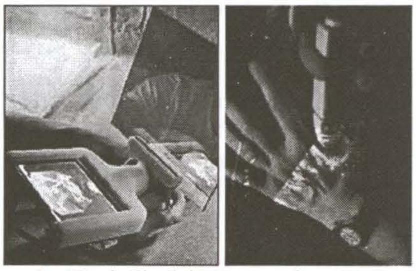

Figure 2 – "Sonic Flaslight" (extract from [Stetten02]).

3. SYSTEM ARCHITECTURE

To deploy our new tangible interface paradigm for the cardiology medical field, a number of modules comprise our system, referred to as DIE-HEART Augmented Reality Visualization (see Figure 3).

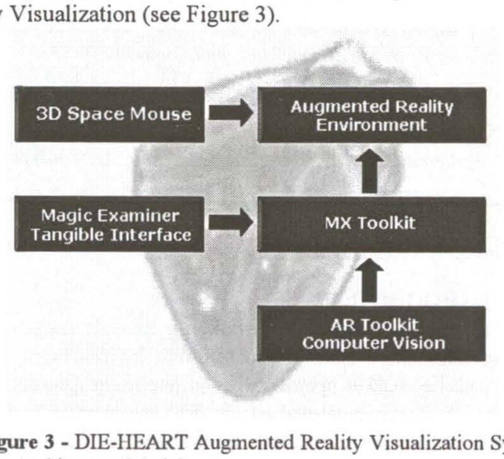

Figure 3 - DIE-HEART Augmented Reality Visualization System Architecture Module.

This architecture includes 5 different modules, which are:

- For the human-computer interface:
  - **3D Space Mouse**
  - **Tangible Interface (Magic Examiner)**
- For the system functions:
  - **Augmented Reality Environment**
  - **MX Toolkit**
  - **AR Toolkit/Computer Vision**

The **Augmented Reality Environment** module is the heart of our system architecture. This module registers 2D, 3D and 4D virtual models with real objects and enables the user to interact naturally with these virtual models, using either a physical artifact (tangible interface), or a 3D mouse, sensing these interactions in the real world. The module manages directly the 3D Space Mouse interface. To handle the Tangible Interface, to perform virtual camera calibration and to register virtual objects into physical settings, the Augmented Reality Environment utilizes the services of the **Mixed Reality Toolkit** or **MX Toolkit** [Dias03], developed in our lab. This Toolkit is a software development platform oriented to the AR/MR application developer, aiming at simplifying his/her programming tasks. This platform comprises a Software Development Kit (SDK) for the Windows environment, consisting of a set of C++ Classes packaged into modules. The toolkit utilises extensively the **AR Toolkit** and **Computer Vision** layer, for all matters regarding marker-based tracking and virtual object registration, but is defined at a somewhat higher abstraction level than the AR Toolkit software layer, by hiding from the programmer, low level implementation details and facilitating AR/MR object-oriented programming. The MX toolkit comprises eight system modules communicating with each other through the main system core. They are:

- Core System;
- Peer-to-Peer Communication;
- Peripheral Communication;
- Database Communication;
- Video Capture;
- Marker Tracking;
- Image Processing;
- 3D Rendering.

Amongst these eight different modules, three of them are indispensable elements: the Core - the only system part that cannot be replaced, but only upgraded; the Video Capturing; and the 3D Rendering. One of the main advantages of having modules in the system architecture is the construction of a flexible system, that can be simply upgraded or its modules replaced, without having any concern with the remaining components.

The **Augmented Reality Environment** module brings echocardiography imaging visualization techniques into a new stand. By allowing our system to have a AR option of visualization and interaction, we free the observer from conventional visualization, by bringing the 3D and 4D LV model to the real world, thus introducing new visualization techniques into the echocardiology medical field that are only now being exploited.

The system supports two different ways to interact with the AR environment. The first one, the 3D Space Mouse, is used primarily as a 3D user interface that, combined with AR visualization, allows an experienced user to guide with precision a 3D model to the appropriate place in the physical setting, registering the model in echocardiography images (also visible in AR). In Figure 4, the contour of a section of the LV is being manually registered, with the help of the 3D Space Mouse in the background echocardiography image of the same section, in an AR setting. The **3D Space Mouse** could be also attached to the echograph probe to help on the calculation of the different angles the probe does during each exam.

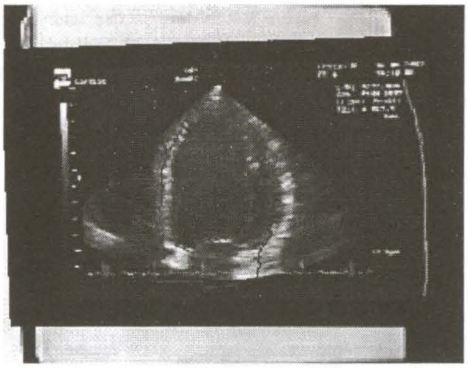

Figure 4 – Red contour of a LV section, being registered on an Echocardiography image of the same section, in an Augmented Reality Environment.

A more advanced scenario is to first register an echocardiography live video input, taken on a given section of the deformable LV, on the corresponding location of the patient body and then, to register the 4D deformable model of the LV, in correct sync with the input video. The 4D model of the LV should be registered around the thorax cavity. The user could easily know where to guide the 4D model once the echocardiography video is displayed over the "patient" or "dummy", using Augmented Reality. In Figure 5 we see a simplified version of this scenario, were the instead of a echocardiography live video input, we have a still image.

Figure 5 – Registration of the 4D model of the LV on the human body.

The other modality to interact with our system and to support LV model visualization in AR, is via a tangible interface, which provides, under certain limits, 6 Degrees of Freedom (6DOF). Users generally require real-time user interaction in AR. Having this in mind, we have developed a tangible interface as simple and natural as possible and we have come up with a tool, similar to the ones found in [Kato01a] or [Kato01b], or [Kato01c] but in the shape of a cube, which is suitable for our tangible interfaces requirements.

We refer to this physical tangible interface as the "Magic Examiner". This interface is a physical cube with different fiducial markers attached on each side, with the exception of one side, which has a small stick (like a pen) (See Figure 6). Each marker, which is tracked by the system, is associated to a coordinate system defined in the virtual camera reference frame. If the user manipulates this tangible interface, the system is able to recognize 6 DOF, enabling the examination of 3D and 4D virtual models.

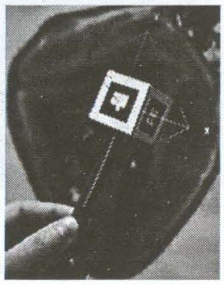

Figure 6 – The Magic Examiner tangible interface.

3.1 System Configuration

The typical hardware and software platforms required by our system, are as follows:

- Hardware:
  - CPU: HP Pentium III 1GHz; RAM: 256 Mbytes; Graphics Card: NVIDIA GeFORCE2 32 Mbytes; Video Camera: WebCam 5 from Creative Labs; Video see-through head mounted display; Olympus Eye-trek FMD 700, Multimedia Glasses (800x600 pixel)
  - 3D Space Mouse
  - Echocardiograph (not necessary if we have previously acquired echo images)
  - Magic Examiner
- Software:
  - MS Visual C++ 6.0 enterprise edition
  - MXToolkit
  - VTK (Visualization Toolkit)
  - ITK (Insight Segmentation and Registration Toolkit)
  - Space Mouse SDK
- Video Input: Direct X 9.0.
- Graphics: OpenGL and Open VRML
- Indoor Tracking method - Computer vision-based approach (MX Toolkit) with sparsely placed fiducial markers.

4. THE MAGIC EXAMINER TANGIBLE INTERFACE

The two major activities that can be performed by the Magic Examiner are the ability of transporting the virtual LV model from the world marker reference frame to its own reference frame and, to examine the model from all possible angles and distances, within certain limits.

The process for these two tasks begins exactly in the same way. There will be three reference frames (see Figure 7):

1. The camera;
2. The world marker;
3. The Magic Examiner top marker.

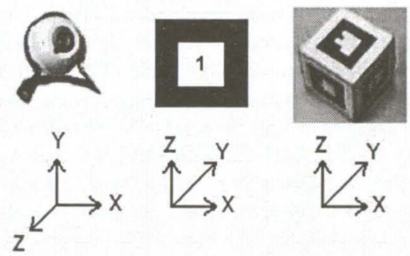

Figure 7 – The three reference frames: from left to right – camera, world and top marker of the Magic Examiner.

The first step is to transform the camera reference frame into the world marker one. For that, the user must issue a gesture with the Magic Examiner, that slightly approximates the interface to the LV and afterwards gently separates from it (see Figure 8). The procedure is as follows. In the initial situation, the user can notice the LV virtual model registered in the centre of the world marker. As the Magic Examiner cube approaches this world marker, this is detected by MX Toolkit. In fact, by computing the distance between the centre of the world marker and the centre of the top marker of the cube, in the camera reference frame, it is possible to detect if this distance reaches a pre-defined tolerance value.

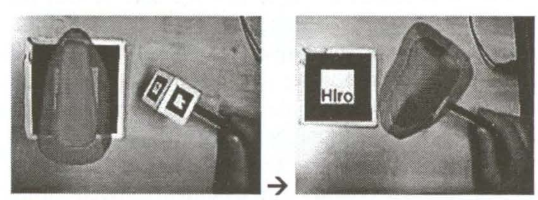

Figure 8 – Transporting the LV between the world marker to the Magic Examiner top marker.

If that tolerance is violated, an internal state is activated and MX Toolkit waits until the recognition of the world marker becomes impossible, due to the occlusion of the world marker by the cube top marker, in the approximation gesture. The system will then record the last visible position of the world marker centre. When the distance between this position and the cube top marker centre position, reaches a value within a certain small tolerance (in the separation gesture), the MX Toolkit will perform the transformation of the LV model between the mentioned marker reference frames. The toolkit simply disables the association of the LV model with the world marker centre and enables the association with the cube top marker.

When the model is finally placed on the top marker of the cube, the examination task can be performed. Each of

the five face markers of the cube have a pre-defined transformation matrix, relatively to the top marker reference frame, that will be passed to the model as there are transitions between markers, by means of the manipulation of the tangible interface. As an example, we show here one of the cases being handled:
From one marker to the cube top marker, the transformations are, by order:

1. Rotation in relation to the *zz'* axis of -90°
2. Rotation in relation to the *xx'* axis of 270°
3. Translation of $(x, y, z) = (0, 15, -15)$

The examination algorithm works as follows:

1. The initial marker reference frame is always the one associated with the top marker of the cube.
2. Once this marker becomes invisible by the camera, one or more markers of the cube become visible and the corresponding transformation matrixes, from camera to the each marker, are retuned by the MX Toolkit in a list.
3. The algorithm picks the first matrix of this list and transforms the LV model in the following way: first from the camera to the new marker reference frames; and then from the new marker to the top marker reference frames.

The LV model will be transformed accordingly, achieving a smooth transition between the cube markers, as the tangible interface is manipulated (see Figure 11).

5. CLINICAL USE CASE AND DISCUSSION

To evaluate if this model is feasible for the medical environment, we have tested it with 4D echocardiography. Echcocardiography is a widely used diagnostic technology in cardiology, as it is non invasive, doesn't use biological hazardous radiation and the size of the machines allows bedside examinations. Additionally it is already used as an imaging aide to perform several procedures (v.g. pericardiocentesis) and, if our system proves to be feasible and with technical advantage, could be used in still others, as catheter placement.
As mentioned in the introduction, the Magic Examiner tangible interface was developed as an integral part of a larger project, referred to as DIE-Heart (see Figure 9). The final purpose of this project is to better access the damage made to the myocardium muscle after a myocardial infarction.

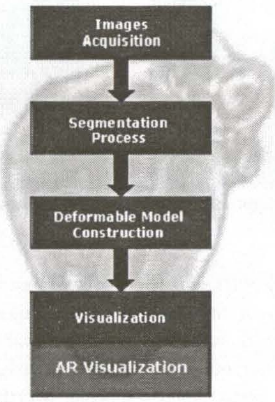

Figure 9 – DIE-HEART General System Architecture.

In DIE-HEART, echocardiography images of the Left Ventricle - LV of the patient are acquired and, subsequently segmented and post-processed in order to extract the information, needed to reconstruct a 4D deformable model of the patient LV during a cardiac cycle. A detailed description of this process can be found in [Dias04]. The extraction of the myocardium internal and external contour is performed on a segmentation phase, using an adapted version of the Level Sets algorithm. The next phase is to improve and consolidate the geometric and topological model, to create a first model of the LV. The created points are grouped into cells, in order to create a Boundary Representation (BRep) surface model representing the LV live tissue. The final result is a mesh of polygons for the internal contour of the LV (see Figure 10). As the human cardiac cycle normally takes 0.7 seconds and with an obtained echography movie frame rate of 25 frames per second, we end up with a virtual cardiac cycle of 14 times steps correspondent to the 0.7 seconds of the deformation period of the LV Model.

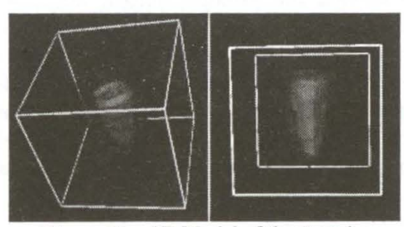

Figure 10 – 3D Model of the Systole.

As a result of the mentioned algorithm, we come up with a 4D deformable model of the LV algorithm, which can be inspected with the tangible interface so that the physicians can better access the results of this process. This algorithm could also be applied to other human organs or tissues.

Figure 11 – 'Magic Examiner' visualizing a 4D Model in an AR Environment.

In addition to the visualization of a 3D and/or 4D Model of a certain organ or tissue in a real environment, it is also possible to place this model on a real patient, registering it in its correct position and orientation, with the help of the 3D Space Mouse device. Moreover, an echography image of that specific part of the body can also be viewed in AR and registered on the patient's skin. This way we can assess the quality and similarity of the model comparing it with the real live organ or tissue. The physician takes advantage of the comprehensive visualization of the organ, allowing accurate localization of the pathology, while looking at the patient himself.

Figure 12 – 3D Model and Echocardiography in AR.

The production of AR models from echocardiographic images can potentially improve diagnostic accuracy, allow the implementation of invasive techniques and improve teaching and training. The creation of AR models that can be physically manipulated will enable echocardiography to move from an anatomic diagnostic tool to a more physiologic and pathophysiologic diagnostic ability. With help of AR it is possible to foresee the use of echocardiography to place catheters in the heart, both for diagnostic purposes – vg electrophysiological studies - as for therapeutic purposes – v.g. pacemaker implantation. Finally the AR models are more natural and allow simple interaction, therefore teaching tasks such as teaching anatomy and physiology becomes easier.

6. CONCLUSIONS AND FUTURE DIRECTIONS

The system presented in this paper describes a general object visualization and user interaction technique. It allows the visualization of 3D and 4D objects in AR, in our case, LV deformable models, making it possible to interact with virtual objects, within a real world environment. Although the use case reported in this paper refers to echocardiology visualization, our technique is also applicable in general tangible interaction tasks in other scientific domains. As a contribution of our work, we have shown the feasibility of AR and tangible interfaces in the cardiology medical field. However, the system still needs to be evaluated in concrete field trials in echocardiography, namely to assess the accuracy of the vision-based tracking system adopted and the usability of the tangible interface. In this context, both animal (first) and clinical (subsequently) field tests are envisaged for the near future. Several other future directions can be envisaged for this kind of technique, namely, enabling the manipulation of organs or other anatomical aspects of the human body with 6 DOF, giving the medical users new means to analyze, comprehend and achieve diagnosis. In the future, this interaction technique, once more accurate, could be also used to assist in planning surgical operations, allowing its utilization as a base for new education and medical practices.

7. ACKNOWLEDGEMENTS

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