An Augmented Reality System for Training and Assistance to Maintenance in the Industrial Context

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ABSTRACT

Complex Assembly and Maintenance tasks in industrial environments are excellent domains for Augmented Reality (AR) applications. The need for good training and the access to large amounts of documentation are conditions making the use of AR techniques most promising. The basic idea of Augmented Reality is to bring additional information as seamlessly as possible into the view of a user. In this paper an AR system for training and assisting in maintaining equipment in industrial context is presented. The key hardware features of the system are an optical see-through Head Mounted Display, which superimposes the augmentations in the view of the user; the tracking system, which gives the system the poses of user and equipment; and a special stand for the installation of the whole application. Aspects of the usage of an infrared optical tracking system and the calibration procedures needed for good results of the virtual overlays are discussed. Finally a scenario-based concept, which takes users step by step through training or maintenance tasks, is described.

Keywords

Augmented Reality, Maintenance, Computer Vision, Tracking, Interactive Workspace

1. INTRODUCTION

In industrial environments maintenance processes are both very important to guarantee quality and often quite cumbersome. In the case of complex mechanical equipment, such processes usually demand access to documentation such as technical manuals, either in traditional paper form or digitally e.g. CD-ROMs. This is especially important where & when the procedures are performed infrequently.

Another aspect, where documentation and guidance is key, is the training of workers on new maintenance or complex assembly tasks. As the complexity of the assembly or maintenance task increases, training becomes the significant factor in respect of both time and money.

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The system specified in this paper is dedicated to those situations and aims at:

- Providing assistance to a user who has to perform demanding working processes on complex mechanical assemblies.
- Increasing the skills of users to perform such processes by providing a variety of training scenarios.

As a difference with simulation tools, the training can be done with this system directly on real equipment with very limited risk. Users can perform the real procedures and therefore do not need simulation tools such as gloves, tactile feedback to *feel* what they are doing.

Augmented Reality (AR) is the technology used to implement this assistance to the user, which consists in giving users all information, called augmentations, necessary to carry out safely and efficiently complex maintenance procedures. This information is provided directly into the working environment by the use of an optical see-through Head Mounted Display (HMD). Additional to the HMD are a microphone and head phones. The AR system comprises a fixed stand with the tracking systems attached, the user equipment and the actual equipment to be maintained or assembled. A more detailed description of the system set-up is given in section 3.

As basic augmentations, the user can be provided with instructions (text displayed in the HMD and audio through the head-phones). While those augmentations do not demand tracking of the user or the mechanical assembly (object), 3D overlays, e.g. highlighted parts of the object to work on, do. The tracking provides the relative position of the user and the object, thereby making possible a projection of the overlays at their correct visual place on the object.

The tracking aspects and the resultant calibration procedures are described and discussed in section 5.

All augmentations and rendering of the visual augmentations, together with the scenario concept, that allows the user access to them, are illustrated in section 4.

Results from the recent implementation and future plans concerning business aspects and system improvements are discussed in sections 6 and 7.

The work presented here is embedded in the European project STARMATE, which consists of a consortium of six partners from different European countries. Researchers as well as end-users belong to the consortium, allowing easy implementations and tests in real working environments during the project.

2. AUGMENTED REALITY IN INDUSTRY

Augmented Reality (AR) is a growing field for current research, realised in different domains such as medicine, e.g. in [Fig01a] and [Sch02a], Cultural heritage, e.g. in [Gle01a], engineering design, e.g. in [Fio02a], and others. Though the idea to use AR for Manufacturing, Maintenance, Repair and Training in industrial environments dates back to the early 1990's [Cau92a], up to now it has not been implemented as a real product.

A more recent description of the early ideas concerns the assembly of bundles of electric wires in aircraft [Cur98a]. More AR applications in the Aerospace domain are described in [Miz01a].

More industrial approaches of an AR demonstrator have been the insertion of a lock into a car door [Rei98a], repair of copier machines [Fei93a] and a guided assembly application [Sha97a].

In contrast to other domains, where AR technologies are applied, industrial environments require both mobile and non-mobile AR systems. A case study of mobile AR systems for the maintenance of power plants can be found in [Kli01a]. The system presented in this paper is not mobile in the sense, that the user still is connected to a stand. On the other hand the flexibility of the stand itself is an important aspect, to be able to apply the system in different places within a larger work environment.

The use of a stand has an impact on the choice of the tracking system. Many AR applications use optical tracking with cameras on the head of the user and markers placed in the work environment, e.g. [Bar02a]. Due to the integration of the stand into the system, electromagnetic trackers and infrared stereo tracking systems with two fixed cameras and small retro-reflective markers can be used in the system, as present in this paper.

A recent project quite close to the idea of STARMATE is ARVIKA [Wie01a],[Alt02a]. It has a stronger focus on the evaluation of different approaches, both mobile and non-mobile.

Similar to the decision to implement a mobile or non-mobile system is the choice of video see-through or optical see-through display devices. There are only few optical see-through devices available, but they have the advantage of full resolution and no time delay for the real world view, which are important aspects for safety reasons. Moreover, with these headsets, the 3D perception of the environment is maintained both for the real view of the environment and the synthetic elements. Therefore a see-through HMD is used in STARMATE.

The work presented in this paper was described in an earlier phase of the project from a more conceptual point of view in [Sch00a].

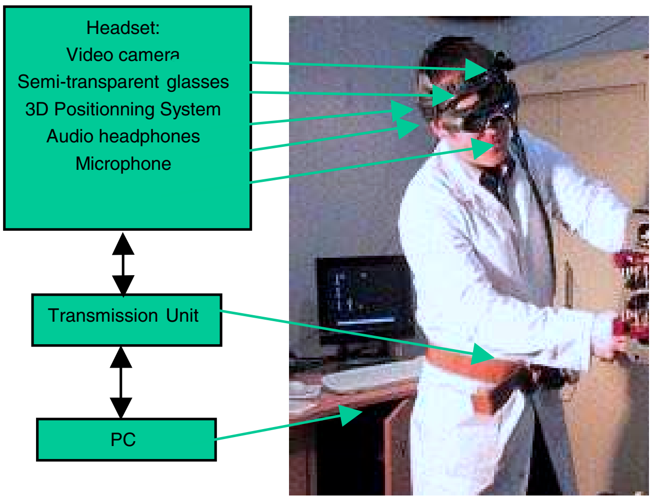

Figure 1: User equipment

3. SYSTEM COMPONENTS

In this section the hardware components of the system are described. It is composed of the following components:

- The user equipment including a headset and the belt allowing communication between user and processing unit.
- A processing unit for calculations and storing the database (ie. all augmentations relative to the object)
- A stand including the 3D-tracking systems (optical and magnetic) as well as spots-lights.

Those components are described in more detail in the following sections.

User Equipment

As mentioned before, the system is based on Augmented Reality technology: it consists of mixing computer-generated images, called augmentations, with the real world view to improve the user's perception of the environment.

For a typical use of the STARMATE system, the user is equipped with a lightweight helmet, as illustrated in Figure 1, which integrates an optical see-through HMD, a microphone, headphones, and a 3D-positioning sensor with the following functions:

- The HMD allows the user to see the real world augmented by computer generated images.
- The headphones provide the user the possibility to get audio information on the procedures to be achieved as well as visual data.
- 3D augmentations can be directly superimposed on their real counterparts thanks to the data provided by the 3D-positioning sensor of the tracking system (which gives the position of the objects of interest in the space in relation to user's position). This enables parts of interest to be highlighted and shows as well how to interact with them. The type of this sensor depends on the tracking system.
- The microphone allows the user to easily interact with the system by using speech recognition technology.

As the users have their hands free, they can easily manipulate the equipment being worked on. The need to keep referring to extensive paper documentation is now removed. To have "hands free" operation is a key benefit for industrial applications. However, it should be possible to select objects not only by speech control, therefore a virtual pointing device is provided. This is a virtual ray, fixed relative to the head of the user, which allows objects to be designated in a multi-modal way, which compliments the speech recognition. When the virtual ray intersects the required object in 3D space, a simple speech command completes the selection.

The described lightweight unit, carried by the user, is connected to a powerful control unit that manages all procedures and the dataflow.

The Stand

Though the system is not mobile in the sense that the complete set-up is attached to the user, it is designed to be mobile in that it can be used in different places without much effort. Therefore it is important that the complete equipment is easily installed and configured by the user.

Consequently, a stand has been designed and developed so as to attach all the elements needed by the system as e.g. lights and tracking systems. Figure 2 shows a side view of this stand.

Figure 2:The stand from side view

The stand is up to 3 meters high, 2.5 meters wide & 0.6 meters deep. It is telescopic and has a series of stops to allow the regulation of height. The stand can be adjusted to a height between 1.75 meters and 3 meters. It is foldable, easily movable and takes into account all the constraints required by the system and in particular by the tracking system (e.g. the distance between the cameras and their orientation).

Metallic parts of the stand are avoided as much as possible in order to keep distortions of the electromagnetic tracker to a minimum. It has a mat finish to prevent reflections, which could distort the optical tracking system.

Technological Choices

Below are some details of the hardware (HW) and software (SW) choices made for this system:

- The choice of Augmented Reality was made rather than Virtual Reality so that users do not loose the perception of the real environment: by using semi-transparence the real world view is maintained. Another solution would have been an immersive headset in which a mixing of the reality (recorded with a camera) with the augmentations would be projected on the displays of the HMD. But in that case the user would have a more limited field of view and have a worse perception of the real environment, which can be dangerous in a maintenance operation.
- For the visual Rendering, WorldToolKit, an off-the-shelf product, was used. It manages the positioning and appearance of the augmentations, as well as the 3D graphical user interface, such that all information is provided at the right time to the user.
- The speech recognition software integrated uses Microsoft Speech SDK. A major restriction is that it is only available in English (and Japanese). If it is planned to implement the system in other languages then a change of the tool will be necessary.
- It was decided to use a wired datalink to transmit information from the PC to user, but an ideal solution would of course be wireless. This shall be studied in a later step, once the concept is validated with a working prototype.
- An optical tracking system is being developed within the project. More details about this system are provided in section 5. However, the system is designed in a way that it is usable with any kind of tracking system. The integration of a magnetic tracking system has already been done successfully. So far optical and magnetic tracking systems are the most suitable for this kind of applications, not only because of their price, but more importantly because of their precision.

4. AUGMENTATIONS AND SCENARIOS

The basis of the system is the use of scenarios to guide users step by step through difficult maintenance procedures, thereby increasing the reliability and the safety of the operations.

The aim is to bring automatically all the information required by the user to achieve complex operations, directly into the working environment, where and when needed.

Augmentation Types

Practically speaking, depending on their purpose, information can be instructions of "what to do and how", but also pictures, plans, videos, sounds, 3D animations and CAD models.

The display mode depends on the type of the augmentations:

- Headset registered information: General information such as instructions, symbols, warnings are always displayed in front of the user's eyes,
- Equipment registered information: Information specific to the maintained equipment is superimposed on the real worldview.

Indeed, it can be very helpful to see a 3D model of a particular complicated piece of the equipment directly registered on its real counterpart. It enables to see all the subparts, how they are integrated into the equipment and how it works.

Figure 3: 3D augmented workspace

The idea is to focus the attention of the user on the main elements of interest, keeping in mind as well the safety procedures.

An interactive 3D-augmented workspace is thereby created around the user. This way of working with 3D "augmented" elements enables each user to feel that the equipment and its documentation as well as the maintenance procedures are all integrated in one single world.

The workspace can be different for each user as it can be easily configured, depending on their preferences. For the hardware point of view, the stand is designed for that purpose. From a software/3D point of view, the user-friendliness lies in the usage of the AR environment, but also in the use of vocal analysis/synthesis that enables a kind of dialog between user and system. Using voice commands, the user can navigate in the scenarios, place information where preferred, configure voice, etc., in an easy way.

Look & Feel Concept

The information displayed in the headset is semi-transparent and as such it is always possible for users to distinguish virtual information and real equipment.

In order to give users more flexibility & efficiency in the viewing of information, a "Look & Feel manager" was designed and integrated to the system. This module is in charge of augmented elements general appearance and behavior. It discharges scenario authors & users from specifying the appearance and position of all augmented elements. The L&F will manage the position of all windows, their sizes and colors, the position of the menus… Main objectives are to avoid problems of occlusion & conflicts between information windows, and to provide several default information display modes, depending on the context of the applications. Of course users also have the possibility to modify existing Look & Feel files or create their owns.

Scenario Concept

The scenario mechanism of the system relies on XML technology. XML maintenance scenarios are written, which make the links between equipment database and maintenance procedures. A tool is provided to help in a semi-automatic way.

The database can contain almost any kind of data formats.

The procedure for its development is different depending on the equipment on which STARMATE is implemented:

- If it is "old" equipment, 3D models might have to be developed specifically. It is anyway possible to reuse all existing information associated to the equipment documentation.
- If the equipment is new or still in development, the idea is to associate people working on the product documentation to develop in parallel a STARMATE database.

The scenarios are transferred to the system, which sends information to the user relative to each step of the procedure.

5. TRACKING AND CALIBRATION

While the accurate tracking of user and equipment is not important for text augmentations, as they do not need to be registered to anything in the real world, it becomes essential for 3D overlays and all other augmentations, which are registered to some object in the real world.

In this system, two different tracking systems were chosen and implemented. For fast evaluation of the whole set-up an off-the-shelf electromagnetic tracker was integrated. It allows six degrees of freedom (DOF) tracking of the user, by placing a sensor on user's head.

The main drawback of an electromagnetic tracking system is of course the sensitivity of the system towards metallic environments. This is an important constraint to take into account, as metallic and magnetic machines, e.g. motors, can seriously perturb the functioning of the tracker. Those perturbations can however be avoided if precautions are taken. Another drawback of non-wireless systems is the cable, connecting the sensor to the processing unit of the tracker, which limits user's freedom of movement. Especially the tracking of a movable object in the work environment gets unpractical, because of such a cable, and also concerns safety reasons. To overcome those problems and constraints, an infrared stereo tracking is currently being developed and integrated into the system. A short description of the system follows in the next subsection.

To set the correct projection for a good overlay in the HMD, it is not enough to know the head position of the user. In a further step, the relation between user's eyes and the HMD has to be calibrated. This is described in more detail below.

Infrared Stereo Tracking

The infrared stereo tracking system consists mainly of two CCD cameras with infrared filters blocking out the visible light, two infrared spots, retro-reflective markers and a corresponding PC. It was implemented partially during the STARMATE project. The basic principles of such a tracking system, like the camera calibration, has been described and discussed in

[Ase95a] and [Tsa86a]. Similar infrared stereo tracking systems have been introduced in [Mad96a], [Dor99a] and [Rib01a].

Figure 4: View on tracked person and object from a normal camera and the infrared camera

The passive markers have a diameter of about 15 mm and reflect the infrared light from the spots to the cameras. Three of them with a fixed geometry define a rigid body, which can be tracked and distinguished from other rigid bodies with different geometries. From such a rigid body, rotation and translation (6 DOF) can be calculated. Figure 4 shows a scene with a tracked user and a tracked mechanical object. The left image is a photo with emphasized markers, the right image is the original view from one of the infrared cameras with overlays on the camera image as monitoring function.

The cameras are positioned about 2m from the center of the interaction volume of about 1m x 2m x 2m. The accuracy of the distance measurements is around 1 mm at 21 frames per second.

Before using the infrared stereo tracking system, the cameras have to be calibrated and a world coordinate system defined. This is done by moving a single marker in the work environment to define sequentially the positions of the world coordinate system.

The camera calibration is based on 3D point correspondences from the two synchronized cameras. The positions relative to the cameras are calculated by applying the Levenberg-Marquardt method [Mar63a].

HMD Calibration

The calibration of an optical see-through HMD is also a critical step for these types of AR applications. It is necessary to calibrate the HMD, to get good augmentations, i.e. to allow for differences in eye distances and the wearing of the HMD. These parameters are not the same for every user, and may change slightly each time the HMD is put on.

The basis for the HMD calibration is a set of corresponding 2D points on the HMD display and 3D points, e.g. on a known object, in the real environment. This set of correspondences is gained by moving the head in certain positions such that a displayed tripod in the HMD superimposes a real tripod, e.g. three edges of a special calibration cube. If the tripods are aligned, the head position, consisting of rotation R^H and translation T^H, for this alignment step is stored on user command.

This means in each step four point correspondences between a 2D display point X_D and a 3D point in world coordinates X_W are gained. These points are transformed to points X_H in the head coordinate system by

$$X_H = R^H \cdot X_W + T^H .$$

Applying this transformation after every alignment step allows the usage of all points from different alignment steps to one minimization problem.

The algorithms used in the presented work to calculate the parameters like the center of projection, focal length, and principle point, match in principal with methods presented in [Azu94a] or [Tuc00a].

The map M maps from 3D points in head coordinates *(x,y,z)* to 2D points in display coordinates *(u,v)* and consists of a projection P after a rotation R and translation T:

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & 1 \end{bmatrix} = P \cdot \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}.$$

It can be transformed such that the parameters to calibrate can be gained by solving the over-determined linear equation system

$$\begin{bmatrix} x & y & z & 1 & 0 & 0 & 0 & 0 & -ux & -uy & -uz \\ 0 & 0 & 0 & 0 & x & y & z & 1 & -ux & -uy & -uz \\ & & & & & & \vdots & & & & \end{bmatrix} \begin{pmatrix} m_{11} \\ m_{12} \\ \vdots \\ m_{33} \end{pmatrix} = b,$$

with b resulting from the know entry m_{34} =1. The matrix M can then again be decomposed into the projection P, rotation R and translation T.

At least six point correspondences are needed, which are available after the second alignment step. The number of points for the optimization is growing. After the second step there are eight points, than twelve and so on.

Beginning with the second alignment step, the parameters are calibrated after each step. If the variation of the parameters to calibrate between two steps is below a certain threshold or a maximum number of steps is reached, the calibration is finished.

6. BUSINESS ASPECTS

A market analysis has been carried out within the project, requiring the help of an external consultant. Its objective was to know as precisely as possible the reaction of the market regarding a system such as STARMATE, as well as studying in a more general view what are its needs and expectations in terms of products dedicated to maintenance and training.

Summing up, the results of that study tend to indicate that systems based on Augmented Reality, like the system presented here, might be commonly used for maintenance and training within some years.

Before, it will be necessary to educate users to such a kind of tool, which will completely change their way of working.

It will also be necessary to improve the system by integrating some useful additional functionality. The market is certainly here but some work is necessary to get a product that could be commercialized. It appears in particular, that it is not absolutely necessary to develop a tool that would be dedicated to both training and assistance to maintenance. It seems to be more pertinent to develop two separate tools, based on the same principle and technologies, with specificity related to each domain of application.

7. CONCLUSION AND FUTURE WORK

As the results of the market analysis and the feedback collected from end-users tends to show, some work is still needed to get a usable and commercially viable final product for real applications.

The improvements identified relate to all the typical tasks for Augmented Reality applications. In particular the wearability of the system is a crucial point i.e. reducing the weight of the user equipment and making it completely wireless. The displaying of the 3D augmentations in form of overlays can also be made more seamless by an improvement in the accuracy and reduction of the latency of the tracking system. Furthermore better access to information and faster internal communication between the internal sub-parts of the system will improve the usability of the system.

Even though the system is still under development, the results of the survey are very positive and provide confidence that this type of AR product, could one day become the standard for many maintenance and training applications.

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