REGISTRATION APPROACHES FOR AUGMENTED REALITY
A Crucial Aspect for Successful Industrial Application

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Abstract: In the past years, a variety of Augmented Reality (AR)-based applications were created, aiming to support industrial processes. Although these first demonstrator applications or prototypes cover all parts of the industrial product process - design, planning and production, service and maintenance - only a few of them actually turned into established and applied solutions. Reasons for this lack of acceptance are - amongst others - their insufficient usability and accuracy.
One crucial step in the accuracy chain for an Augmented Reality system is the registration of real and virtual world. This paper presents different approaches for industrial registration, which are being investigated in the context of an Augmented Reality based factory planning application. The resulting toolbox promises to be helpful and valuable for general application in industrial AR. To support the choice for an optimal registration method for a given scenario, the toolbox is currently being evaluated according to usability and accuracy criteria. The current state of this evaluation as well as future planned studies are also outlined here.

1 INTRODUCTION

In the past years, a variety of AR-based applications were created, aiming to support industrial processes. These applications cover all parts of the industrial product process: design, production and planning, or service and maintenance. However, only a few of them actually managed to develop from demonstrator applications or prototypes into valuable and established solutions. Regenbrecht et al. state, that the maturity of contributing technologies (tracking, displays, etc.) does not suit the demanding industrial conditions yet regarding robustness, reliability, quality and practical experience (Regenbrecht, 2006).
With respect to quality and practical experience, a successful industrial AR application must be easy to use and sufficiently accurate, offering a well thought out interface which meets the concrete needs of the industrial environment.
One important aspect for AR applications in general and in specific for industrial AR scenarios is precise alignment of virtual content with the user's view of the real world, hence good registration accuracy.

1.1 Motivation

The overall registration accuracy is depending on several influence factors. In (Holloway, 1997), Holloway lists tracking, calibration and modeling as main error sources in AR systems. For industrial environments, the tracking factor often needs to be extended by a referencing offset pose (translation and rotation) connecting the tracking target (or tracking world) coordinate system with the model coordinate system which later holds the virtual content (see figure 1).
The tracking system in general provides as output the transformation between the tracking world coordinate system and the tracking target coordinate system. However, sometimes an additional offset is needed to move from the tracking target to the required model coordinate system. Digital car bodies or car parts for instance, usually have a specific model coordinate system which lies in the middle of the front axle (right-handed, y pointing to the back of the car, z going up). When tracking a real car body in an AR factory planning scenario, the tracking target cannot be placed in accordance with the model coordinate system, but needs to be attached to some surface part of the car body. To overlay virtual information on the real car body, it is thus necessary to determine the

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offset from the target coordinate system to the model coordinate system.

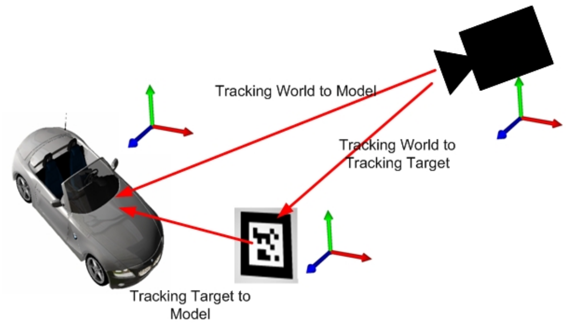

Figure 1: Coordinate systems in an industrial AR environment.

1.2 Support for Industrial Registration

Motivated by these needs, this work presents different tools for supporting industrial registration. The following approaches for the determination of the reference offset are described:

- Referencing using an external coordinate measurement machine (CMM): The most reliable referencing process requires a CMM at hand.
- Referencing using 3D-3D correspondences: Given tracking data and CAD data, manually defined correspondences can be used for referencing.
- Referencing using 2D-3D correspondences: In this case, image data and CAD data are combined to do the referencing process.
- Referencing using digital data manipulation (CAD-based): Finally, the referencing process can be bypassed by bringing model and tracking target coordinate system into accordance.

The different approaches shall be evaluated according to their usability and accuracy. This evaluation process is currently undertaken and its results will support the choice of referencing tools for concrete application scenarios. Usability is measured in terms of needed input data, needed knowledge for performing the registration and time consumption of the task. For accuracy evaluation, an estimate for the resulting pose accuracy shall be determined based on the underlying calculations.

2 RELATED WORK

Registration and registration error analysis have been subject to many publications in the area of Augmented Reality. A comprehensive overview on registration error analysis is given in (Holloway, 1997). Here, Holloway states tracking, calibration and modeling as main sources of registration error. Based on these sources of error, research has been done to improve or analyze registration accuracy in terms of tracking systems (Hoff and Tyrone, 2000), (Davis et al., 2003), calibration methods (Gibson et al., 2002), (Vigueras Gomez et al., 2005) or complete AR systems (Kato and Billinghurst, 1999).

This work covers another aspect of registration, needed besides good tracking and calibration, when the tracking target cannot be placed at the desired location: the determination of a referencing offset, as described above (see figure 1).

In their work on the integration of Augmented Reality in the assembly domain, Reinhart et al. mention the importance of referencing, that is the determination of the relative position of displayed objects to known reference marks (Reinhart and Patron, 2003). Another example of referencing problems is given in (Appel, 2003). The author states the great effort which is needed to reference markers (of a marker based optical tracking system) in the spacious environment and to place them at the needed positions.

In the following sections, this problem shall be met by presenting several approaches for industrial referencing.

3 APPROACHES FOR REGISTRATION

In the context of an AR application for factory planning, several approaches for registration were developed. The application itself is described in detail in (Pentenrieder et al., 2007). 3D digital planning data is augmented onto high-resolution 2D images of the real factory to offer possibilities for AR-based factory planning in terms of distance measurements, collision detections or variance comparisons. Tracking is realized through an optical marker-based tracking.

Depending on the type of application and the available resources, it is necessary to calculate an additional referencing offset as described above. The following possibilities for referencing are available:

3.1 Referencing using an External Coordinate Measurement Machine

With an external coordinate measurement machine (CMM), the referencing process can be achieved by using the referencing functionalities of the CMM. CMMs provide high-precision measurements based on a measuring probe. They are equipped with a measuring software, that allows to transform the internal origin coordinate system to an arbitrary location using point correspondences.
Using CMM referencing in the context of AR-based factory planning, requires a CMM which is already referenced to the model coordinate system (e.g. the car body coordinate system). This can be achieved using the CMM measuring software. Then, 3D point correspondences between tracking target coordinate system and model coordinate system are used to determine the needed offset. Figure 2 shows an excerpt of the tool for CMM referencing. The user needs to specify the four marker corner points of a paper marker (tracking target) in the CMM coordinate system (model coordinate system). Based on these four points the transformation between the marker coordinate system and the model coordinate system is calculated, by setting up the transformation matrix using the point coordinate vectors.

$$\begin{pmatrix} u_x & v_x & w_x & c_x \\ u_y & v_y & w_y & c_y \\ u_z & v_z & w_z & c_z \\ 0 & 0 & 0 & 1 \end{pmatrix}^{-1} \quad \text{with } u = \overrightarrow{P1P4}, \; v = \overrightarrow{P1P2} \text{ and } w = u \times v$$

For our marker tracking, the origin lies in the center of the marker ($c = (P1+P2+P3+P4)/4$). The coordinate axes are indicated in figure 2, z pointing to the observer.

In addition, an accuracy value for the corner point accuracy can be specified which is then used to estimate the accuracy of the resulting transformation (positional and rotational accuracy), see section 4.

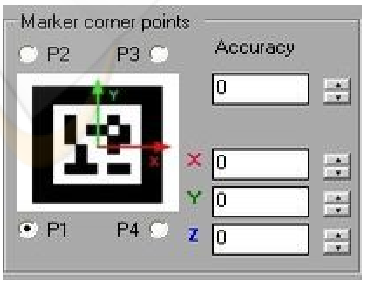

Figure 2: CMM referencing.

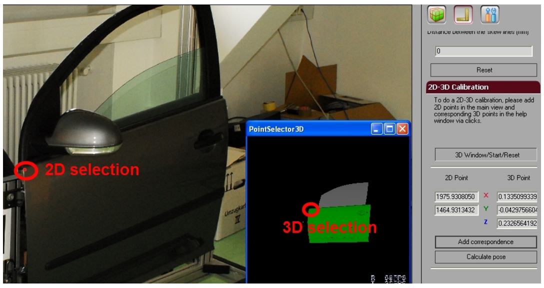

Figure 3: Referencing using 2D-3D point correspondences.

3.2 Referencing using 2D-3D Correspondences

The next option for referencing is based on 2D-3D point correspondences which are provided by the user through clicks. The tool requires image data and corresponding 3D digital data. Figure 3 presents the tool in usage. 2D points are selected in the image of the scene and 3D points are chosen in a viewer showing the corresponding digital model. The point correspondences are sent to a camera pose estimation algorithm, that calculates the transformation from the camera coordinate system (in our case this is the tracking world coordinate system) to the model coordinate system.

3.3 Referencing using 3D-3D Correspondences

When information on specific points in the 3D model is available, 3D-3D correspondences can be used for referencing. In this case, selected locations are used which are known in the 3D digital model and can be tracked easily in the real environment. An example from industry are specific drill-holes which are calibrated precisely when the object is manufactured. These holes are known exactly in the digital data. Their real counterparts can be tracked by using adapters, that fix the tracking target to the calibration point (e.g. drill hole). Figure 4 depicts a marker equipped with an adapter to fit the drill holes of an align fixture. The 3D-3D referencing tool uses shots of a scene featuring adapter markers for selected calibration points and a list of corresponding digital 3D coordinates to estimate the transformation between camera (tracking world) coordinate system and model coordinate system. Given this transformation, the offsets from each marker (tracking target) to the model coordinate system can be calculated, referencing thus each single marker to the model coordinate system.
For optimization purposes, the tool first optimizes the

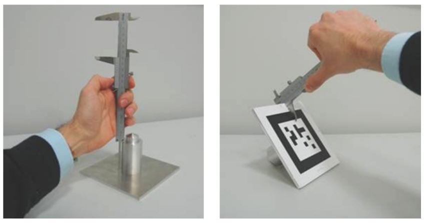

Figure 4: Adapter for 3D-3D referencing.

offsets between all available markers over all given images and then performs the referencing step to the model coordinate system. That way, the resulting transformation is optimized with respect to the given images and offers thus optimal conditions for later planning and analysing tasks based on the same image data.

3.4 Referencing using a CAD-based Approach

The last approach requires some knowledge in the CAD environment. Here, the digital model itself is manipulated to fit better the requirements for its usage in the AR scenario. A favorable location in the real environment is chosen which can be easily retrieved in the digital representation, for instance a drill-hole. The tracking target is placed at the chosen location in the real world. Then, a CAD tool is needed to move the coordinate system of the digital model from its current position to the location chosen for the tracking target in the real environment. That way, the transformation from the tracking target coordinate system to the model coordinate system does no longer require a translation, as their origins are identical. To compensate for the rotational discrepancy, the model is loaded in the factory planning environment and rotation changes around the different axes are performed with sub-degree precision, until optimal visual consistency is achieved.

4 EVALUATION APPROACH

The referencing toolbox shall be evaluated with respect to accuracy and usability criteria. As this work is in progress, this section presents the current state of our analysis.

4.1 Accuracy Evaluation

For the evaluation of accuracy, some assumptions on the input accuracy are needed which can then be used to calculate an accuracy statement for the resulting translation and rotation. The next paragraphs describes the basic work which has already been done in order to prepare for a comprehensive accuracy study.

CMM Referencing. When a CMM is used for referencing, the input accuracy is provided by the positional accuracy of the CMM which is usually stated in the machine specification. Given this value, the resulting transformation accuracy can be calculated using backward error propagation (see for instance (Hartley and Zisserman, 2003)).

The base formula for backward propagation is given by

$$[R|t] \cdot q_k = p_k \quad \Rightarrow \quad [R|t] \cdot q_k - p_k = 0$$

where $[R|t]$ denotes a 4×4 transformation matrix based on rotations around the three axes r_x, r_y, r_z and a three-dimensional translation (t_x, t_y, t_z), p_k are the measured points in the CMM coordinate system and q_k are the corresponding points in the marker (target) coordinate system.

For the calculation, three point correspondences are needed which form the matrix

$$F = \begin{pmatrix} [R|t] \cdot q_1 - p_1 \\ [R|t] \cdot q_2 - p_2 \\ [R|t] \cdot q_3 - p_3 \end{pmatrix} = 0$$

The Jacobian matrix which represent the uncertainty is then given by

$$J_F = \frac{\delta F(q_k, p_k)}{\delta(t_x, t_y, t_z, r_x, r_y, r_z)}$$

This calculation process is integrated in the tool depicted in figure 2. Concrete accuracy values can be calculated by entering a positional accuracy for the used coordinate measurement machine together with the determined 3D points.

2D-3D Referencing. For 2D-3D referencing the input accuracy is the accuracy with which the user can click a specific point in an image and on a 3D digital model. To determine this click accuracy tests were performed using our marker tracking as basis. The participants were asked to click on three example images of a paper marker (1: camera image 640x480 pixel, 2: camera image 3008x2000 pixel, 3: simulated image 3008x2000) of different quality and select a specific corner point within the environment of the 2D-3D referencing tool. For image 1 and 2 the results were compared with the respective corners detection results of our marker tracking algorithm, for image 3 the real values were known due to simulation. The results of this study (average euclidean distance and standard deviation in pixel) are shown in figure

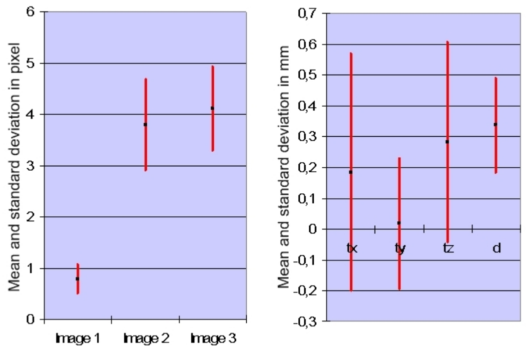

Figure 5: Results of the click tests: (a) 2D case (b) 3D case.

5 (a). A similar test was performed for the 3D case, whose results are visualized in figure 5 (b) (mean error and standard deviation in 3D and for the euclidean distance). In a second step, the detected errors and standard deviations were used to add Gaussian noise to the correct marker corners and compare the noisy pose results with the correct ones. Figure 6 presents those results for the low (image 1) and the high resolution case (image 2). User clicks can thus compete very well with image based corner detection.

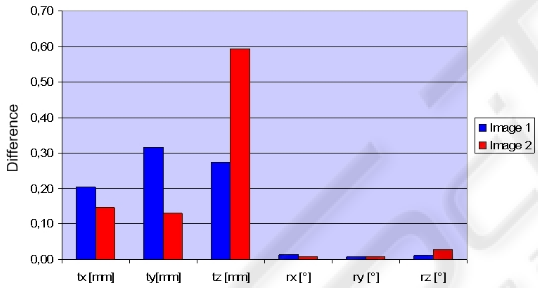

Figure 6: Differences in translation and rotation for the images.

3D-3D Referencing. For the 3D-3D referencing case we consider the 3D model data to be perfect. Thus, the optimization depends on the quality of the adapter and on the marker tracking determining the location of the marker. Figure 7 shows a pose error calculation for a representative 3D-3D referencing scene based on the accuracy information determined for our marker tracking (see (Pentenrieder et al., 2006)).

CAD Referencing. For the CAD approach it is difficult to create an accuracy statement. The output again depends on the quality of the target adapter and the tracking. The position is then fixed manually through coordinate system movement. Due to

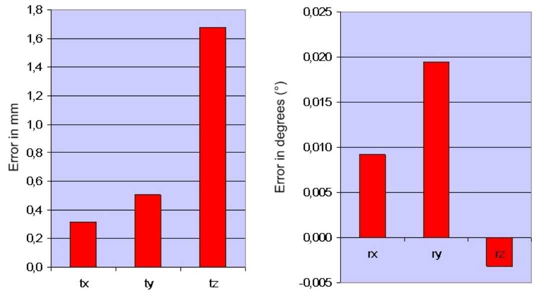

Figure 7: Pose error for 3D-3D referencing.

CAD scaling and the selection of favorable points the re-positioning of the coordinate system can be done with model accuracy, meaning with the accuracy of the model tessellation (polygonal representation of the real object). The rotation is adapted manually. In case a 0.1° step size is taken, the maximum accuracy achievable is in this range.

4.2 Usability Evaluation

For the usability evaluation the following criteria are regarded: input requirements, needed knowledge to perform the referencing process and output information.

CMM Referencing. CMM referencing requires knowledge about the usage of the CMM and its measuring software. Thus a skilled person needs to do the task, providing CMM point coordinates as input for the referencing tool. The output consists of a transformation from the marker coordinate system to the CMM coordinate system and a corresponding accuracy value for the calculation.

2D-3D Referencing. 2D-3D referencing is probably the easiest way of creating a reference offset. Corresponding image and model data needs to be available. By simple clicks, the user identifies correspondences between 2D and 3D world. The result is given as a transformation from the camera to the model coordinate system. Different from the other approaches, here no intermediate marker coordinate system is needed.
Still, it is important to have image data available where correspondences can be identified easily.

3D-3D Referencing. 3D-3D referencing requires a set of images which show markers attached to selected locations of an object, that are also known in

the digital world. The tool then calculates the referencing offsets based on this input data. However, the crucial aspect is the acquisition of this data, hence the positioning of the markers using adapters and the identification of the corresponding CAD point information. For special locations (e.g. drill holes) this digital data might already be given and adapters for such holes need to be manufactured once and can then be reused.
As the referencing offset is optimized over all markers and over all images, the outcome is favorable for analysis with the given image set.

CAD Referencing. Similar to the CMM referencing, the CAD-based approach requires a skilled person who is able to manipulate the given digital model data, such as moving the model coordinate system to a specific location. Furthermore, the marker needs to be placed at the corresponding location of the real object, similar to the 3D-3D case. Then, the manipulated model needs to be superimposed onto an image of the real scene with the marker in place to optimize the orientation of the model using manual adjustment. Next to CAD knowledge, this approach therefore also requires experience in manual adjustment.

5 CONCLUSIONS AND OUTLOOK

Accurate registration of real and virtual data is crucial for many Augmented Reality application. In industrial environments, specific data, knowledge and systems are available which can support the registration process. Still, available resources differ from application to application. It is therefore necessary to provide the users with a comprehensive toolbox of different referencing methods, offering the flexibility to choose the referencing approach suiting best the given application.

We created a toolbox of various referencing methods and are currently evaluating the different approaches with respect to accuracy and usability. Our first studies show, that each tool has its advantages and disadvantages. Based on these first results, we will further evaluate the different approaches using industrial scenarios in factory planning. The concrete application of all approaches to the same scenario will allow an absolute comparison and actual user feedback will help us to verify the current implementations and gain experience for improvements and extensions.

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