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Dissertation

Augmented Reality based Factory Planning

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Zusammenfassung

Die heutige Fabrikplanung zeichnet sich durch immer kürzere Produktlebenszyklen aus, verursacht durch sich rasch verändernde Kundenanforderungen. Es besteht daher großer Bedarf für Planungswerkzeuge, die eine flexible und schnelle Umstrukturierung von Produktionsanlagen unterstützen. Die Virtuelle Realität (VR) Lösung für dieses Problem wird durch die Digitale Fabrik verkörpert, ein Netzwerk aus digitalen Modellen, Methoden und Werkzeugen, welche eine Überprüfung von Planungsprojekten erlauben bevor diese tatsächlich umgesetzt werden. In der Praxis sind die Digitale Fabrik und die realen Produktionsbetriebe jedoch immer noch zwei verschiedene Welten, die auf Grund von unvollständigen oder überholten digitalen Daten oft nicht übereinstimmen.

Die Erweiterte Realität (englisch: Augmented Reality (AR)) bietet eine intuitive Schnittstelle zwischen der realen und der digitalen Welt. Diese Technologie kombiniert reale und virtuelle Informationen durch lagegerechte Einbindung virtueller Daten in Ansichten der realen Umgebung. Angewendet auf das Fabrikplanungsszenario können digitale Planungsdaten mit Ansichten der realen Fertigungsumgebung überlagert und damit visuell synchronisiert werden. Durch die damit erhöhte Planungssicherheit können Zeit und Kosten eingespart werden.

Diese Dissertation beschreibt Entwicklungen und Untersuchungen auf dem Weg hin zu einer produktiven Anwendung der Erweiterten Realität für die Fabrikplanung: Roivis. Roivis ist das Ergebnis eines iterativen Prozesses, der in enger Zusammenarbeit mit Anwendern aus der Industrie durchgeführt wurde. Durch diesen schrittweisen Prozess konnten Anforderungen abgeleitet werden, die entscheidend sind für den Erfolg und die Akzeptanz der Anwendung. Dabei werden zwei Aspekte von besonderer Bedeutung herausgestellt: Systemgenauigkeit und Prozessunterstützung.

Genauigkeit ist eine kritische Anforderung für erfolgreiche AR-basierte Fabrikplanung. Da auf Basis von Planungsergebnissen Entscheidungen über Neuplanung oder Umbau von Fertigungsbereichen oder ganzen Fabriken getroffen werden, müssen diese verlässlich sein. Dies erfordert zum einen genaue Eingangsdaten durch geeignete Hardware und Software. Zum anderen ist aber auch eine Qualitätsaussage für die Planungsergebnisse nötig.

Neben der Genauigkeit spielt die Benutzbarkeit des Systems eine wichtige Rolle. Sie beinhaltet eine intuitive Benutzerschnittstelle und vor allem die generelle Unterstützung des Nutzers in seinem Arbeitsprozess. Hier ist die Registrierung von realer und virtueller Welt von besonderer Bedeutung. Da dieser Schritt für jedes Planungsszenario durchgeführt werden muss und seine Güte direkt Einfluss auf die Genauigkeit des Planungsergebnisses hat, müssen bei der Registrierung sowohl Bedienbarkeit als auch Genauigkeit berücksichtigt werden.

In dieser Arbeit wird die konkrete Umsetzung dieser Anforderungen sowie damit verbundene Untersuchungen im Detail beschrieben. Roivis wurde bereits erfolgreich für viele Fabrikplanungsszenarios eingesetzt und zwei Beispiele aus der Automobilindustrie - Störkantenanalyse und Soll-Ist-Vergleich - werden diese Anwendung verdeutlichen. Weiterhin erfolgt eine kritische Bewertung der erzielten Ergebnisse durch Untersuchung von Roivis speziell im Hinblick auf das Hauptziel Produktivität. Schließlich wird am Ende ein Ausblick auf zukünftige Aspekte im Bereich AR-basierte Fabrikplanung gegeben. Roivis wird weiter verbessert und das letzte Kapitel wird die nächsten Schritte in der Entwicklung kurz vorstellen und weitere Themen im Bereich Fabrikplanung ansprechen, die noch zu erkunden sind.

Abstract

Factory planning today is characterized through shortened product life cycles caused by rapidly changing customer demands. Thus, there is a growing need for planning tools that support flexible and fast re-engineering cycles of production facilities. The Virtual Reality (VR) solution for this planning problem is embodied in the generic term Digital Factory, a comprehensive network of digital models, methods and tools allowing to virtually pre-check planning projects before actually realising them. However, in practice, the Digital Factory and the real production plants are still two worlds. And often, these two worlds are not consistent, due to incomplete or out-dated digital data.

Augmented Reality (AR) can be an intuitive interface between the real and the digital world. This technology combines real and virtual information by integrating virtual data seamlessly into views of the real world. Applied to the factory planning scenario, digital planning data can be directly overlaid onto views of the real factory. That way, a visual synchronization of real world and digital data can be performed, leading to more planning reliability and thus to time and cost reduction.

This thesis presents the path of exploration, development and testing on the way to a productive application of Augmented Reality for factory planning: Roivis. Roivis is the result of an iterative development process, performed in close cooperation with users from industry. Through this step by step process, a list of requirements, which are crucial for the success and acceptance of the application could be identified. Thereby, two aspects of special importance are highlighted in this work: system accuracy and process support.

Accuracy is a crucial requirement for successful AR-based factory planning. As decisions on plant rebuilding or shop-floor modification are taken based on the planning results, they need to be reliable. This requires accurate input data through according hardware and software. In addition, a quality statement for the planning results needs to be available.

Besides accuracy, the usability of the system is essential. This includes an easy to use graphical user interface and in particular a general support of the user's working process. Here, the registration of real and virtual world is of special importance. As this step has to be performed for each planning scenario and has great influence on the accuracy of the final planning result, the realisation has to take care of both usability and accuracy aspects.

In this work, the concrete implementation of these requirements, as well as corresponding evaluations are described in detail. Roivis has already been successfully applied to many factory planning scenarios and two examples from automotive industry illustrate its use: interfering edge analysis and variance comparison. The thesis concludes with a critical review on the achievements by investigating Roivis particularly with respect to productivity as the main goal. Finally, an outlook on future key aspects in the area of AR-based factory planning closes this work. Roivis is further being improved and the last chapter outlines next steps of development as well as further topics in the area of factory planning that are still to be explored.

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1 Introduction

Motivation and Overview

This chapter presents the motivation for this thesis and gives an overview on the content and the main contributions.

1.1 Factory Planning Today

Factory planning is the systematic planning of factories and deals with problems of planning, realising and putting factories in operation. It comprises various tasks such as layout planning, material flow planning or logistics and aims to secure the economics of the factory, its flexibility and variability, as well as its attractiveness [Wien 96].

Today, factory planning is characterised by shortened product life cycles caused by rapidly changing customer demands. Manufacturers have to meet the increasing request for product varieties and customised designs, as well as the continuous pressure for rationalisation and reduced investments. Thus, there is a growing need for planning tools that support flexible and fast re-engineering cycles of production facilities.

Planning instruments for these tasks have developed over time from simple pencil and stencil to complex software systems. Since the late 80s and 90s, Computer Integrated Manufacturing (CIM) has become more and more applied and is today indispensable for factory planning. About the turn of the millennium, a new term has been established in the context of CIM, the Digital Factory. It is seen as the planning instrument of the future aiming at holistic planning, realisation, control and continuous improvement of all major factory processes and resources connected to a product [Digi 08]. Tools of the Digital Factory, namely 3D simulation and Virtual Reality (VR) techniques, meet the requirements for fast and flexible planning and have been successfully used for several years now [Rein 03]. Their main benefits are a decrease in planning times and an increase in planning reliability.

1.1.1 Challenges

Shortened planning cycles and more and more complex and cross-linked factory processes require constant involvement of all areas of the factory in planning processes to assure complete and up-to-date planning data. Each planning step in the virtual world affects the real production plant. Therefore,

each change in the real world needs to be reflected in the digital planning data.
However, in operational practice, there are still two worlds today: the Digital Factory where all production facilities are digitally represented and the real factory where the products are actually produced. In the ideal case, these two worlds should be identical, but in reality they diverge, as there is no automatic connection between them [Schr 05]. The big challenge is to synchronise these two worlds and keep the Digital Factory up-to-date with the real world [Rein 02].
This synchronisation task has to face several problems. Many existing plants were built prior to the Digital Factory and thus no digital data is available. Other planning processes still do not use the tools of the Digital Factory despite their availability. And finally, the factory itself is a dynamic environment. Changes in the production environment happen every day due to restructuring, improvement or maintenance tasks. In most cases, these changes are not documented and can not be transferred back to the digital database. Thus, it is difficult to create and maintain consistent planning data [Rein 03].

1.1.2 Current Solutions

Depending on the given planning problem and the available data, different approaches are used to deal with this gap between real and virtual world.
One example for a planning task, which has to face the problem of inconsistent planning data, is interfering edge analysis. This kind of analysis aims to identify required plant modifications in case of product dimension changes. If no reliable digital data of the factory is available, the whole production line needs to be checked manually for possible collisions. To do this, real mock-ups made from plastics, styrofoam or wire meshes are driven through the production line. Distances and sufficient clearance can then be measured directly, but at the cost of interfering with the actual production causing output loss. Furthermore, actual collisions can damage both the mock-up and the production facility [Bosc 08].
For general layout planning in an existing factory, a possible approach is to rely on the combination of available 2D factory designs and 3D planning data. Using Computer Aided Design (CAD) software, the 3D data can be projected onto the 2D designs allowing for a rough planning. However, due to impreciseness and incompleteness of data, the results are not reliable and have to be supported by concrete distance measurements in the real factory. Again, the process is time and cost consuming and the resulting planning information is difficult to document.
Finally, the gap between real and digital world can be filled using digital reconstruction techniques. Here, methods such as 3D laser scanning are promising, but require time and cost effort for manual data post-processing [Rein 03].

1.2 Potential of Augmented Reality Technology

An alternative is given through Augmented Reality (AR). This technology can combine real and virtual information by integrating the virtual data seamlessly into views of the real world. Thus, AR can bring additional information to the real world at the right time at the right place. Thereby, it meets all three driving forces for the introduction of a new technology in the industrial environment: cost reduction, speed-up of processes and quality improvement [Rege 06].
Over the past years, this potential of AR technology has lead to the creation of a variety of AR-based applications aiming to support industrial processes. These applications cover all parts of the industrial product process: design, production and planning, logistics, service and maintenance, as well as

product presentation and sales.

Factory planning is a promising field of application for Augmented Reality. Digital planning data can be directly overlaid onto views of the real factory. That way, the synchronisation of real and digital world is performed visually and does not require a fully digitalised shop floor or real mock-up representations of digital data. Augmented Reality technology can thus be an intuitive interface between the real and the digital world (see figure 1.1). It offers an easy, fast and affordable possibility for factory planning with various concrete areas of application such as the above mentioned interfering edge analysis or variance comparison between real and virtual data.
Collision detection for the real factory environment and new digital products can be done by simply superimposing the digital model data onto images of critical areas in the factory. And through the overlay of real world objects with virtual planning data, a direct comparison of both worlds can be performed. Thereby, planning errors in production environments can be detected faster and more efficiently, leading to an increase in planning reliability.

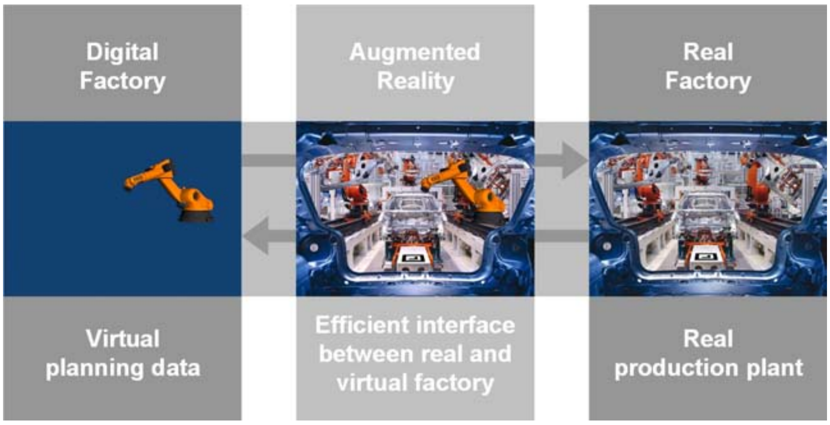


Figure 1.1: AR as an Interface Between the Digital and the Real Factory (Source: Volkswagen AG)

1.3 Making AR-Based Factory Planning Productive

A variety of industrial AR applications has been created in the past, but only a few of them actually managed to develop from demonstrator applications or prototypes into valuable and established solutions. AR-based factory planning has great potential, but requires thoughtful realisation in order to convince the customers from industry.

1.3.1 General Requirements for Productivity

General requirements for a successful and accepted industrial Augmented Reality (IAR) application are for instance stated by Navab [Nava 04], who searches for killer applications for AR, which attract a large number of customers and create economic benefits for industry. He identifies three major advantages that an IAR application has to provide: reliability, user-friendliness and scalability beyond simple prototypes. A different view on the same problem is given by Regenbrecht [Rege 06], who finds that the contributing technologies (tracking, displays, content generation or wearable computing) are not mature enough to suit the demanding industrial conditions regarding robustness, reliability, quality and practical experience.

1.3.2 Roivis

Aiming to create a productive and beneficial industrial Augmented Reality application for factory planning, the system Roivis has been implemented. Roivis is the result of an iterative development process, performed in close cooperation with users from industry. Its history of development went through several stages, which allowed determining crucial requirements for serviceability and acceptance. Besides general demands such as the ones presented above, two key aspects were identified for the success and acceptance of the system: system accuracy and process support for registration between real and virtual world.

Accuracy Accuracy is one crucial requirement for Roivis. Based on the results of planning tasks, decisions on plant rebuilding or shop-floor modifications are taken. Thus, the planning results must be reliable. This involves the necessity for hardware and software that provide the desired accuracy. In addition, the quality of the final result is of interest and uncertainty statements for the different components of the system and the overall result need to be available.

Process Support Besides accuracy, the usability of the system is essential. This includes an easy to use graphical user interface and in particular a general support of the user's working process.
The integral aspect identified in the context of AR-based factory planning is the registration of real and virtual world. As this step has to be performed for each planning scenario and has great influence on the accuracy of the final result, the implemented approaches have to meet both usability and accuracy requirements.

1.4 Scope of this Thesis

This work presents the path of exploration, development and testing on the way to a productive industrial application of Augmented Reality for factory planning. Roivis has been created iteratively and went through several steps of development. For completeness and understanding, this thesis outlines the historical stages and the general system details. The focus of this work lies on selected aspects of implementation and use.

1.4.1 Contributions

The main contributions of this thesis fall into three different categories.

Accuracy Accuracy is introduced as a crucial requirement for successful AR-based factory planning. To provide the user with a quality statement on the reliability of the given AR scene, a new approach for accuracy processing is described, which is tailored to the given industrial scenario. Concepts from measurement engineering are transferred to the industrial Augmented Reality environment, treating the AR-system Roivis as a measurement system. This innovative combination for uncertainty

propagation has been patent-registered [Pent 07d].
The overall accuracy of an AR scene is depending on the quality of the used input data. For the Roivis system, the base input for augmentation is provided through optical marker-based tracking. To determine accuracy information for this tracking system, a detailed evaluation of the tracking quality with respect to important influence factors has been performed. Different from other studies on marker tracking accuracy, this evaluation is based on simulation data. Therefore, the results offer more detailed information and allow creating an error function with much higher resolution than previous analyses.

Process Support Meeting the second key requirement for Roivis, a registration toolbox is presented. This toolbox provides various approaches for registration between the real and the virtual world based on point and pose correspondences. To assure the suitability of the approaches in the context of factory planning, a comprehensive evaluation with respect to accuracy and usability criteria has been performed. Based on the results, guidelines for applying the toolbox are derived, which provide valuable support during practical use. Parts of the work on registration support have been published in [Pent 08].

Productive Industrial Augmented Reality Today, productive industrial Augmented Reality applications are still rare. This work offers useful insight into the iterative development of Roivis and the identification of critical demands for serviceability and acceptance. As the system has already been successfully applied to real industrial planning problems, practical experience with industrial Augmented Reality can be presented. Finally, the degree of productivity achieved so far is discussed based on available sales statistics.

1.4.2 Overview

Roivis is the result of the above mentioned process of exploration, development and testing. The following chapters introduce the factory planning application step by step.

Background First, chapter 2 lays the foundation for the two main domains involved in this work: Augmented Reality as the applied technology and factory planning as the field of application. Furthermore, the potential of AR-based factory planning is described, motivating the implementation of Roivis.

System Overview After that, chapter 3 introduces the Roivis system, its stages of development and the thereby deduced requirements for acceptance and serviceability. The different system components are described such as the underlying Augmented Reality system Unifeye SDK and the graphical user interface of Roivis with its various tools for AR scene creation, configuration and measuring.

Accuracy and Registration Then, chapter 4 and 5 discuss two crucial aspects of this thesis, accuracy and registration for AR-based factory planning. Each chapter presents the fundamentals for the respective topic and elaborates afterwards on the concrete use and implementation within the Roivis application.

Applications Having described the system with all its features, chapter 6 shows AR-based factory planning in use. The chapter starts with a section on the practical process of applying AR for factory planning and continues by illustrating the application of Roivis using two specific industrial scenarios from the automotive sector: a variance comparison scenario at Volkswagen and interfering edge analyses at Opel.

Evaluations Next, chapter 7 presents several evaluations performed in the context of Roivis. These evaluations handle different aspects of the system according to relevant criteria. The accuracy of the underlying tracking is analysed as well as the usability and accuracy of the registration toolbox. In addition, acceptance and maturity are discussed, aiming to rate the productivity of Roivis.

Conclusion and Outlook Finally, chapter 8 closes the thesis by summarizing the achievements. Roivis is further being improved and this last chapter provides an outlook on the next steps of development, as well as further aspects in the area of factory planning that are still to be explored.

2 Background

Theoretical and Practical Fundamentals

The focus of this thesis is AR-based factory planning, which is realised using the application Roivis. This chapter lays the foundations for the major aspects for the upcoming elucidations and introduces the following topics:

- Augmented Reality, as the applied technology (section 2.1)
- Factory Planning, as the area of application (section 2.2)

Finally, based on the motivation for AR-based factory planning, section 2.3 briefly recapitulates the focus of this thesis, limiting the scope of this work to promising applications of Augmented Reality for factory planning.

2.1 Augmented Reality

2.1.1 Definition

To find a definition of Augmented Reality (AR), different approaches are possible. A very general classification is given by Milgram et al. [Milg 94], who used the close relation of Augmented Reality with Virtual Reality to create a so called Reality-Virtuality (RV) Continuum. In this continuum, AR finds its place in-between the Real Environment and the Virtual Environment (see figure 2.1), in the Mixed Reality space. In contrast to Augmented Virtuality (AV), Augmented Reality is situated closer to the real world than to the virtual world. Thus, Augmented Reality denotes an enhancement of the user's perception of the real environment.

Another more technical but still technology-independent definition can be found in the AR survey of Azuma [Azum 97], where the following characteristics for AR systems are stated:

- It combines real and virtual.
- It is interactive in real-time.
- Real and virtual objects are registered in 3D.

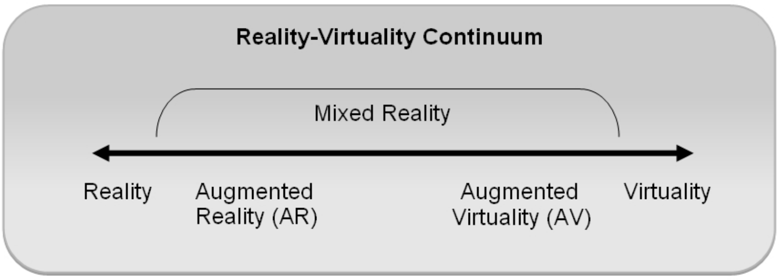


Figure 2.1: Reality-Virtuality Continuum adapted from Milgram et al. [Milg 94]

It is important to note that from a general perspective the augmentation in Augmented Reality is not limited with respect to senses. Audio, visual, tactile or olfactory augmentation is possible. However, in the context of this work only visual augmentation plays a role and thus, the further content focuses on Augmented Reality based on visual information being overlaid onto real-world image data.

2.1.2 Technologies and Architecture

To realise an Augmented Reality system, several technologies are needed. Tracking is required to define a connection between the real and the virtual world. Display systems present the resulting mixed view to the user. Furthermore, the different components have to interact with each other to form a working architecture.
The next sections present different tracking and display technologies, as well as a short overview on AR system architecture.

2.1.2.1 Tracking Technology for AR

Overview To achieve accurate registration of virtual objects with the real world, tracking systems are required, which monitor the user as well as interesting objects in the real world. These trackers provide the AR system with information on the position and/or orientation of the tracked object.
Different technologies for tracking are available today, varying in tracking dimension and accuracy. One possible classification of tracking systems is given by Rolland et al. [Roll 00], who organise the systems based on their physical principles of operation:

- Time of flight (TOF) systems measure the speed of propagation of pulsed signals to determine the distances between features on a reference object and a moving target. Examples of TOF systems are ultrasonic trackers, GPS or optical gyroscopes.
- Spatial scanning uses 2D projections of image features or beam scanning to determine position and orientation of a target. It can be sub-classified in outside-in (fixed sensors follow a moving target with features) and inside-out optical tracking (sensor attached to target and emitters placed on the reference). A third class is stated by Mulder in [Muld 94]: inside-in optical tracking (both sensor and emitter are attached to the moving target and relative tracking information is determined).
- Inertial sensing bases on the conservation of a given axis of rotation (mechanical gyroscope) or a position (accelerometer).

- Mechanical systems use the linkages between reference and target for pose determination.
- Phase-difference sensing measures the relative phase of signals coming from target and reference. Different from the TOF approach, high data rates can be achieved, as the phase can be measured continuously.
- Direct-field sensing uses sensors that measure magnetic or gravity fields for position and/or orientation determination (e.g. compass).
- Hybrid tracking relies on the combination of two or more different sensors to overcome weaknesses of single sensors.

Depending on the application and the working environment, different constraints must be considered when choosing the tracking system. Questions such as the dimension of the tracking result, its accuracy and update rate, as well as robustness and usability of the system in the context of the application are of importance. Depending on the key criteria identified for the given scenario, different tracking systems are preferable for different applications. Such evaluations have for instance been conducted for human-robot interaction applications [Bisc 04] or for AR-supported stud welding [Pent 07b].
Some example tracking systems are shown in figure 2.2.

(a) Intersense InterTrax™ Inertial Tracker [Inte 08]

(b) FARO Platinum Arm Mechanical Tracker [FARO 08]

(c) metaio Stereo Infrared Optical Tracker [meta 08]

Figure 2.2: Example Tracking Systems

Optical Tracking Approaches Within the Roivis application, an optical marker-based tracking system is used. Therefore, this kind of tracking approach is introduced in more detail.
Rolland et al. refer to this approach as pattern recognition [Roll 00]. The pattern is a known 3D geometrical arrangement of features on the target, which is captured by one camera. Based on the recorded 2D pattern in the image and the known 3D pattern information, the position and orientation of the target with respect to the camera can be calculated.
For the marker-based tracking in Roivis, the features are given by the eight corners of the black border of the square marker (see figure 2.3). These features are known in the coordinate system of the square marker. Given an image of the marker, image processing algorithms can be applied to determine the corresponding 2D features points. Based on the corresponding sets of 2D image points and 3D square marker points, the extrinsic camera parameters can be calculated given known information on the intrinsic camera parameters.

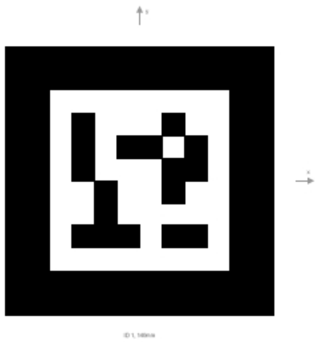


Figure 2.3: Example Square Marker

2.1.2.2 Display Technology for AR

For visualising the output of an AR system, there are a lot of options. Displays differ in their size, the amount of realism or immersion they offer to the user and many other aspects. Literature provides many classifications for display devices for virtual worlds in general and for Augmented or Mixed Reality in specific. The following presentation of displays is based on the displays reviews and classifications available from Milgram et al. [Milg 94], Bimber and Raskar [Bimb 05b] and Bowman et al. [Bowm 04]. Milgram created a taxonomy for mixed reality displays with the intent to support display choices based on the various technology requirements given for AR displays. The display review of Bimber and Raskar uses the spatial location of the display for a classification and introduces advantages and disadvantages for the different types. Finally, Bowman et al. present a general overview on visual output devices in the context of 3D user interfaces.
Here, the classification approach of Bimber et al. is used to provide a brief summary on state of the art in display technologies for Augmented Reality.

Head-Worn Devices The first group of displays contains all visualisation devices that have to be worn by the user. Three main types can be distinguished:

- Head Mounted Displays (HMDs) are available as video-see through or optical see-through devices. The former is based on one or two small CRT, LCD or OLED displays embedded in a closed-view helmet, glass or visor and applies video-mixing to create superimposed information on real world image data. Whereas the latter uses partially reflective mirrors allowing Augmented Reality by imposing the video image reflection on to the user's view of the real world. Examples for current HMDs are Emagin Z800 3D Visor (video see-trough, [Corp 08]) or Lumus PD-22 (optical see-through, [Lumu 08]).
- Retinal displays scan light directly onto the user's retina. The first version of a retinal display was developed by the Human Interface Technology Laboratory at the University of Washington [Tidw 95]. More recent developments are for instance available from Microvision Inc. [Micr 08].
- Head-mounted projectors have two main realisations: Head-mounted projective displays beam images onto retro-reflective surfaces using mirror beam combiners. In contrast, projective head-mounted displays beam the image onto regular ceilings. After the projection onto the ceiling, the images are reflected by half-silvered mirrors to integrate them into the user's field of view.

An example application using a head-mounted projection display can be found in Hua et al. [Hua 01].

Hand-Held Devices The next group of displays are hand-held devices. Examples are tablet PCs, personal digital assistants (PDAs) and mobile phones. The main concept applied for Augmented Reality visualisation is video see-through. Integrated video cameras capture an image from the environment, which is then augmented with virtual model data.
Other concepts of hand-held AR devices are also available, such as optical-see through hand-held devices (e.g. Stetten et al. [Stet 01]), hand-held mirror beam combiners (e.g. Bimber et al. [Bimb 00]) or hand-held video projectors (e.g. Raskar [Rask 03]).

Independent Devices Finally, the third group contains all independent devices in the sense that they are not connected to the user. Again, the environment can be augmented using different approaches:

- Video see-through is given for screen-based Augmented Reality. A standard desktop monitor can be used to visualise an augmented scene.
- Optical see-through is realised through spatial optical displays, which create augmentations in alignment with the physical environment. Example technology used for such devices are transparent screens or mirror beam combiners.
- Projection-based augmentation directly augments images on the surface of physical objects. Various developments are available:
  - Projection-based workbenches offer 2D table based visualisation (e.g. Responsive Workbench [Krug 95]).
  - Hemispherical displays offer a 180° field of view.
  - Surround-screen displays such as the CAVE [Cruz 92] consist of three or more large projection-based display screens.
  - Projection systems for arbitrary surfaces allow seamless projection also onto non-planar physical objects (e.g. Bimber et al. [Bimb 05a]).

(a) Emagin Visor HMD [Corp 08]

(b) AR on a PDA (TU Graz) [Wagn 01]

(c) CAVE System (Fraunhofer IPA) [Frau 08]

Figure 2.4: Example Display Devices

All display devices have their advantages and disadvantages. Depending on the requirements of the given application, different choices on visualisation devices must be considered. Criteria for selection include for instance:

- General issues such as weight, size or cost,
- Aspects of use such as multi-user capability, outdoor capability,
- Image quality aspects such as brightness, resolution, field of view, and finally,
- The overall feeling of immersion and presence supported by the device.

2.1.2.3 AR System Components

Augmented Reality as a technology requires several system components, which need to take care of the different functional aspects related to an AR system, such as tracking the interesting objects in the real world, presenting the augmented world to the user or controlling interactions between the user and the system. In [Reic 03], Reicher et al. conducted a study on software architectures for Augmented Reality systems to identify a reference architecture built from components common to most AR systems. The architecture is shown in figure 2.5 and consists of the following components:

- Application: containing application specific logic and content,
- Tracking: responsible for determining the users' and other objects' poses,
- Control: gathers and processes user input,
- Presentation: uses 3D and other output modalities
- Context: collects different type of context data and makes it available to other subsystems and
- WorldModel: stores and provides information about real and virtual objects around the user.

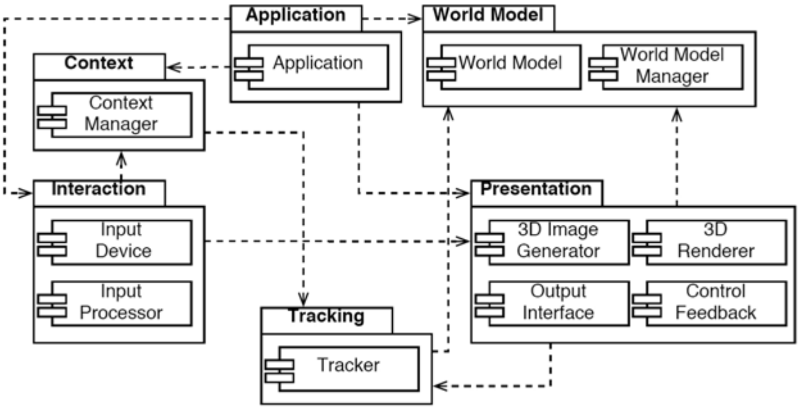


Figure 2.5: Reference Architecture for AR Systems by Reicher et al. [Reic 03]

Depending on the system and the specific application, the different components of such an architecture differ in their dimensions and functional characteristics. The AR-based factory planning application Roivis is based on the metaio Unifeye SDK Augmented Reality system, which includes components for tracking, control, presentation, world model and context. Roivis and the Unifeye SDK are presented in detail in chapter 3.

2.1.3 Applications

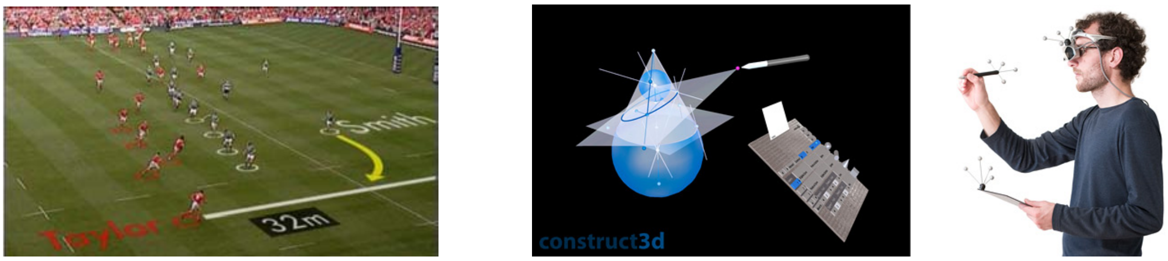
The combination of virtual information with real environments is applicable to many scenarios. Over the past years, research has presented a vast variety of applications for Augmented Reality. However, in industrial and commercial markets, AR applications are rather rare [Rege 06]. This section gives an overview on the fields of application for Augmented Reality technology and presents system implementations from research, as well as industry and commerce.

2.1.3.1 Entertainment

Two promising sectors for AR in entertainment are the TV and film industry and the gaming market. In the media sector, BBC Research explores the potential of Augmented Reality for broadcast and multimedia production [Lali 03]. Example applications are sports scenes augmentation [Thom 07b] or on-set visualisation for film productions, where camera tracking data is used to determine the current view on the virtual world [Thom 07a].
Using Augmented Reality for games offers a variety of possibilities for more interactive playing. Various applications have been developed for indoor and outdoor, single or multi-player or handheld games. ARQuake is an example for an outdoor AR application based on the desktop game Quake [Piek 02]. And in [Wagn 01], Wagner et al. present the first multi-user Augmented Reality application for handheld devices, the Invisible Train.

2.1.3.2 Education

Augmented Reality also provides great potential for general information presentation. In [Adam 04], Mike Adams states Augmented Reality as one of the top ten technologies, mainly with respect to its educational benefits. He depicts the potential of AR for interactive learning and foresees a global industry with applications in education, entertainment, virtual libraries and other areas. A very elaborate educational application of Augmented Reality is described in the work of Kaufmann [Kauf 04]. Contruct3D is a multi-user system for geometry education, which has been continuously improved, tested and evaluated over the course of six years [Kauf 07].



(a) Augmenting Sports Scenes [Thom 07b]

(b) Construct 3D [Kauf 04]

Figure 2.6: Example Applications from Entertainment and Education

2.1.3.3 Medical

The medical field relies in large part on imaging technology. Different pre-operative imaging studies such as computed tomography (CT) or magnetic resonance imaging (MRI) scans provide information for planning and executing surgeries. Augmented Reality can support these processes by providing additional information such as the pre-computed scans correctly registered with the real world, hence the patient.

A lot of research is done and many applications are being developed, often in cooperation with surgery laboratories or clinical centres. Examples are the Sonic Flashlight presented by Stetten et al. [Stet 00], a new device for ultrasound guidance, which uses real time tomographic reflection (RTTR) to superimpose ultrasound information directly onto the outer surface of a patient.

Recent work in medical AR deals with more efficient and automated registration, which is applicable to many medical problems (e.g. navigated bronchoscopy [Klei 07], planning for liver catheterisations [Groh 07]) or automatic surgical workflow analysis and modelling of medical procedures [Pado 07].

2.1.3.4 Military

In military, Augmented Reality can be applied to support the use of devices or to provide tactical information to ground troops.

Very early applications of the former type are given by the Head-up displays used in military aircraft cockpits, which present status information to the pilot.

An example for an AR-system of the latter kind is described by Julier et al. [Juli 00]. The Battlefield Augmented Reality System (BARS) superimposes position-specific information to mobile users in the field. The work was continued and evaluated within the US Army Simulation, Training and Instrumentation Command (STRICOM) Embedded Training Initiative [Livi 02].

(a) Sonic Flashlight [Stet 00]

(b) Head-Up Display in a Cockpit

Figure 2.7: Example Applications from Medical and Military

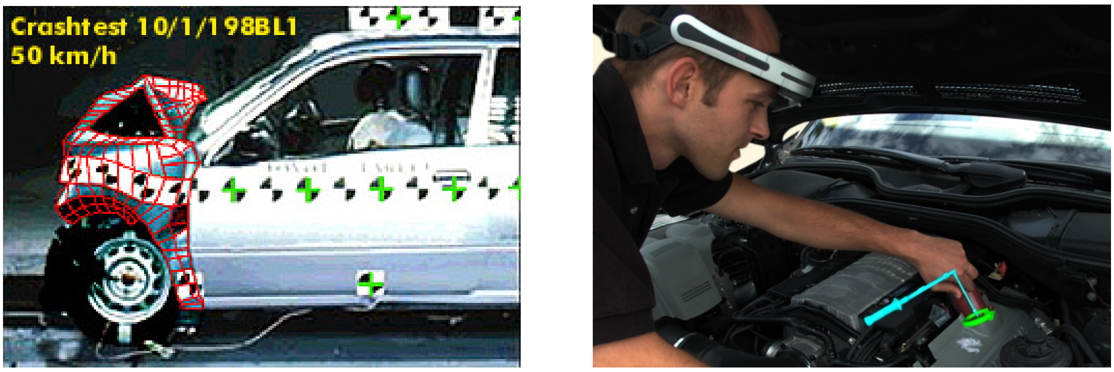
2.1.3.5 Industry

In the early 90s, Boeing created an AR-based application for the assembly of wire harness bundles in airplanes [Mize 01]. Since this first exploration of Augmented Reality for manufacturing, the technology has found its way into many sectors of industry. Due to its potential for improving industrial processes, AR can be successfully applied throughout the production chain. The next paragraphs present example applications for different industrial sectors.

AR for Design and Production For the German industry, the ARVIKA project was the important starting point for the analysis of AR technology for industrial application [Frie 01]. It addressed Augmented Reality supported work in the fields of

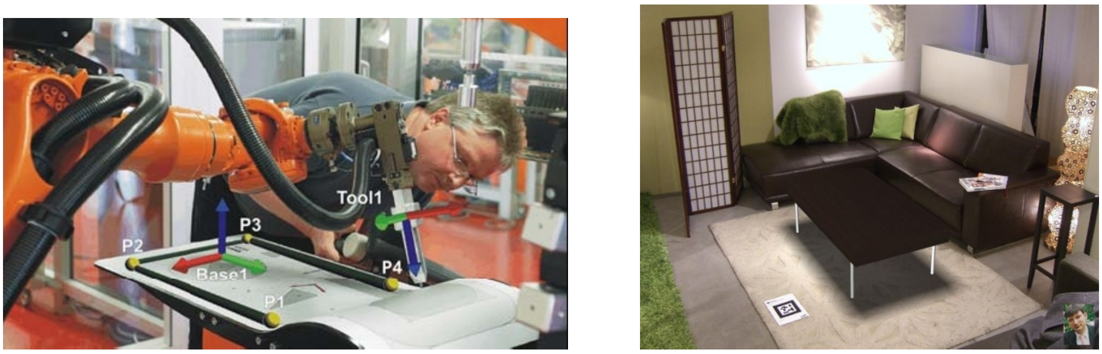
- Industrial design (e.g. crash test data validation, Volkswagen),
- Production and assembly (e.g. cable harnessing for the Eurofighter, EADS or the intelligent welding gun, BMW [Echt 03]), as well as
- Service tasks (see AR for service and maintenance)

Besides this large industrial research project, many other developments have been pursued, amongst them also some applications in the area of AR-based factory planning. In 2000, Sinh et al. presented the team table of Fraunhofer IPA for 2D and 3D layout planning, which uses metallic bricks to reposition objects [Sihn 00]. The table is continuously improved and currently being integrated in a collaborative working environment for Digital Factory applications [Pent 07a]. A recent application for planning validation was developed by Georgel et al. [Geor 07]. The authors perform discrepancy checks in industrial environments by relying on anchor plates as landmarks for tracking, rectangular structures, which are already available in the factory.



(a) Design [Frie 04]

(b) Service and Maintenance [meta 08]



(c) Industrial Training [Kurt 06])

(d) Product Presentation [meta 08]

Figure 2.8: Example Applications from Industry

AR for Service and Maintenance Maybe the first AR application for service tasks was presented by Feiner et al. in 1993 [Fein 93]. The authors applied the technology to show laser printer maintenance using a see-through head-mounted display.

The ARVIKA project also looked at possible use for AR in service and developed an application for AR-assisted troubleshooting by means of a Remote Expert. Building on top of the ARVIKA results, the successor project ARTESAS put its focus on Augmented Reality technologies for industrial service applications [Siem 07a]. Markerless tracking approaches and user-friendly AR devices were developed with fields of applications in service and maintenance in the automotive, aircraft and automation engineering industry. One example prototype for maintenance of a BMW 7 series engine is described by Platonov et al. [Plat 06].

AR for Industrial Training The use of AR for industrial training is in many cases very much related with service and maintenance applications. Training a worker to perform a certain task can be done with a system similar to the ones described for AR-based maintenance. Zhong et al. developed a prototype of a collaborative industrial tele-training system based a wearable computer and an HMD [Zhon 03].

Another type of training application was introduced by Bischoff et al. [Bisc 04]. At KUKA College, students are taught in their understanding of robot coordinate systems, robot operation and programming. An AR interface supports this learning process by displaying virtual coordinate systems in a video stream of the real robot. The system is in use and has been expanded by functionalities for path trace visualisation, simulation mode and movement displays [Kurt 06].

AR for Logistics Besides service and training, the visualisation of information using Augmented Reality technology can also be used for logistics tasks. In [Reif 06], Reif et al. describe a mobile AR system for parts picking based on a hand-held PC, a camera and a head-mounted virtual retina display. Important requirements for these systems are robust hardware as well as intuitive information presentation. Evaluations of different display devices and different visualisation concepts have been performed within the Bavarian research project ForLog [Baye 07], [Schw 06].

AR for Product Presentation and Sales Finally, Augmented Reality can also be applied to deal with the presentation and sales of already fabricated products.

In [Demp 99], Dempski presents the idea of context-sensitive e-Commerce using Augmented Reality technology. Furniture shopping is demonstrated and discussed as an example application, using AR to show 3D and full sized representations of virtual objects in the physical living room [Demp 00].

Around the same time, Zhang and Navab developed a direct marketing system based on AR technology, which is based on marker tracking. A marker plate is shown in a live video and animated 3D models of real products are superimposed [Zhan 00].

In 2003, the first commercial software for interactive furniture planning was presented, the Augmented Furniture Client [meta 08]. During the following years, the application was further improved and an online version was released, which currently offers Augmented Product Presentation for various products from furniture and carpets to industrial robots.

2.2 Factory Planning and the Digital Factory

This section presents an introduction to the area of application for the AR system Roivis. Factory planning, its tasks and tools and the potential of Augmented Reality in this context are discussed.

2.2.1 Introduction

Factory planning describes the systematic planning of factories. Reasons for factory planning can be changes or extension in existing plants as well as re-planning of new factories. Due to the complexity of factories, aspects of factory planning include site selection, layout planning, material flow planning, storage planning, logistics, workplace design and building services engineering (e.g. power supplies, safety at work, fire security) [Grun 06].

Different from many other planning objects, the factory is characterised through a very high investment volume and a long economic life. Therefore, the planning tasks shall be performed with consideration of several general goals, which can be categorised as follows according to Wiendahl [Wien 96]:

- Securing economics of the factory: optimal throughput time, optimal use of equipment, space and personal and advantageous production and material flow.
- Securing flexibility and variability of the factory: equipment, processes and structures of the factory must cover market based fluctuations in sales volume or restructuring to new equipment, processes and organisational principles.
- Securing attractiveness of the factory: motivating and human-oriented working conditions, fulfilment of ecological criteria for environmental protection, modern and aesthetic industry architecture.

2.2.2 Planning Instruments

Instruments to support these planning tasks have developed over time, ranging from simple pencil and stencils to complex software systems. Since the late 80s and early 90s, Computer Integrated Manufacturing (CIM) has become more and more applied and is today indispensable for factory planning. Areas of application include CAD (computer aided design), CAM (computer aided manufacturing), PPS (production planning and scheduling), basic data management, production data acquisition and cross company process chains [Sche 89].

About the turn of the millennium, a new term has been established in the context of CIM, the Digital Factory.

2.2.2.1 Digital Factory

The Digital Factory is seen as the planning instrument of the future [Zulc 05]. The VDI (Association of German Engineers) defines the Digital Factory as a comprehensive network of digital models, methods and tools, including simulation and 3D/VR visualisation, which are integrated through continuous data management. The aim of the Digital Factory is a holistic planning, realisation, control and continuous improvement of all major factory processes and resources connected to a product [Digi 08].

Zäh analysed several definitions of Digital Factory and concluded that it represents both the model of a factory and also the tools used to create this model [Zah 03]. He identifies three Digital Factory components:

- Modelling and visualisation,
- Simulation and evaluation and
- Data management and communication.

2.2.2.2 Digital Factory Solutions on the Market

The three components of the Digital Factory stated above can be expanded to a set of tasks. Such a list is for instance presented by Lurse [Lurs 02]: parts list processing, process planning, assembly planning, cost planning and calculation, operational planning, programming of numeric controls and industrial robot cells, ergonomic analysis, production logistic planning, factory layout planning and factory simulation.
Regarding this huge number of tasks, a vast number of commercial tools and solutions is available on the market:

CAD Systems Today's CAD systems support 3D computer aided design. Solutions are amongst others available for

- Aesthetic product development, e.g. Dassault's CATIA V5, which is the leading and dominant platform with a worldwide market share of 80% in automotive industry [Dass 08],
- Industrial engineering, e.g. PTC's Pro/Engineer for machine and industrial equipment design [Para 08] and
- Factory planning, e.g. Siemens FactoryCAD, which provides a huge layout library for factory layouts [Siem 07b].

Integration Platforms The market of integration platforms is characterised by two key players, who offer all-embracing Digital Factory solutions including engineering data management, manufacturing process planning and simulation of various kinds of processes related to manufacturing.

- Dassault's Delmia [Dass 08] with solutions for process planning, process detailing and validation, resource modelling and simulation and ergonomics,
- Siemens PLM Software (formerly UGS) [Siem 07b] with components for part manufacturing, assembly planning, resource management, plant design, human performance and ergonomics, product quality planning and analysis, production management and manufacturing data management.

General VR Solutions Besides the big players presented above, further providers for general industrial VR solutions are for instance

- Lanner Group: Witness VR (3D modelling, simulation and photorealistic rendering) [Lann 06],
- vrcom: Virtual Design 2 (virtual prototyping software) [GmbH 08b] or
- tarakos: taraVR builder/control/optimizer (3D material flow planning, 3D process visualisation and CAD-optimisation) [GmbH 08a].

2.2.2.3 Other Planning Instruments

Besides the tools of the Digital Factory, numerous other solutions are available on the market, which can be used for planning processes such as

- General electronic data management (EDM) systems,
- Enterprise resource planning (ERP) systems or
- Supply chain management (SCM) systems.

In [Bail 06], Bailor lists SAP, Oracle, Sage, Microsoft and SSA Global Technologies as the five top sellers of commercial ERP software world-wide.

2.2.3 Factory Planning at the Border Between the Real and the Digital World

Today's factory planning is characterised by shortened product life cycles. Manufacturers have to meet the demand for more product varieties and customised designs. This results in reduced periods of amortisation for each product model and requires therefore a reduction of investments per piece in production. As this trend will continue in the future, there is a growing need for planning instruments that support flexible and fast re-engineering cycles of production facilities while providing high quality [Schr 05].

The Digital Factory with its tools and methods meets these requirements. In comprising the functionality for virtually pre-checking planning projects before actually realising them, it allows for shorter planning times and more planning reliability.

2.2.3.1 Problems in Digital Factory Planning

Shortened planning times and more and more complex and cross-linked factory processes require constant involvement of all areas of the factory in planning processes to assure complete and up-to-date planning data. Each planning step in the virtual world affects the real production plant. Thus, for consistency, each change in the real world needs to be reflected in the digital planning data. The tools of the Digital Factory fully rely on the digital database. If the digital data is erroneous or incomplete, planning processes cannot be executed or result in incorrect planning, which causes delays in realisation. Such delays are costly as planned start-ups of production cannot be met and more time and resources are required for re-planning.

Ideally, the Digital Factory and the real world should be identical but in reality they diverge as there is no automatic connection between the two worlds. On the one hand is the Digital Factory, where the whole production facilities are digitally represented. On the other hand is the real factory, where the products are finally produced. The big challenge is to synchronise these two worlds and keep the Digital Factory up-to-date with the real world [Rein 02].

This challenge of keeping the two worlds consistent has to face several problems. 3D data is usually not available for all existing plants. Many of the factories and machines that are in use today were planned without the Digital Factory and are only represented through 2D layout or production designs. And although the tools of the Digital Factory are available in an enterprise, there are still planning processes that do not yet use these tools (e.g. supply lines in factories or plant components such as electric, pneumatic or hydraulic systems) [Bosc 08].

Furthermore, the factory is a dynamic environment. Already during the realisation phase, changes with respect to the originally planned structure occur. In addition, continuous improvements during operation as well as adjustments for machine and plant maintenance lead to changes. In most cases, these changes are not documented and can thus not be transferred back to the virtual planning data of the Digital Factory.

2.2.3.2 Critical Planning Tasks

For some tasks the gap between the real world and the Digital Factory is not of much consequence. The planning of a new factory for instance does not require a synchronisation of the real and the virtual world, as the information is created from scratch for all involved components.

However, this planning from scratch is rather rare in factory planning. The serviceable life of a building is far higher than the serviceable life of the production lines. Thus, many factory planning tasks deal with restructuring, modification and extension of existing factories.

If product changes are the reason for plant modification, it is crucial to identify the concrete locations that require structural alterations. Some components are easily identified as they are directly connected to the design change. Though, if the product dimensions have changed, the whole production line needs to be checked for collisions. This task is called interfering edge analysis. Here, planning based on an incomplete or erroneous digital database might not reveal all possible collisions. These planning errors then require according changes, which lead to delays and thus to unbearable costs.

Similar problems occur when performing general layout planning tasks for plant modifications or extensions. To integrate newly planned components in an existing shop floor, the virtual representation of the shop floor must be reliable. Possible locations and dimensions of new machines are chosen based on available information. If the planning data is erroneous or incomplete, the planning results may be incorrect. Again re-planning tasks are required causing delays and increased planning costs.

To face the problem of incomplete and erroneous digital planning data, several approaches are currently used to fill the gap between the real and the digital world. Either the gaps in the digital data are avoided by relying on available data, or these gaps are filled through digitalisation of the real objects by means of 3D reconstruction techniques.

2.2.3.3 Approaches Based on Available Data

Available data for planning is given through incomplete 3D data, 2D construction data and the real production site (see for instance Bösche [Bosc 08]):

Planning Based on Available 3D Data Given 3D digital planning data of the factory, CAD software is applied to integrate the new product designs into the existing factory layout. Then, 3D distance measurements can be performed and collisions can be detected easily.

The drawback here is the unreliability of the available 3D factory data. Due to the problems mentioned above, the planning data most likely does not reflect the current situation in the real plant and therefore, the planning results have to be verified through alternative approaches.

Planning Based on 2D Construction Designs Based on available 2D designs of the factory, the newly planned 3D digital model can be projected into the existing 2D layouts. This operation is performed in a CAD tool and the available functionalities allow performing measurements in the 2D plane.

However, this process needs to be done separately for each component. The 2D view can get very unclear due to numerous and complex components and parts. Next, the designs are often simplified and thus imprecise representations of the real factory. Finally, the 2D view limits the possibility for collision analysis as the third dimension is missing.

Planning Through Measurements in the Real Production Site To get more reliable analysis results, measurements in the real production site can be performed. The facility is moved to the desired position and the required measurements and clearance information is determined using conventional measurement devices.
The main disadvantage of this approach is the effort for collecting the data. The production needs to be stopped, causing undesired idle times and output loss. Furthermore, not all required measurements might be easily reachable in the shop floor.
In general, the analysis results can only be documented poorly due to the complex, spacious and/or cumbersome structure of industrial facilities.

Planning Based on Real Mock-Ups Finally, a very common approach for interfering edge analysis relies on real mock-ups, which are driven through the production line to directly check for collisions. Such mock-ups are built from plastics, styrofoam or wire meshes. Here, the analysis for collision is performed in a straight forward way and the distances and clearance values can directly be measured.
This approach requires the availability of a mock-up, which is a costly procedure. Then, similar to the previous approach, the production process is disturbed as instead of the manufactured products mock-ups are send through the production line. Furthermore, in case of collisions, both the mock-up and the corresponding part of the factory can be damaged. Thereby, additional costs occur and the production process might be interrupted longer than estimated.

2.2.3.4 Approaches for Digitalisation

As mentioned above, available virtual data is not necessarily reliable. It is very likely that the data does not or no longer reflect the actual real factory. To fill the missing parts of the Digital Factory, 3D reconstruction techniques can be applied. Hereby, two main approaches for capturing geometric data are distinguished: active and passive techniques.

Active Capturing Approaches Active capturing approaches are based on light beams, which scan the environment to create point clouds of detected objects in a scene. Very popular examples are laser scanners. Different techniques are used to achieve distance measurements [RP P 08]:

- Triangulation: Based on the knowledge that light beams propagate without large divergence over large distances, light is essentially used as a pointer here. Diffuse or specular reflection are monitored and used to calculate the angle between the light beam and the returning reflected light. Based on this information, the distance can be calculated.
- Time of flight: The time of flight of a light pulse from the light emitter to an object and back is measured for distance calculation.
- Phase shift: Constant waves of varying length are projected and reflected by objects in the scene. The distance is calculated by measuring the phase shifts in the waves.

- Interferometers: This optical device uses beam splitters to separate and recombine light beams. The power or the spatial shape of the resulting beam can then be used for measurements.

An example of such light-based active capturing devices is the FARO Laser Scanner LS, which is based on the phase-shift principle and is able to capture 120.000 points per second up to a distance of 70 meters [FARO 08]. Another time-of-flight device was presented by Oggier et al., the SwissRanger^{TM}, an optical range camera for 3D real-time imaging [Oggi 03] (see figure 2.9).

(a) FARO Laser Scanner [FARO 08]

(b) SwissRanger^{TM} [Oggi 03]

Figure 2.9: Example Tracking Systems

Passive Capturing Approaches The passive capturing techniques rely on image data, which is processed for relevant image features (edges, corners, line segments or curve segments). These basic structures are afterwards used to reconstruct 3D object representations. Again different approaches are possible such as:

- Interactive photogrammetric modelling: Here, the user performs interactive modelling of polyhedral objects, which are not too complex in structure (e.g. basic building structures using user defined line segments [Debe 96] or 3D reconstruction based on primitives [Park 05]).
- Structure from motion: 3D reconstruction is performed based on the motion of detected object points in a video stream (e.g. based on a hand-held camera [Poll 04]).
- Multi-view stereo: This approach uses a larger number of images of calibrated camera poses for detailed object reconstruction. A comparison and evaluation of different algorithms is presented by Seitz et al. [Seit 06].
- Semi-automatic segmentation of objects in real scenes: This specific approach aims to handle occlusion problems [LePe 00].

Problems Digital reconstruction is a cost-intensive task. Such approaches are therefore usually performed when a larger environment has to be digitalised.
The result of such reconstruction processes are large point clouds. To use these point clouds for factory planning, the data has to be post-processed to reduce complexity and create structures, which can be reasonably visualised and used for measuring, such as plane-based objects. Therefore, besides its

costs, the reconstruction is also time consuming [Rein 03].
However, the idea of having an up-to-date digital database afterwards might be worth the effort. Then, this digitalisation process has to be executed in regular intervals to assure the continuous up-to-dateness of the digital data with the real world.

2.2.3.5 Potential of AR Technology

An alternative to the approaches presented before is given by Augmented Reality technology. In contrast to the other methods, AR does not require real or digital substitutes for missing objects in the Digital Factory, but works as an interface between the real factory environment and the virtual planning data [Rein 03]. Its benefit lies in the provision of knowledge and information support for the user, based on available data and according to the situation [Frie 04]. That way, the problem of modelling (real or virtual) becomes redundant, as missing virtual data is exchanged by views of the real world. Furthermore, the technology can be applied instantly without requiring time-consuming preparation steps.
For factory planning the potential of Augmented Reality can be used for various tasks. The following list of planning problems is taken from an overview of areas of application at Volkswagen (see figure 2.10).

Interfering Edge Analysis and Collision Detection Interfering edge analysis has already been introduced above. Given AR, collision detection between the real production environment and new digital products can be performed without requiring a mock-up or a prototype. The simple overlay of real world image data with virtual objects allows verifying sufficient clearance or detecting collisions directly (e.g. Schreiber and Doil [Schr 05]). The figure presents an analysis for a new car body, which is checked for collision with the real production line.

Concept Planning and Planning Workshops Using AR technology, virtual components can be integrated in their future real environment. Planning tasks can be validated without having to model the surrounding production site. Through the combination of real and virtual information, the planning problem is eased and the quality of the planning results can be improved [Doil 03]. Furthermore, through Augmented Reality, an understandable visualisation and presentation of the planning results is achieved. Planning workshops can benefit from this intuitive visualisation. The figure presents a virtual conveyor overlaid onto a real car. The augmented view is an ideal basis for discussion and collaborative evaluation.
Besides this direct way of filling the gap between the real and the digital world, AR can also serve as a intuitive interaction device for factory planning. Through the technology, virtual assembly and layout tasks can be performed in a real workplace environment. Such interface applications are for instance presented by Sinh et al. [Sihn 00] or Ong et al. [Ong 07].

Change Management and Discrepancy Checks Finally, another important application for AR in factory planning is change management. This task addresses the problem of divergence between the digital planning data and the corresponding real world objects. Through superimposition of virtual data over the real-world counterpart, discrepancies between both worlds can be detected easily. This allows for comparison in both directions. On the one hand, manufactured parts can be compared with the original digital design to verify their consistency and look for production errors on the real object

(part verification). And on the other hand, digital model data can be compared with the real world to detect faults and gaps in the virtual planning data (variance comparison). As the figure shows, the concepts can be applied to single components or to a whole shop floor.
Concrete example applications are given by Alt [Alt 01], Nölle [Noll 06b], Georgel et al. [Geor 07] or Schoenfelder and Schmalstieg [Scho 08].

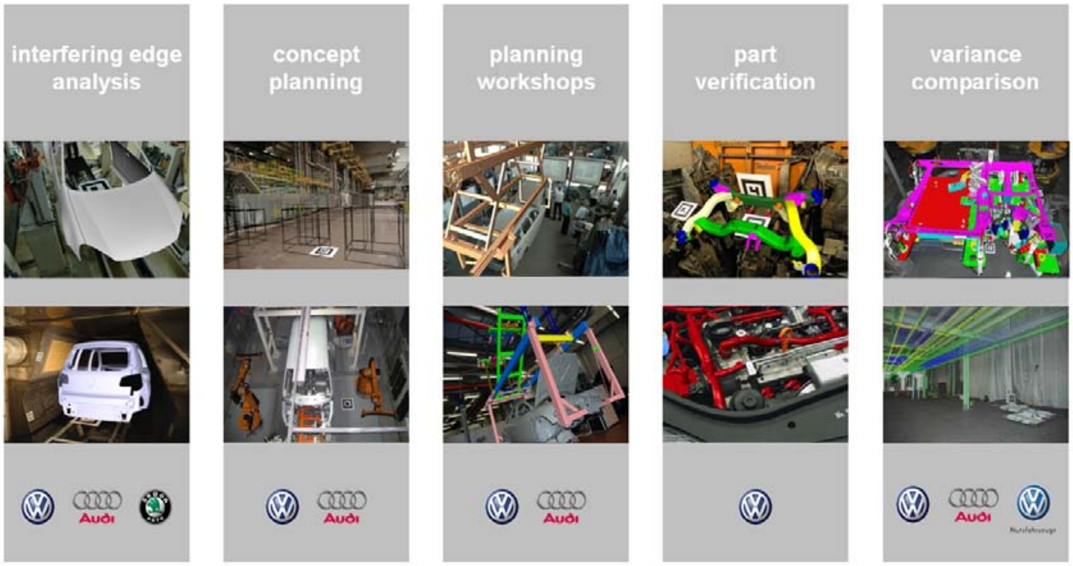


Figure 2.10: Roivis Fields of Application (Source: Volkswagen AG)

2.3 Focus of this Thesis

The previous sections introduced AR as technology and factory planning as the field of its application. Both fields are wide and encompass various research topics. This thesis cannot cover all the pending issues in both fields and therefore limits its focus to selected aspects within the context of AR-based factory planning.

2.3.1 Augmented Reality

As mentioned in section 2.1, Augmented Reality is a mixture of real and virtual elements and the augmentation can address all human senses. This work focuses on visual augmentation, which is created by superimposing virtual information onto real world image data. To be more specific, the AR system relies on high-resolution still images. This image data is processed by an optical marker-based tracking system to determine a reference in the real world, which can be used for positioning virtual information. As a consequence, Roivis does not actually fulfil the real-time requirement of Azuma (see section 2.1.1). However, virtual augmentation is used to enhance the user's view of the real environment, which is in accordance with Milgram's definition.
Reasons and details on this specific choice of tracking system and the restriction to high-resolution still image data are presented in chapter 3.

2.3.2 Factory Planning

The tasks performed within the field of factory planning are numerous and only a few of them can beneficially apply Augmented Reality technology. AR is supportive where ever a bridge between the real world and the digital world is required. The previous section already presented promising fields of applications, motivated by the open challenges related to the Digital Factory. Tasks like AR-based layout planning, collision detection and variance comparison can fill the gap of incomplete or outdated digital data and lead to a reduction of planning errors and an increase in planning reliability.

2.3.3 Roivis

This thesis presents the path of exploration, development and testing on the way to a productive application for AR-based factory planning. In the following chapters, the system Roivis is introduced step by step. Its historical development allowed identifying requirements crucial for the serviceability and acceptance of the application. The implementation of these requirements, as well as corresponding evaluations are described in the following chapters. In addition, concrete examples of use and a review on the productivity of the current system are presented.

3 System Overview

Roivis and its Functionalities

This chapter introduces the Roivis system with its basic functionalities. Roivis is the result of an iterative development process aiming to create a productive and beneficial AR-based factory planning application (see also [Pent 07c]). Section 3.1 describes this iterative process in detail. The requirements that could be extracted from the different implementation stages are presented in section 3.2. Thereby, two aspects are highlighted: system accuracy and process support for registration between real and virtual world. Finally, section 3.3 presents the resulted application on two levels: the underlying general AR functionalities are encapsulated in the metaio Unifeye SDK, while the factory planning specific manipulation and measurement functionalities are implemented at application level (Roivis graphical user interface).

Details on the two crucial aspects of accuracy and registration of real and virtual world are presented separately in chapters 4 and 5.

3.1 History of Development

The development of a productive application for AR-based factory planning was performed in close cooperation with partners from industry and went through several stages. During the iterative process, various hardware and software configurations were analysed for their suitability for the production and planning environment. In addition, the application areas varied throughout the different stages of expansion. Every realised prototype was used to deduce requirements for the next development step, in order to continuously improve the AR application.

The following sections outline the two main stages of development, which preceded the Roivis application.

3.1.1 Prototype 1: Hardware and Software Exploration

The first prototype was web-based and used an AR visualisation system, which was developed in the ARVIKA research project [Frie 01]. Two tracking approaches were tested, an optical marker-based system and an infra-red tracking system of the company A.R.T. [ART 08]. The hardware setup was

realised as a mobile client-server architecture using an HMD and a mobile touch screen as information display devices (see figure 3.1). The main applications were factory layout planning and work place ergonomics [Doil 03].
Three main weaknesses were identified for this prototype:

- The client-server architecture was not serviceable due to interrupted network access in the shop floor.
- The display devices (HMD and wearable PC) were rather low-performing and clumsy.
- The infra-red system was rather unstable and had a small working range.

Figure 3.1: Planning System Stage 1 [Doil 03]

3.1.2 Prototype 2: Stability and Functionality

The second prototype built on the experience of the first one and was developed in a cooperative project with the Volkswagen Group Research, Siemens A&D and the metaio GmbH. The primary field of application for the resulting software AR-Planner was interfering edge analysis [Schr 05]. Figure 3.2 shows the interfering edge analysis of a Volkswagen car body.
The mobile client-server architecture was replaced by a static application installed locally on a high-performance desktop system. Based on the tracking system experience of the first prototype, this second prototype used optical marker-based tracking, implemented in the metaio Unifeye SDK [meta 08].
Besides the general AR functionality, several planning related functionalities were integrated. A graphical user interface offered the possibility to load image data (video streams or live-camera images), 3D model data, tracking configuration and camera calibration. In addition, a data import interface from the planning system eM-Planner was realised. Created projects could be stored for documentation.

Although the AR-based approach offered time and cost advantages for the given application scenario, the context of interfering edge analysis also raised two concerns:

- The accuracy of the video-based approach was not sufficient.
- It was unknown, how reliable the virtual overlay was.

Figure 3.2: Planning System Stage 2 [Schr 05]

3.2 Requirements Collection

The Roivis system is based on the experience of the two presented prototypes. Through the iterative development process, the first two prototypes allowed deriving three key criteria, which were considered when undergoing the third iteration of the factory planning application: usability, analysis functionality and accuracy.
The following sections outline these three key criteria and derive concrete requirements for the application.

3.2.1 Key Criteria Identified

3.2.1.1 Usability

The first key aspect is the usability of the AR-system. The weaknesses of the first prototype showed the importance of hardware and software components that are easy to use.
On the hardware side, this includes systems and devices that are reliable and powerful, as well as helpful and task-oriented. They need to fulfil the requirements for the given environment (for tracking systems this includes for instance a specific tracking range or robustness towards different light conditions). In addition, a system is preferable, which provides high performance also with standard hardware components.
On the software side, the required expertise should be limited to address also non-experts in the field of Augmented Reality. The application itself should have an intuitive user interface offering the necessary functionalities to support fast and flexible planning. Thus, input data should be easily acquirable or already be given in the planning environment.
Another aspect of usability is the time consumption throughout the planning process, especially during the preparation phase. This is of special importance with respect to the acquisition of image data and the registration of real and virtual world. Due to running production lines and production schedules, the time for data acquisition in the shop floor might be limited. Thus, flexible approaches for registration are essential, which are accurate and suitable for the given scenario.

3.2.1.2 Analysis Functionalities

The second important criterion, which was identified, is the need for analysis functionalities. The different stages of prototypes revealed the potential for applying AR to factory planning in the sense of a measurement tool. AR as the interface between the real and the Digital Factory cannot only visualise both worlds in one place, but also allows analysing both worlds with respect to each other. Section 2.2 presented promising applications such as interfering edge analysis and variance comparison. For a successful use of the AR-based planning software in these areas, different functionalities for measuring such as distance measurements or collision detection tools are required. In addition, documentation possibilities for the current planning stage must be supported to be able to revisit previous planning tasks at a later point in time, as well as to present planning results easily.

3.2.1.3 Accuracy

Finally, accuracy is considered as a crucial aspect for productive AR-based factory planning [Pent 07c]. The second prototype raised these accuracy related concerns and implied the need for precise systems throughout the AR tracking pipeline. To assure suitable results, errors in influencing systems (tracking, calibration) must be reduced or prohibited as far as possible.

In addition, it is necessary to provide a quality measure for the planning results to know how reliable the measured values actually are. The AR-based analysis can be the foundation for decisions on plant rebuilding or shop-floor modifications. It is thus of great importance to be aware of the quality of the shown overlays.

3.2.1.4 Relation to Application Acceptance

The three key criteria presented above, are essential for a serviceable and accepted AR-supported planning application. The criteria can be related to the general requirements for productivity already introduced in section 1.3. According to Regenbrecht [Rege 06], the contributing technologies of current AR applications are not yet mature enough for industrial conditions regarding their robustness, reliability, quality and practical experience.

In addressing the identified criteria, the goal of a productive AR-based factory planning application can be approached.

- **Robustness and reliability** shall be achieved by means of a usable system with stable hardware, an easy to use graphical user interface and process support.
- Furthermore, the **quality** of the AR-based factory planning tool is based on the quality of the analysis that can be performed by the user. Thus, accurate overlays and the necessary functionalities for measuring and planning are essential to fulfil this criterion.
- Finally, **practical experience** is a key issue for AR-based factory planning. As Roivis is developed in close cooperation with industry, the system is designed with the end user in mind. System tests and evaluations can be performed based on industrial conditions using real world data. Overall, the list of requirements identified above is based on practical considerations.

The three key criteria had been identified prior to the publication of Regenbrecht in 2006. Nevertheless, the identified analogies, assure the importance of the criteria for a successful and applied AR system. A more detailed review of the system with respect to aspects of productivity and acceptance is presented in section 7.5.

3.2.2 Application Requirements

Based on the three criteria for successful AR-based factory planning, requirements for the application were derived. Functional requirements, as well as acceptance-oriented demands were considered regarding hardware, software and functional features.

3.2.2.1 Hardware

With respect to hardware, the key criteria ask for standard hardware components and simple devices, which provide high performance and accurate results. They shall be easy to use and suitable for industrial production environments.

The hardware components that are needed for the AR system are mainly a tracking system and the computer to run the AR application. The third version of the AR factory planning tool therefore has to run on a standard PC, preferably a portable device for easy use in the shop floor. Its underlying tracking system must be usable by non AR-experts, easy to setup, robust and accurate at the same time.

3.2.2.2 Software

One major disadvantage of the previous factory planning prototypes was the lack of a comprehensive graphical user interface. For the development of Roivis, an interface is needed, which offers fast and intuitive access to the needed functionalities. These include the general creation and manipulation of AR scenes, measuring and analysis in AR scenes and documentation of results.

General Scene Management For the creation and manipulation of Augmented Reality scenes several types of input information are needed:

- Image data to represent the real world,
- 3D model data to represent the virtual world,
- Configuration data to describe the details of the tracking system,
- Registration information to correctly register real and virtual information and
- Calibration data to describe the intrinsic parameters of the visualisation camera.

The general scene management toolbox must provide functionality for handling all this input information. Finally, functions for 3D object manipulation are needed to perform basic translation, rotation and scaling operations on objects present in the scene.

Analysis Functionality Given an AR scene, different kinds of analysis are of interest, depending on the type of application. For openness to a large number of different applications, the analysing toolbox shall provide a basic set of important measurement and evaluation methods, which can be applied to many scenarios:

- Model views to visualise 3D objects in different ways,
- Clipping functionality to limit the view on VR elements and
- Measurement functionalities for objects in the scene (e.g. distances, poses).

In addition, expandability as well as configurability are important. On the one hand, it should be easy to add new features to the system. On the other hand, too many features can distract the user and trouble fast access to searched functions.

Documentation Functionality Finally, functions for documenting created AR scenes are of great relevance for later exploitation of the analysis results. A scene storage tool must handle all relevant data for the given AR scene to be able to save a current status and re-work it at a later point in time.

Furthermore, snapshots of the current working stage can be helpful for presenting the analysis process.

3.2.2.3 Accuracy

Concerning accuracy, three aspects are necessary for successful factory planning. First, the underlying AR system needs to be precise enough to satisfy the requirements of the given application. Hence, the input data for the AR system - mainly tracking, calibration and modelling (see Holloway [Holl 97]) - must be as precise as possible. Second, a quality statement is needed to indicate the reliability of the given AR scene. Therefore, different input accuracy values must be combined to form an overall quality statement for the given scenario. Finally, the resulting value must be presented to the user in an intuitive and correct way.

3.2.2.4 Process Support

Usability and accuracy do not only apply for planning with the AR application, but also have to be considered when preparing and collecting the data for this planning process. As listed above, this data includes images, configuration, calibration, registration and model data. The system should support these pre-planning steps, where possible.

One crucial part of the preparation phase is the registration of real and virtual world. Very often, tracking information alone does not suffice for positioning virtual model data correctly and an additional registration offset is needed. As chapter 4 shows, the registration offset has considerable influence on the overall accuracy of the AR planning result. Allowing to determine this offset in a serviceable and accurate way is thus an important requirement for the acceptance of the application.

3.3 System Components

This section presents the Roivis system, which superseded the prototypes described above. In implementing the requirements identified in the previous section, weaknesses of its predecessors could be overcome.

Here, an overview of the underlying AR system, the metaio Unifeye SDK, is given and the graphical user interface, as well as the general functionality of Roivis are outlined. The two crucial requirements of accuracy and registration support are key aspects of this thesis and discussed separately in chapter 4 and chapter 5.

3.3.1 Unifeye SDK

3.3.1.1 Overview

The factory planning software builds on the metaio Unifeye SDK, a framework for the creation of Augmented Reality applications. The Unifeye SDK consists of functionalities for tracking, rendering and various other AR related functionalities (see figure 3.3). Wrapped in an ActiveX component, the Unifeye SDK offers a comprehensive interface to access the different functions e.g. for loading an image source, a tracking configuration or a 3D virtual model.

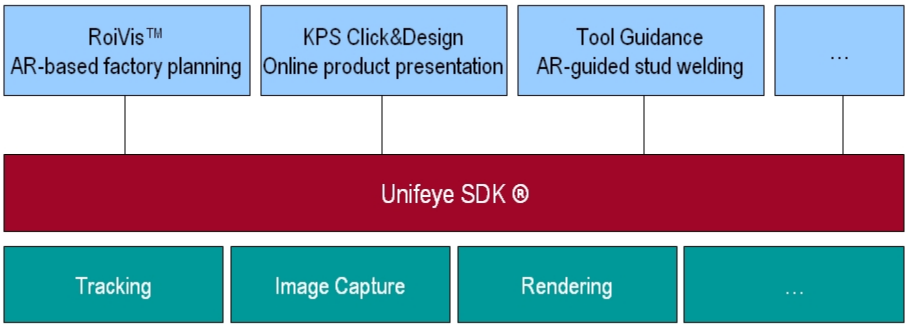


Figure 3.3: Unifeye SDK Overview

3.3.1.2 Tracking Configuration

Tracking for the Unifeye SDK is realised through so called *Sensors*. A *Sensor* can for instance be an optical marker tracking or an optical infra-red tracking. For each *Sensor*, *SensorCoses* can be configured, which represent one tracking entity of the specific *Sensor*. For marker tracking a *SensorCos* represents one marker, for infra-red tracking a *SensorCos* represent one infra-red target.
SensorCoses can then be combined to actual coordinate systems (*Coses*), which are the final tracking pose results that are provided by the system. That way, different *SensorCoses* can also be fused to form one *Cos*.

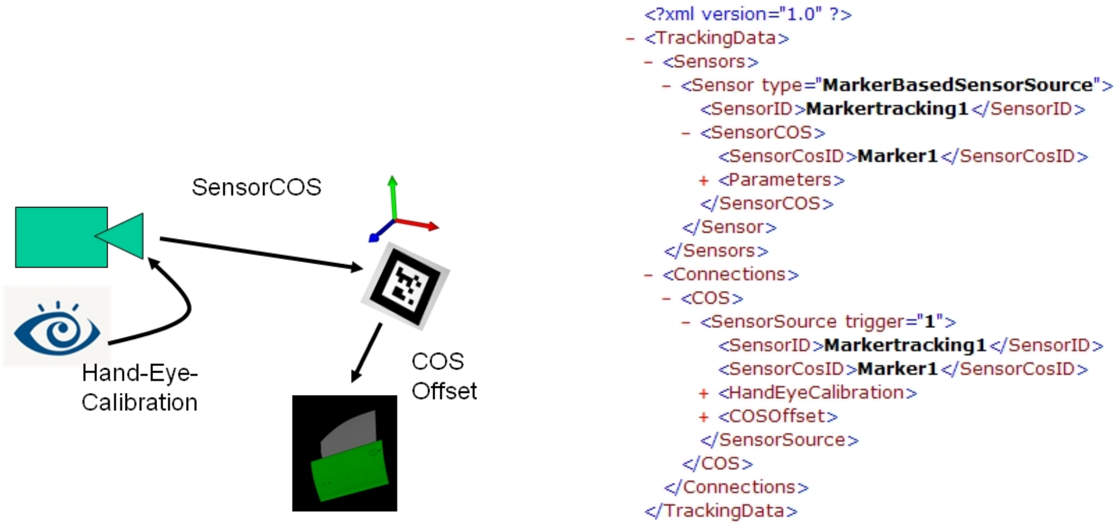
A tracking configuration file is divided in two sections: a *Sensors* section, where all the *Sensors* are defined, and a *Connections* section containing the specified *Coses*. Each *Cos* contains one or more *SensorSources*, which build the coordinate system. Thereby, each *SensorSource* element can be equipped with two transformation matrices:

- A *Hand-Eye calibration* transformation $T_{HandEyeCalibration}$ and
- A *COSOffset* transformation $T_{COSOffset}$.

The resulting transformation pose T_{Cos} for one *Cos* is then the fused result of the different *SensorSource* transformations, which are calculated as

$$T_{SensorSource} = T_{COSOffset} \times T_{SensorCos} \times T_{HandEyeCalibration}$$

For optical marker tracking, the *COSOffset* can for instance be used to reference several markers to the same virtual coordinate system. In contrast, the *HandEyeCalibration* transform is required in optical-see-through AR applications, where it represents the offset from the user's eye to the visualisation camera coordinate system. Figure 3.4 presents an example scenario for the use of the different transformations and an excerpt of a tracking configuration file.



```
<?xml version="1.0" ?>
- <TrackingData>
  - <Sensors>
    - <Sensor type="MarkerBasedSensorSource">
        <SensorID>Markertracking1</SensorID>
      - <SensorCOS>
          <SensorCosID>Marker1</SensorCosID>
        + <Parameters>
        </SensorCOS>
      </Sensor>
    </Sensors>
  - <Connections>
    - <COS>
      - <SensorSource trigger="1">
          <SensorID>Markertracking1</SensorID>
          <SensorCosID>Marker1</SensorCosID>
        + <HandEyeCalibration>
        + <COSOffset>
        </SensorSource>
      </COS>
    </Connections>
  </TrackingData>
```

(a) Example Scenario (b) Tracking Configuration File

Figure 3.4: Unifeye SDK Tracking Configuration

3.3.1.3 Virtual Content

Virtual data is supported in terms of VRML 97 files, which can be loaded and visualised in the Unifeye SDK. The interface provides methods for loading and unloading VRML content, selection of the coordinate system (*Cos*) to which the model shall be bound, as well as basic manipulation functions for 3D translation, rotation and scaling.

3.3.2 Roivis - General Overview

3.3.2.1 Motivation

Roivis is the result of the iterative development process described before and aims to meet the needs and demands of AR-supported factory and manufacturing planning, which were identified above. It provides the necessary tools for production planning and measuring tasks, while keeping the use of AR technology as easy and uncomplicated as possible.
Roivis is a C# application, which is implemented on top of the Unifeye SDK framework. It is thus a combination of functions provided by the Unifeye SDK interface, which are accessible via the graphical user interface of Roivis, as well as functions provided by C# tools, which expand the SDK functionalities through additional logic and calculations.

3.3.2.2 Hardware and Software

Roivis relies on optical marker-based tracking, which is available through the tracking component of the Unifeye SDK. The use of a marker-based tracking offers an easy interface where only a printed marker and a camera are needed to start planning with the software. To assure high accuracy for the tracking results, Roivis requires high-resolution still images. The picture source should provide stable optics to allow good calibration results. For running the application a standard PC or laptop with a good graphics card is sufficient. The suggested digital camera for Roivis is the Nikon D200 [Niko 08] with a resolution of 3872 × 2592 pixels and a lens with a fixed focal length.
Concerning software requirements, the Unifeye SDK and Roivis are implemented for the Windows operating system. Additional required software (e.g. license software) is included in the Roivis installer package.

3.3.2.3 GUI Structure and Usability Concepts

The graphical user interface (GUI) was created based on a user centred development process [Purs 06]. As main development goals, functionality, usability and look were identified, which should be realised based on the user's needs.
The resulting application provides easy and fast access to basic functionalities, such as image source selection, model loading and manipulation. In addition, a flexible toolbox is available, which can be easily expanded or limited to provide exactly the needed functionality to the user. To offer a clear overview, the toolbox is divided in three categories:

- Objects category, which holds all object management tools,
- Measuring category, which offers the different measurement functionalities and
- Configuration category, which provides the tools for tracking and calibration configuration.

Additional functionality is provided through the menu bar, where functions for scene storage, language selection or help are accessible.

Figure 3.5 presents a plain view of the graphical user interface of Roivis with the menu bar on top and the toolbox on the right side of the window. Image source selection is provided in the panel below the main rendering window.

3.3.2.4 Basic AR Functionalities

Creating a complete AR scene, requires four steps:

Image Source Selection Through the image source selection in the lower panel, the user can choose the desired image source. The image is directly displayed inside the rendering window.

Calibration Configuration In the configuration section of the toolbox a calibration configuration tool is available. Calibration files can be loaded and the intrinsic camera parameters are passed to the Unifeye SDK. The camera is stored internally for correct visualisation of the virtual model data. In addition, the system automatically rectifies the image using the specified parameters.

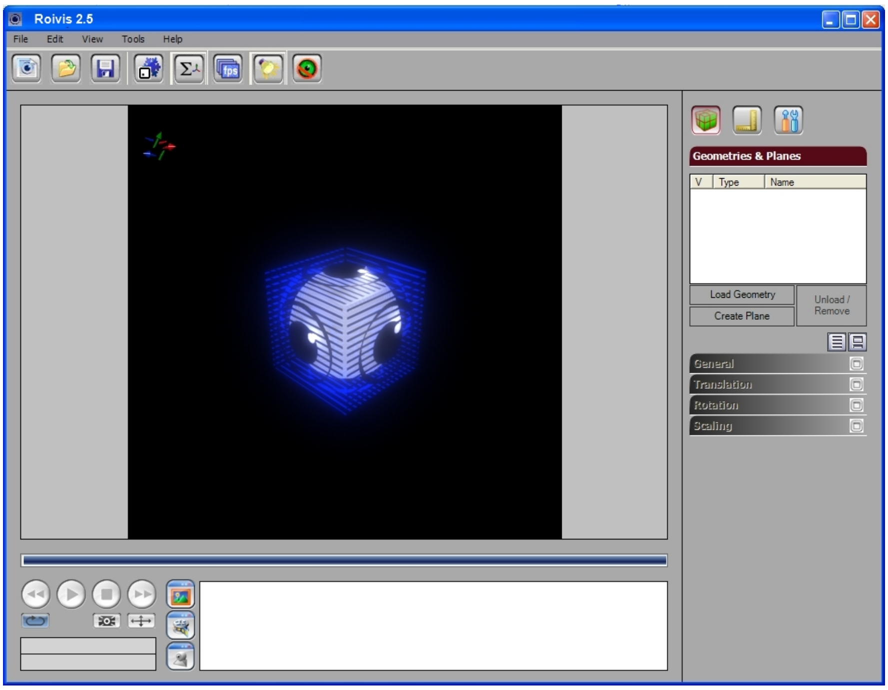


Figure 3.5: Roivis - Overview of Graphical User Interface

Tracking Configuration The configuration section also holds a tool for tracking configuration, which offers the possibility to load a tracking configuration file. For a Roivis scene, this file contains a marker tracking configuration with a set of coordinate systems (*Coses*), each defined by one or several square markers. The file is loaded into the Unifeye SDK and the configured coordinate systems are created automatically. The Unifeye SDK then parses available image data for configured markers and creates according coordinate system references.

Virtual Model Selection Using the geometries and planes tool in the objects category, virtual model data can be added to the scene. Roivis accepts digital model data in VRML 97 format. The chosen object is loaded and automatically bound to the first configured coordinate system reference. If this coordinate system has a valid tracking result, the virtual model is visualised in the scene at the corresponding location.

3.3.2.5 Measuring Functionalities

Given an AR scene, the measuring functionalities of Roivis can be used for scene analysis.

Geometry Views The first functionality for supporting AR-based planning and measuring is given through different views on the 3D geometries. Roivis offers the following views:

- Visible: This standard view simply shows the geometry as it is.
- Invisible: This mode hides the geometry, it has no effect on the virtual environment, but is kept loaded in the system for performance reasons.

- Wire frame: This mode only shows the edges of the geometry providing a so called wire frame view (see figure 3.6). It is very useful for visual comparison of real and virtual data and is, for instance, applied to perform discrepancy checks in manufacturing [Noll 06a].
- Occlusion: The last view does not show the geometry, but it still effects its virtual environment. In this way, objects in the real scene can be equipped with 3D properties and occlude other virtual objects that lie behind them.

The idea of different geometry views and an analysis on their use is presented in detail by Nölle in [Noll 06b].

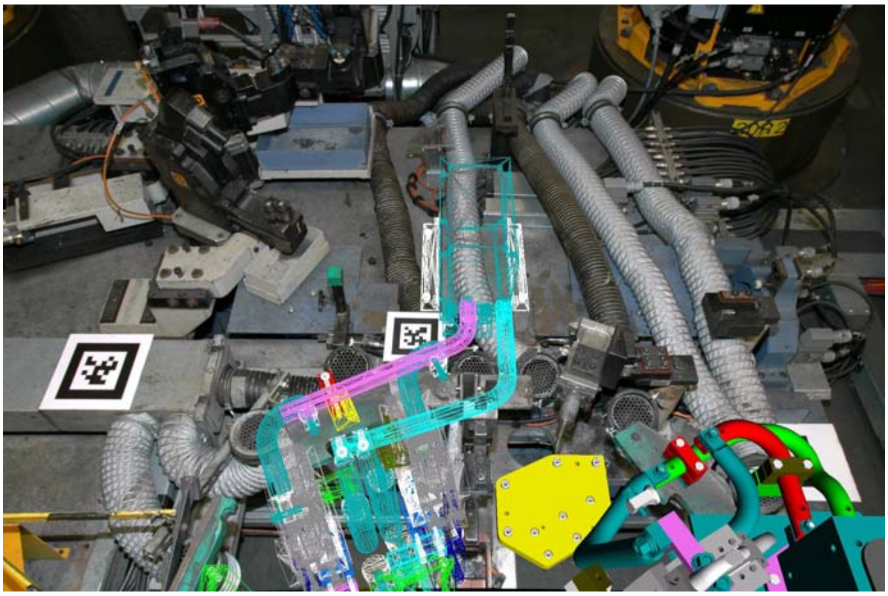
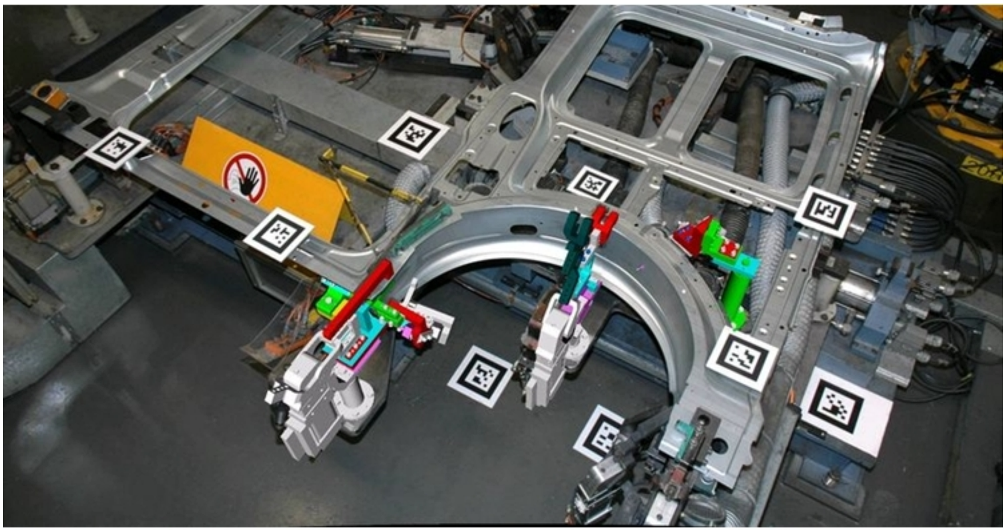


Figure 3.6: Wireframe View of a 3D Geometry (Source: Volkswagen AG)

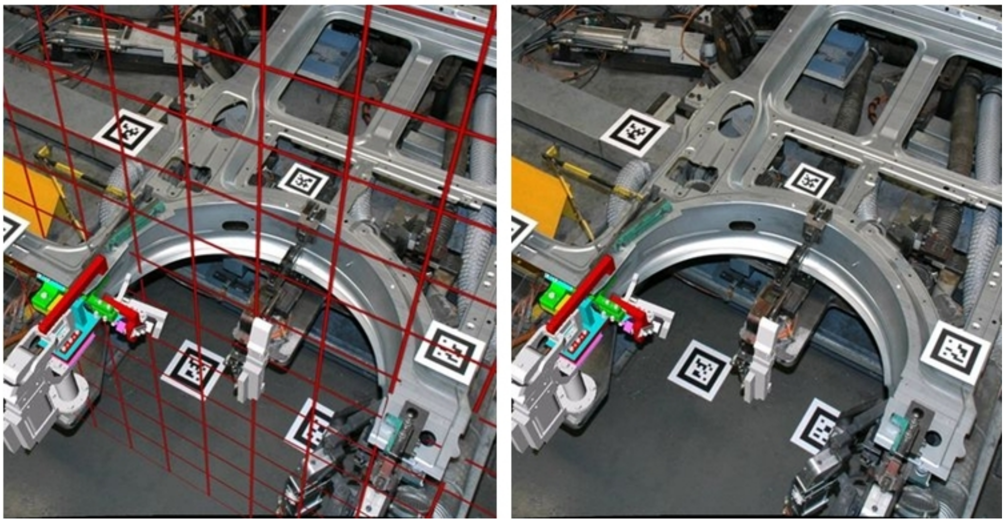
Clipping Planes Furthermore, Roivis offers so called clipping planes, which clip away virtual elements lying on the specified side of the plane. Similar to geometries, the plane is attached to a marker or an offset coordinate system and can then be oriented in different directions $(\pm X, \pm Y, \pm Z)$ for clipping the respective parts of the scene. This functionality can be applied to hide parts of the scene, which are not important for the current analysis. However, more valuable is the application for visual collision detection and interfering edge analysis. The plane is positioned to represent a pillar or some other interfering object in the planning scene. During the analysis, virtual production elements can be checked for collision with that pillar by simply testing for interference with the clipping plane (see figure 3.7).

Collision Detection The algorithmic equivalent for the visual collision detection is implemented in a collision detection tool, which checks for collisions between two virtual objects in the scene (see figure 3.8 (a)).

Distance Measurement In addition to collision detection, distance measurements between 3D geometries are of great importance for AR-based planning. Even if there is no collision between a



(a) View without Clipping Plane



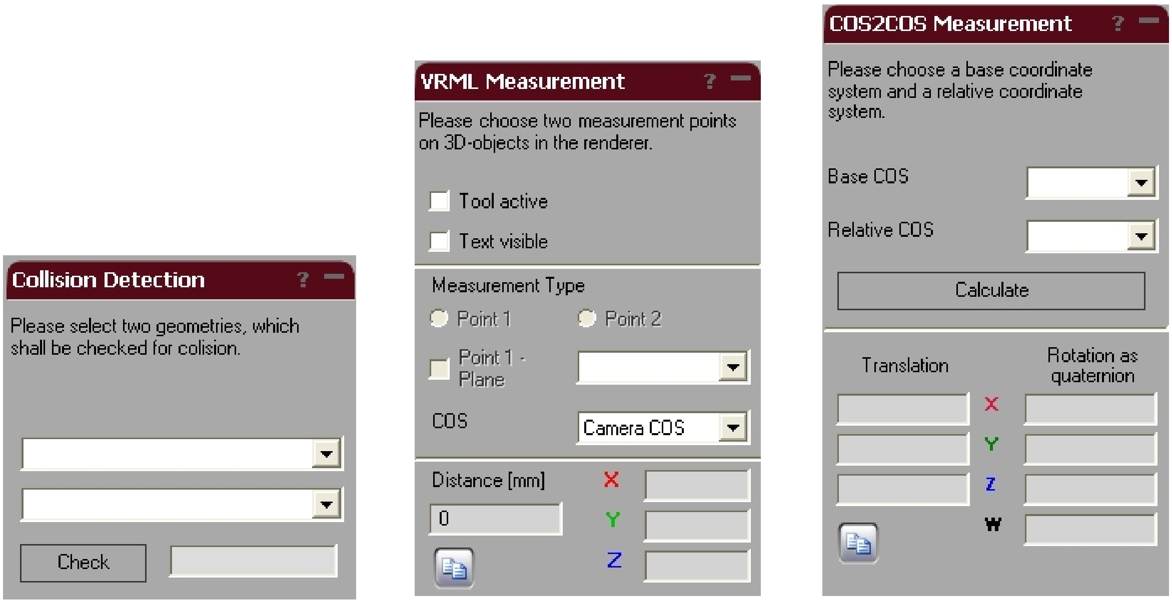
(b) View with Clipping Plane Visible and Invisible

Figure 3.7: Use of Clipping Planes (Source: Volkswagen AG)

virtual production element and the existing real environment (pillar, etc.), the distance between those components might be very small. In factory planning, a safety buffer must be included as objects in the shop floor are not only moving along certain paths, but are also swinging due to this movement. The difference between 1 or 10 cm of distance is thus quite important. Roivis provides a 3D distance measurement tool, which calculates and visualises the distance between two arbitrary 3D points given on geometries in the scene (see figure 3.8 (b)). The distance is available as Euclidean distance, as well as in 3D and can be expressed in any available coordinate system in the scene (marker or camera).

Inter-Coordinate System Measurement The Cos-2-Cos measurement tool calculates the offset between two specified coordinate systems. It can be used as a registration tool to determine the offset of a new marker to already configured markers in the scene. The graphical user interface is presented in figure 3.8 (c). As registration is one of the crucial aspects for successful AR-based factory planning, more registration support is available. The comprehensive presentation of the Roivis registration toolbox is given in chapter 5.

Accuracy Measures The accuracy measurement tool provides the user with a quality measure for a chosen 3D point in the AR scene. As the underlying functionalities of this calculation and visualisation process are one of the major contributions of this work, they are presented separately in chapter 4.


Please select two geometries, which shall be checked for colision.

Please choose two measurement points on 3D-objects in the renderer.

☐ Tool active

☐ Text visible

○ Point 1 ○ Point 2

☐ Point 1 - Plane

COS: Camera COS

Distance [mm]: 0

Please choose a base coordinate system and a relative coordinate system.

(a) Collision Detection Tool (b) Distance Measurement Tool (c) Inter-COS Measurement Tool

Figure 3.8: Roivis Measurement Tools

3.3.2.6 Documentation Possibilities

For documentation of a planning scene, Roivis offers two possibilities. First, screen shots can be taken of the complete scene including 3D geometries, distance measures and accuracy visualisation. This

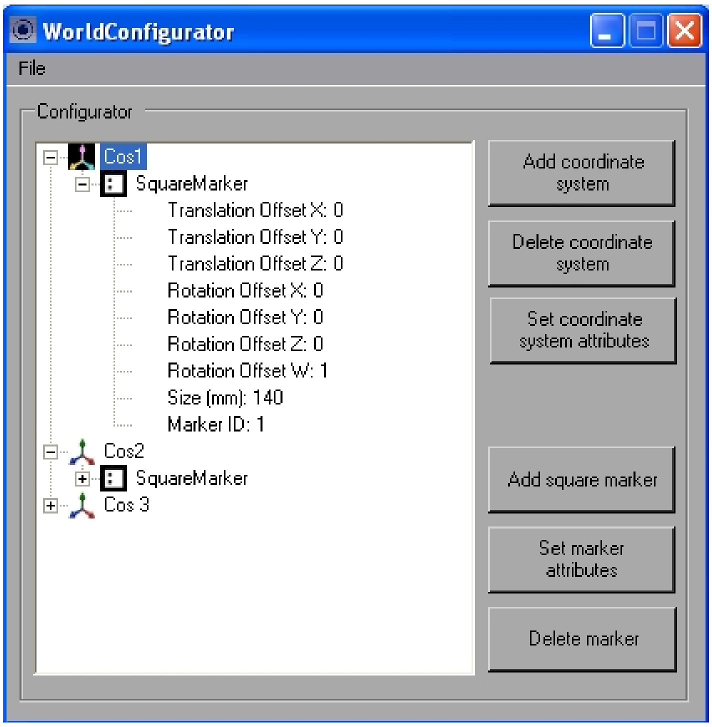
image-based documentation is very useful for off-line presentations of the planning process and its results.
Furthermore, complete planning scenes can be saved in an XML format, which contains references to the chosen image data, model data, calibration and configuration information. Based on these scene files, the planning process can be restored and continued at any time.

3.3.3 Further Tools

Besides the functionalities that are integrated in the Roivis graphical user interface, a variety of other external tools is available to support working with the Unifeye SDK. For AR-based factory planning, the tools for tracking configuration and camera calibration are important.

3.3.3.1 Tracking Configuration

The tracking configuration is represented by an XML file as described before. To ease working with this rather complicated format, an external tool is available to create marker configuration files through a graphical user interface. The tool is shown in figure 3.9. Each file consists of a set of coordinate systems (*Coses*), which are themselves composed of a set of markers. For each marker the necessary information for identification (unique marker id and size) can be specified. In addition, a *COSOffset* can be specified.
The tool does not cover all available configuration possibilities and is limited to marker-based tracking. However, for factory planning scenarios with Roivis, this functionality is sufficient.



- Cos1
  - SquareMarker
    - Translation Offset X: 0
    - Translation Offset Y: 0
    - Translation Offset Z: 0
    - Rotation Offset X: 0
    - Rotation Offset Y: 0
    - Rotation Offset Z: 0
    - Rotation Offset W: 1
    - Size (mm): 140
    - Marker ID: 1
- Cos2
  - SquareMarker
- Cos 3

Figure 3.9: Marker Configuration Tool

3.3.3.2 Camera Calibration

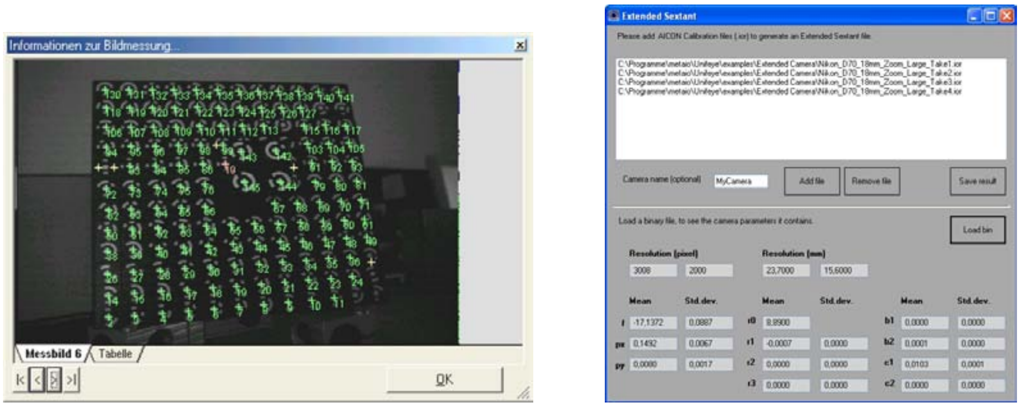
For the Unifeye SDK in general, two different approaches for camera calibration are supported.

Sextant Calibration The metaio Sextant tool allows computing a basic camera calibration using a paper chessboard pattern. Based on the known properties of the chessboard pattern, the tool can determine the intrinsic parameters of a camera using a set of images. The resulting calibration file contains the following information:

- Image resolution in pixels (res_x, res_y),
- Camera focal length in pixels (f_x, f_y) and
- Camera distortion modelled through radial (k_1, k_2) and tangential distortion (p_1, p_2) parameters.

The advantage of this approach is its easy execution, as only a paper chessboard pattern is required and results can be achieved very quickly.

Extended Sextant Calibration For AR-based evaluations using the Roivis system, an extended calibration approach is recommended. The Extended Sextant calibration relies on calibration results determined with the AICON 3D Studio software [AICO 08]. This software computes intrinsic camera parameters based on a 3-dimensional calibration pattern. The distortion model consists of radial, tangential and affine distortion parameters and is presented in more detail in section 4.3.
In contrast to the Sextant calibration, the extended approach requires more time, as well as extra calibration hardware. However, the results are more stable and accurate due to the special pattern with high-precision calibrated land marks and a 3-dimensional structure.
Figure 3.10 depicts the process of calibration. First, AICON 3D Studio is used to compute the intrinsic camera parameters based on images of a 3D calibration pattern. To be able to determine statistical information, this process has to be repeated several times. The resulting calibration files are loaded into the Extended Sextant. There, mean and standard deviation of the different calibration parameters are computed.



Please add AICON Calibration files (.ior) to generate an Extended Sextant file

C:\Programme\metaio\Unifeye\examples\Extended Camera\Nikon_D70_18mm_Zoom_Large_Take1.ior
C:\Programme\metaio\Unifeye\examples\Extended Camera\Nikon_D70_18mm_Zoom_Large_Take2.ior
C:\Programme\metaio\Unifeye\examples\Extended Camera\Nikon_D70_18mm_Zoom_Large_Take3.ior
C:\Programme\metaio\Unifeye\examples\Extended Camera\Nikon_D70_18mm_Zoom_Large_Take4.ior

Camera name (optional): MyCamera

Load a binary file, to see the camera parameters it contains.

Resolution (pixel): 3008 2000
Resolution (mm): 23,7000 15,6000

	Mean	Std.dev.		Mean	Std.dev.		Mean	Std.dev.
f	-17,1372	0,0887	r0	8,8900		b1	0,0000	0,0000
px	0,1492	0,0067	r1	-0,0007	0,0000	b2	0,0001	0,0000
py	0,0000	0,0017	r2	0,0000	0,0000	c1	0,0103	0,0001
			r3	0,0000	0,0000	c2	0,0000	0,0000

(a) Detected Calibration Pattern in AICON 3D Studio [AICO 08]

(b) Extended Sextant with Loaded AICON Calibration Files

Figure 3.10: Calibration with the Extended Sextant

3.4 Summary

Through the iterative development process, important criteria for the success and acceptance of Roivis could be derived: usability, analysis functionalities and accuracy. These criteria led to a number of critical requirements for the hardware and software components of the system.

This chapter introduced the factory planning application Roivis as the result of this iterative process. The underlying AR system Unifeye SDK was described and a general overview on the Roivis graphical user interface with its tools for configuration, manipulation and measuring was provided, indicating how the identified requirements were implemented concretely.

The realisation of the two crucial aspects of accuracy and registration support, key contributions of this thesis, is presented in the following chapters.

4 Accuracy in Roivis

Determination and Presentation of Uncertainty

One of the key criteria identified in the previous chapter is accuracy. It deals with the question on how reliable the resulting AR scene is, which means how accurate the virtual overlay is positioned with respect to the real world. As stated in the previous chapter, dealing with accuracy involves three main aspects:

- Providing an accurate result by using accurate input data and accurate system components,
- Providing a quality statement for the outcome to have a measure how reliable the result is and
- Presenting the result in an understandable and correct way

The problem of accuracy in an AR scene is founded on the difference between the actual and the target position of the virtual model in the given view. Figure 4.1 depicts an abstract visualisation of this problem. The AR view shows a virtual model at a certain location. Due to errors in the calculation, the virtual model ought to be at a slightly different location. The error is the cumulation of a number of error sources and is unknown. However, the user can be provided with statistical information on the reliability of the currently presented virtual model position in the context of the current application scenario [Pent 06a].

Accuracy is a general requirement in the context of AR-based factory planning. However, it is especially of interest when it comes to measurements. Given an Augmented Reality scene, questions to analyse the scene are asked, such as

- Does the new virtual product fit into the existing production line? (collision detection)
- How much space is between two objects in the scene? (distance measurement)
- Are the virtual object and its real counterpart identical? Where are discrepancies and how large are they? (variance comparison)

For all these questions, the Augmented Reality system can be considered as a measurement system. The user creates the AR scene with the intention to perform measurements. From the field of measurement engineering, guidelines for the calculation and presentation of uncertainty in measurement are known, which can be transferred to measurement tasks within an AR scene. The approach of combining relevant influencing factors in an industrial AR environment to a global uncertainty

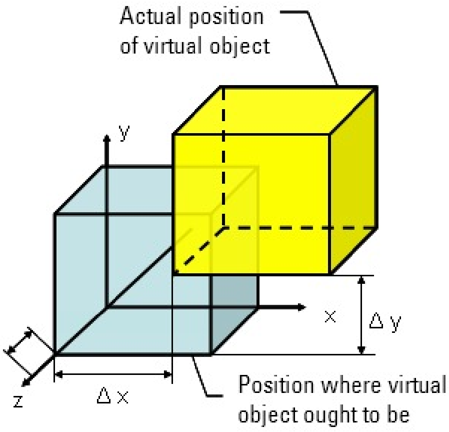


Figure 4.1: Actual and Target Position of Virtual Models

statement in the context of an AR measurement system is one of the main contributions of this thesis. In the following sections, this patent-registered [Pent 07d] concept is developed step by step. As a basis, section 4.1 introduces the fundamentals of errors and uncertainty and describes the guidelines mentioned above. These theoretical concepts are then applied to the concrete case of an AR scenario in Roivis. First, section 4.2 identifies the influencing factors on accuracy in an AR system and derives the relationship between those factors and the final AR result. Afterwards, section 4.3 presents the mathematical equations for calculating the overall uncertainty information based on this chain of influencing factors. Finally, the documentation of the result according to the guidelines from measurement engineering is explained in section 4.4. Given the general process to determine the overall quality statement for a point in an AR scene, the practical realisation is discussed next. The creation of the necessary input data for the calculation is described in section 4.5 and the implemented tools for actual calculation are shown in section 4.6.

As the task of measuring and the desired measurement are different for each scenario, this chapter focuses on the description on how the results of a measurement and its uncertainty are obtained. Specific examples can be found in chapter 6.

4.1 Errors and Uncertainty

An AR scene, the overlay of virtual information onto real world image data, is the result of several measurements (e.g. the camera pose). However, measurements are only estimates of real values. Therefore, a quantitative value of the quality of each estimate is needed to rate its reliability.

This section introduces the basics for understanding the concepts of errors and uncertainty and their calculation and presentation. It is based on information provided by the Guide for the Expression of Uncertainty in Measurement (GUM) [Guid 99], an ISO standard with two main goals:

- Comprehensive information on how to determine uncertainty statements and
- Foundation for the international comparison of measurement results.

4.1.1 Fundamentals

4.1.1.1 Measurement Process

When performing measurements, a set of operations is executed with the objective of determining a value for a measurable quantity. The physical variable that is subject to measurement is called the measurand.

In general, measurements are subject to errors, which denote the discrepancy between the result of the measurement and the true value of the measurand. Errors are caused by influence quantities, which affect the result of a measurement.

Two kinds of errors can be distinguished:

- Random errors are non-repeatable errors. They arise from unpredictable or stochastic temporal and spatial variations of influence quantities. Their value is given by the difference between the result of a measurement and the mean of an infinite number of measurements.
- Systematic errors are repeatable errors. They arise from recognized effects of influence quantities on a measurement result. Their value is given by the difference between the mean of an infinite number of measurements and the true value of the measurand.

4.1.1.2 Accuracy and Precision

When dealing with measurements, two general error concepts have to be distinguished: the accuracy and the precision of a measurement. The accuracy of a measurement denotes the closeness between the result of a measurement and the real value of the measurand. In contrast, the precision of a measurement denotes the repeatability of the measurement results meaning the closeness between the results of successive measurements of the same measurand carried out under the same measurement conditions. Figure 4.2 presents the concepts of accuracy and precision in a graphical way.

4.1.1.3 Uncertainty

The GUM uses the term uncertainty with respect to measurements and states that they can only be an approximation or estimate of the true value of the measurand as they are subject to errors. The description of a measurement is thus only complete, when accompanied by a statement of the uncertainty of the estimate. This uncertainty characterises the dispersion of the values that could reasonably be attributed to the measurand.

With respect to terminology, uncertainty and precision describe the same information for a measurement. In both cases, the true value is unknown and only the dispersion of repeated measurements can be expressed.

4.1.2 Expressing Uncertainty

4.1.2.1 Notation

The introduction of uncertainty concepts is based on the following notation. A measurand is described by a capital letter Y. An estimate of a measurand Y is denoted by y. The mean or average of several observations y_i is presented by $\bar{y}$. For the multi-dimensional case, bold letters are used: $\mathbf{Y}, \mathbf{y}$.

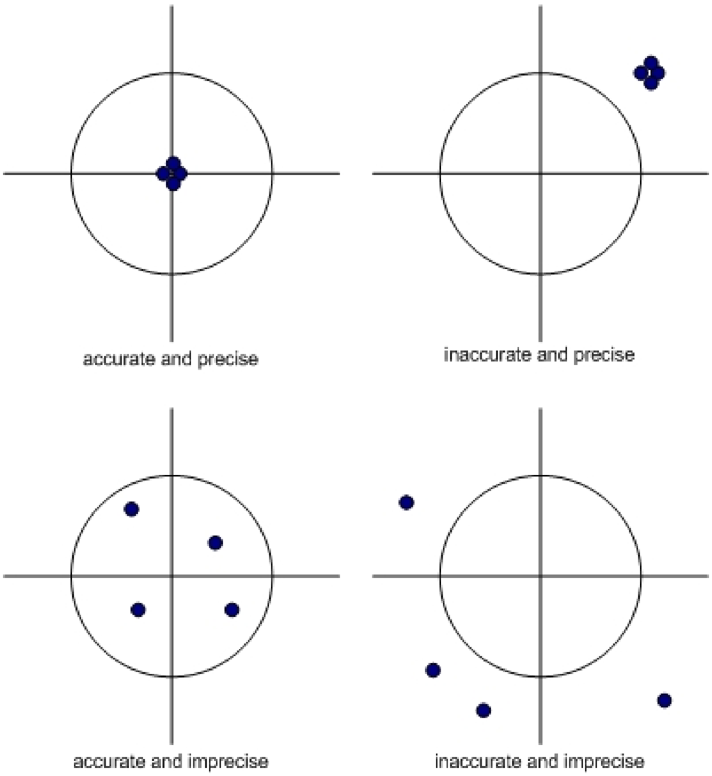


Figure 4.2: Concept of Accuracy and Precision

4.1.2.2 Modelling the Measurement

In most cases, a measurand Y is not measured directly, but is determined from n other quantities $X_1, X_2, ...X_n$ through a functional relationship f:

$$Y = f(X_1, X_2, ...X_n) \tag{4.1}$$

The input quantities $X_1, X_2, ...X_n$ may themselves be viewed as measurands and may themselves depend on other quantities.

An estimate of the measurand Y is denoted by y and is obtained through input estimates $x_1, x_2, ...x_n$ for the values of the n quantities $X_1, X_2, ...X_n$.

$$y = f(x_1, x_2, ...x_n) \tag{4.2}$$

4.1.2.3 Determination of Uncertainty for a Quantity

Mean, Variance and Standard Deviation In case n independent observations q_k of a quantity Q are available, the best available estimate of the expectation is the arithmetic mean or average $\bar{q}$ of the observations

$$\bar{q} = \frac{1}{n} \sum_{k=1}^{n} q_k \tag{4.3}$$

The individual observations differ in value because of random variations in the influence quantities or random effects. The experimental variance of the observations s^2, which estimates the variance σ^2 of the probability distribution of q is given by

$$s^2(q) = \frac{1}{n-1}\sum_{k=1}^{n}(q_k - \bar{q})^2 \tag{4.4}$$

The positive square root $s(q_k)$ of the estimated variance is termed the experimental standard deviation.

$$s(q) = \sqrt{s^2(q_k)} = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(q_k - \bar{q})^2} \tag{4.5}$$

They both characterise the variability of the observed values q_k, i.e. their dispersion about their mean $\bar{q}$.

Variance and Standard Deviation of the Mean The best estimate of $\sigma^2(\bar{q})$, the variance of the mean, is given by

$$s^2(\bar{q}) = \frac{s^2(q_k)}{n} \tag{4.6}$$

The experimental variance of the mean $s^2(\bar{q})$ and the experimental standard deviation of the mean $s(\bar{q})$, quantify how well $\bar{q}$ estimates the expectation of Q. Either may be used as a measure for the uncertainty of $\bar{q}$.

Multi-Dimensional Case The equations presented above can be expanded to the multi-dimensional case, where an input quantity $\mathbf{A}$ is an m-dimensional vector $\mathbf{A} = (A_1, A_2, ...A_m)^T$. Then, the arithmetic mean $\bar{\mathbf{a}}$ of n observations $\mathbf{a}_i$ of $\mathbf{A}$ is given by

$$\bar{\mathbf{a}} = \frac{1}{n}\sum_{k=1}^{n}\mathbf{a}_k \tag{4.7}$$

The experimental variance of the observations is represented by an $m \times m$ covariance matrix where the α_i denote components of the vector $\mathbf{a}$:

$$C = \begin{pmatrix} s^2(\alpha_1) & s(\alpha_1, \alpha_2) & \ldots & s(\alpha_1, \alpha_m) \\ s(\alpha_2, \alpha_1) & s^2(\alpha_2) & \ldots & s(\alpha_2, \alpha_m) \\ \ldots & & & \\ s(\alpha_m, \alpha_1) & s(\alpha_m, \alpha_2) & \ldots & s^2(\alpha_m) \end{pmatrix} \tag{4.8}$$

The diagonal entries $s^2(\alpha_i)$ of the covariance matrix are determined using equation (4.4) or for the variance of the mean $s^2(\bar{\alpha}_i)$ equation (4.6). The other covariance entries are calculated as

$$s(x,y) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \tag{4.9}$$

$$s(\bar{x},\bar{y}) = \frac{s(x,y)}{n} \tag{4.10}$$

4.1.3 Representation through Gaussian Distribution

Gaussian Distribution Given the set of measurements for a quantity, the determined information on the dispersion of the measurements can be visualised graphically. For visualisation, either the measurements can directly be used and plotted as a large point cloud or the properties of the distribution, the standard uncertainty and the mean of the measurements, are taken for representation.
In the latter case, the normal or Gaussian distribution function can be applied, as it is a probability distribution function, which is fully represented by a mean (average) μ and a variance (squared standard deviation) σ^2. The equations for the one-dimensional ($f_{\mu,\sigma}$) and for the multi-dimensional ($f_{\mu,\Sigma}$) case are:

$$f_{\mu,\sigma}(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)} \tag{4.11}$$

$$f_{\mu,\Sigma}(x_1,\ldots x_N) = \frac{1}{(2\pi)^{\frac{N}{2}}\sqrt{|\Sigma|}} e^{-\frac{1}{2}(x-\mu)^T\Sigma^{-1}(x-\mu)} \tag{4.12}$$

Mapping the measurements to a Gaussian distribution means to assume that the given data is approximately normally distributed. This assumption can be justified by the so called central limit theorem.

Central Limit Theorem The central limit theorem (CLT) states that the sum of a large number of independent and identically-distributed random variables will be approximately normally (Gaussian) distributed, if the random variables have finite variance [Sten 94]. In the context of measurements, this allows modelling errors using Gaussian distributions, although the actual sources of error may have other characteristics.

Graphical Representation Figure 4.3 shows the graphical representation of a one-dimensional Gaussian probability distribution with mean μ and standard deviation σ. The colour intervals represent different levels of confidence for the given distribution. An interval within one standard deviation from the mean $\mu \pm \sigma$ has a level of confidence of 68.27%. These levels of confidence are used later in this section to express the so called expanded uncertainty (see section 4.1.6).

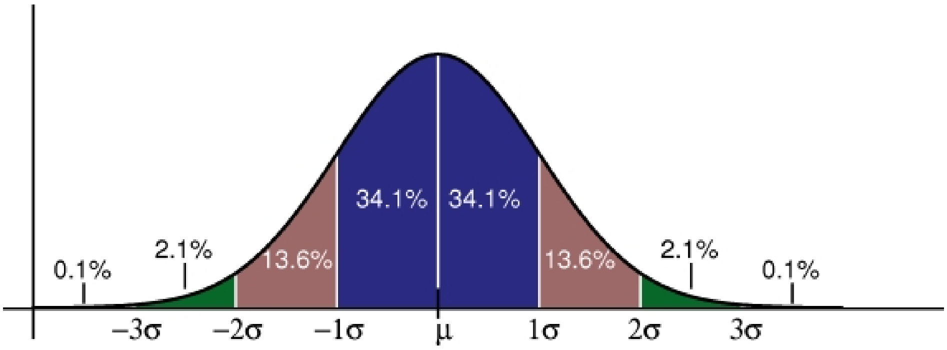


Figure 4.3: 1D Gaussian Probability Distribution

4.1.4 Propagating Uncertainty

Given a functional relationship $Y = f(X_1, X_2, ... X_n)$, the uncertainty of Y can be determined by varying all input quantities and then evaluating the uncertainty by statistical means. However, this is rarely possible in practice due to limited time and resources. Therefore, the uncertainty of a measurement result is usually evaluated using a mathematical model of the measurement and the law of propagation of uncertainty [Guid 99]. This law expresses the determination of a so called combined standard uncertainty $u_c(y) = s(\bar{y})$ based on standard uncertainties of the input quantities $u(x_i) = s(\bar{x}_i)$.

4.1.4.1 Combined Standard Uncertainty

Combined Standard Uncertainty for Dependent Quantities The combined standard uncertainty $u_c(y)$ is obtained by appropriately combining the standard uncertainties of the input estimates $u(x_i)$. It is the positive square root of the combined variance $u_c^2(y)$, which is given according to

$$u_c^2(y) = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\delta f}{\delta x_i} \frac{\delta f}{\delta x_j} u(x_i, x_j) \tag{4.13}$$

where x_i, x_j are the estimates of X_i, X_j and $u(x_i, x_j) = u(x_j, x_i)$ is the estimated covariance associated with x_i, x_j.

Combined Standard Uncertainty for Independent Quantities If the input quantities are independent, the covariances $u(x_i, x_j) = 0$ and the equation changes into the simpler relation

$$u_c^2(y) = \sum_{i=1}^{n} (\frac{\delta f}{\delta x_i})^2 u^2(x_i) \tag{4.14}$$

The partial derivatives $\delta f / \delta x_i$ are often called sensitivity coefficients and describe how the output estimate y varies with changes in the values of the input estimates x_i [Guid 99].

Multi-Dimensional Case Again, the equations for the combined standard uncertainty can be expanded to the multi-dimensional case, where $\mathbf{Y} = f(\mathbf{X}_1, \mathbf{X}_2, ... \mathbf{X}_n)$ is an m-dimensional vector.
The standard uncertainty of the input quantities can be represented as a covariance matrix $C_\mathbf{X}$ using equation (4.8). The sensitivity coefficients are composed to matrices of dimension $m \times n$ with entries $\delta f_i / \delta x_j$ for row i and column j. The entries of the matrix represent all first-order derivatives of the functional relationship f, the matrix is therefore called the Jacobian (matrix) J_f.
The resulting combined standard uncertainty is another covariance matrix C_f of dimension $m \times m$. It is determined by evaluating the following equation at $\mathbf{X} = \mathbf{x} = (\mathbf{x}_1, ... \mathbf{x}_n)$:

$$C_f = J_f C_\mathbf{X} J_f^T \tag{4.15}$$

4.1.5 Non-Linearity of the Functional Relationship

Equation (4.13) and equation (4.14) are based on the assumption that the functional relationship f is linear or that it can be approximated sufficiently well by a linear function in a neighbourhood of the

point of evaluation.
Given a linear function f and a Gaussian distribution for the input quantities, the resulting distribution will be again Gaussian, with mean and standard deviation calculated as shown before. However, if f is significantly non-linear, the resulting distributions for the combined uncertainty will also be significantly different from the Gaussian distribution and therefore more difficult to handle [Sten 94].
Nevertheless, the Gaussian distribution can still be used by referring to the central limit theorem. Typically, the approximation is better close to the mean and less accurate towards the tails of the distribution. So for small errors, normal distribution can be assumed.

4.1.6 Guidelines for the Expression of Uncertainty

4.1.6.1 Expanded Uncertainty

The combined standard uncertainty $u_c(y)$ can be used universally to express the uncertainty of a measurement. However, commercial or industrial applications often require a measure of uncertainty that defines an interval about the measurement.
The additional measure of uncertainty that meets this requirement is termed the expanded uncertainty U. It is obtained by multiplying the combined standard uncertainty $u_c(y)$ with a coverage factor k:

$$U = ku_c(y) \tag{4.16}$$

The result of a measurement is then conveniently expressed as $Y = y \pm U$. This expression means that y is the best estimate of Y and the interval $[y-U; y+U]$ may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to Y.

4.1.6.2 Choosing a Coverage Factor

The value of the coverage factor k is chosen depending on the level of confidence required for the interval $[y-U; y+U]$. In general, k will be between 2 and 3. Ideally, one would like to choose a specific value corresponding to a particular level of confidence p (e.g. 95% or 99%). This requires extensive knowledge of the probability distribution characterised by the measurement result y and its combined standard uncertainty $u_c(y)$.
Assuming normal distribution, the value of the coverage factor k_p that produces an interval with a level of confidence p is given by table 4.1 (see also figure 4.3).

Level of confidence p	Coverage factor k_p
68.27 %	1.000
90.00 %	1.645
95.00 %	1.960
95.45 %	2.000
99.00 %	2.576
99.73 %	3.000

Table 4.1: Coverage Factor k_p for Specific Levels of Confidence p

4.1.6.3 Reporting Uncertainty

Reporting uncertainty includes the description of the measurement process and the list of uncertainty components. In addition, certain guidelines should be met when presenting the result of a measurement according to the GUM [Guid 99].

When reporting the result of a measurement and when the measure of uncertainty is the expanded standard uncertainty $U = ku_c(y)$, one should:

- Give a full description of how the measurand Y is defined,
- State the result of the measurement as $Y = y \pm U$ including units,
- Include the relative expanded uncertainty $U/|y|, |y| \neq 0$, when appropriate,
- Give the value of k used to obtain U,
- Give the approximate level of confidence associated with the interval $y \pm U$ and state how it was determined and
- Describe how the results of a measurement and its uncertainty were obtained.

4.1.7 Bridging to AR-Based Factory Planning

The following sections apply the presented concepts of uncertainty in measurement to the concrete case of AR-based factory planning. First, the relevant influencing factors (input quantities) are identified. Afterwards, the propagation and documentation of uncertainty for the factory planning application Roivis are described. Finally, the concrete creation of input data and the practical implementation of the presented concepts in Roivis are presented.

4.2 Influencing Factors on Uncertainty in an AR Scene

4.2.1 Influencing Factors

In his often cited survey on Augmented Reality, Azuma distinguishes between static and dynamic errors, which influence registration in an AR system [Azum 97]. Four main static error sources are identified, namely optical distortion, errors in the tracking system, mechanical misalignments and incorrect viewing parameters. Dynamic errors occur because of system delays or lags, where the registration is incorrect due to a time difference between the moment of the tracking measurement and the moment of display of the corresponding generated virtual image. As these registration errors are only caused in case of motion, they are of no consequence for the Roivis overall system accuracy, as the system is based on still images.
Holloway's research on registration errors focuses on static error sources and lists tracking, calibration and modelling as main influencing factors [Holl 97].

Tracking A tracking system calculates an estimate of the real pose of a tracked object. Although a large variety of tracking methods are available, as well as hybrid systems, which combine different technologies, there is no approach that is likely to provide perfect pose estimation [Welc 02].

Calibration In the general case of an arbitrary AR system, the relationship between tracking system and display system must be known. For video-see through representation, this calibration mainly concerns the intrinsic parameters of the camera, such as focal length and optical distortion. Calibration methods determine these parameters based on image data of known calibration patterns, but again the results are only estimates and subject to error.
For optical-see through augmentation, the situation is even more complex, as the augmentation needs to be aligned with the users field of view and the computation of the required offsets is highly dependant on user input.
In the case of Roivis, still images are used for augmentation. Thus, calibration only includes the calibration of the intrinsic camera parameters as stated for the video-see through case.

Modelling The third influence factor is the model of the real world. It will just be an approximation of the physical object. In today's modelling process, CAD systems offer very high precision and configuration properties for the degree of tessellation of exported 3D models. This means that the number of polygons used to describe a shape can be chosen by the user. Still, even a very high number of polygons cannot reflect real objects perfectly. In addition, systematic modelling errors might occur.

To fit the industrial process of AR-based factory planning, the list of influencing factors above has to be expanded for this thesis. More concrete, a fourth factor has to be included.

Registration Offset The registration offset represents the transformation needed to bring the marker coordinate system in accordance with the model coordinate system. More detailed descriptions on why this offset is needed and how it is determined are presented in chapter 5. For now, it suffices to know that such an offset is often required and must be determined by the user based on the positioning of the markers in the specific case of application. Again, the offset is only an estimate and its quality is mainly depending on the care with which the registration process is performed by the user.

4.2.2 Chain of Uncertainty

Based on the influencing factors stated above, a chain of uncertainty can be created that connects the different error sources to form a global error for the AR system. Figure 4.4 depicts a graphical representation of this chain. The components of the chain are mathematical operations, e.g. a 3D coordinate system transformation or a 2D projection.
The figure also reflects the influencing factors of tracking, calibration, offset and modelling stated above and represents the process given by an AR scene in Roivis. The result provides statistical information on how reliable the chosen point in the AR scene is with respect to the real environment represented by the image data in the scene background.

In detail, the process includes:

- Rectification of the input image based on the given camera calibration: The result is an undistorted image, which serves as input for marker tracking and as background image for the resulting AR scene.

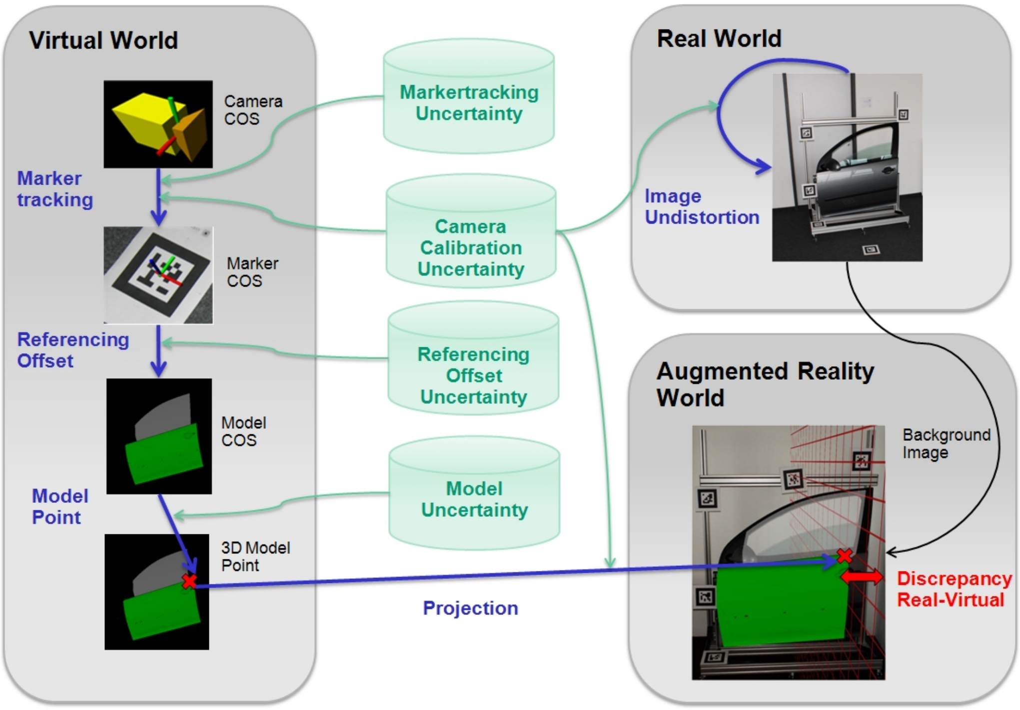


Figure 4.4: Chain of Uncertainty

- Determination of 3D tracking information[1] from camera coordinate system to marker coordinate system: Influencing factors are the input image and the camera calibration, which result in tracking uncertainty.
- Application of the 3D offset transformation from marker coordinate system to model coordinate system: This offset depends on the application. Its uncertainty is based on the means of calculation.
- Application of the 3D object transformation to one specific point in the model coordinate system: The point is selected by the user and is influenced by the quality of the 3D model reflected by the model uncertainty.

The list above represents the determination of uncertainty for a selected point in 3D space. However, in the AR world of Roivis, the user looks at a 2D visualisation of this 3D scene. Therefore, the uncertainty statement provided by the system shall reflect this 2D view. The aim is to get a quality statement reflecting the 2D uncertainty of a virtual model point with respect to its real representation in the image. To do this, two additional steps are included. The first one deals with the virtual point and maps it onto the image plane. The second one describes the behaviour of the corresponding real point, which is subject to rectification.

- Projection of the selected 3D object point to a 2D image point. Here, the camera calibration containing the intrinsic camera parameters is the factor of uncertainty.

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[1] Please note that for Roivis, tracking only denotes the process of pose estimation of an object without following it over time as the system is based on still image data.

- 2D image rectification. Again, the camera calibration influences the uncertainty of this process.

It is important to note that rectification is included twice in the chain of uncertainty. First, the undistorted image is input for the marker tracking component. Thus, the uncertainty of the intrinsic camera parameters influences the tracking pose. Second, the undistorted image serves as background for the AR view. Thus, the visible discrepancy between real and virtual world also depends on the quality of the intrinsic camera parameters.

4.3 Error and Accuracy Propagation

To form an overall statement of accuracy for the AR scene, the different influencing factors need to be combined. A combination of the three sources of error stated by Holloway was for instance presented in the work of Coelho et al. [Coel 04]. The authors created a toolkit for AR application development including functions for monitoring and adapting to registration errors.
Another example of applying uncertainty concepts to AR scenes is implemented in the Ubitrack system at TU Munich. There, the scene is represented as a spatial relationship graph (SRG), where nodes correspond to objects and coordinate frames and edges represent transformations attributed with quality-of-service information. Within this SRG, error analysis and uncertainty propagation is performed, which can then for instance be used to select the best available path through the graph in terms of uncertainty [Pust 06]. The chain of uncertainty presented in this work can also be considered as an SRG. However, different from the concepts in Ubitrack, where many edges allow choosing a favourable path, the chain of uncertainty is kept as small as possible introducing only the necessary edges ("flat SRG"). That way, uncertainty propagation is limited to the compulsary steps.

This work is based on the idea of considering the AR system as a measurement system. The error and uncertainty propagation presented here follows the guidelines stated in section 4.1.
Usually, the true value for measurements is unknown and thus, the errors cannot be calculated. However, within this work, a tracking study based on simulation data was performed that compares the estimated tracking results of the Roivis marker tracking with ground truth information. Therefore, error information is available and is included in the propagation process. In the following, this step by step propagation along the chain of uncertainty of 3D transformation, 2D projection and distortion is elaborated. More details on the determination and processing of this error information are presented in sections 4.5.1 and 7.2.

4.3.1 3D Transformation Propagation

Functional Relationship The propagation in 3D space is based on the 3D transformation equation, which includes the tracking transformation (pose between camera and marker) $T_{tracking}$[2], the offset transformation T_{offset} and the point transformation T_{point}. The final point in 3D space based on the tracking coordinate system is then given as:

$$T_{3D} = T_{tracking} \cdot T_{offset} \cdot T_{point} \tag{4.17}$$

---

[2] Please note that the notation here is different from the one introduced for section 4.1. It follows general representations of transformations and is described for each formula.

Each transform consists of a rotation matrix R and a translation vector t. R is based on three Euler angles r_x, r_y and r_z, which represent the rotations around the three coordinate axes. And t includes the translations along the three coordinate axes t_x, t_y, t_z.

$$[R|t]_{3D} = [R|t]_{tracking} \cdot [R|t]_{offset} \cdot [R|t]_{point} \tag{4.18}$$

Including Error As a next step, errors are included in the 3D propagation chain. For each transformation, the elements of rotation and translation can be subject to error: R^e, t^e. Therefore, the 3D point including error is calculated as:

$$\begin{aligned} T^e_{3D} &= T^e_{tracking} \cdot T^e_{offset} \cdot T^e_{point} && (4.19)\\ [R|t]^e_{3D} &= [R|t]^e_{tracking} \cdot [R|t]^e_{offset} \cdot [R|t]^e_{point} && (4.20)\\ [R|t]^e_{3D} &= [R+R^e|t+t^e]_{tracking} \cdot [R+R^e|t+t^e]^e_{offset} \cdot [R+R^e|t+t^e]^e_{point} && (4.21) \end{aligned}$$

The error of the final 3D point is then given as:

$$e_{3D} = T_{3D} - T^e_{3D} \tag{4.22}$$

Uncertainty Propagation For propagation, uncertainty information of the influencing factors is weighted and summed up. The weights are determined by calculating the Jacobian matrices of the transformation equation.

$$\begin{aligned} J_{tracking} &= \frac{\partial e_{3D}}{\partial (R^e_{tracking}, t^e_{tracking})} && (4.23)\\ J_{offset} &= \frac{\partial e_{3D}}{\partial (R^e_{offset}, t^e_{offset})} && (4.24)\\ J_{point} &= \frac{\partial e_{3D}}{\partial t^e_{point}} && (4.25) \end{aligned}$$

Given these weights, the final uncertainty $C_{e_{3D}}$ can be computed based on the input uncertainty information given for the influencing factors $C_{e_{tracking}}$, $C_{e_{offset}}$ and $C_{e_{point}}$. The former two are 6×6 matrices for the variance of 3D translation and rotation values. The latter is a 3×3 matrix as the point transformation only includes a 3D translation. The Jacobian matrices have according dimensions for calculating the overall result for the 3D propagation process:

$$C_{e_{3D}} = J_{tracking} \cdot C_{e_{tracking}} \cdot J^T_{tracking} + J_{offset} \cdot C_{e_{offset}} \cdot J^T_{offset} + J_{point} \cdot C_{e_{point}} \cdot J^T_{point} \tag{4.26}$$

4.3.2 2D Projection Propagation

Functional Relationship For 2D projection, the mathematical equation is given by

$$t_{2D} = \begin{pmatrix} x_{2D} \\ y_{2D} \end{pmatrix} = \begin{pmatrix} f_x \cdot \frac{x_{3D}}{z_{3D}} + c_x \\ f_y \cdot \frac{y_{3D}}{z_{3D}} + c_y \end{pmatrix} \tag{4.27}$$

where f_x and f_y are the focal length values in pixels, c_x and c_y represent the principal point in pixels and t_{3D} is the result translation of the 3D propagation process:

$$t_{3D} = \begin{pmatrix} x_{3D} \\ y_{3D} \\ z_{3D} \end{pmatrix} \tag{4.28}$$

Including Error Again, error is added to the equations:

$$t_{2D}^e = \begin{pmatrix} x_{2D}^e \\ y_{2D}^e \end{pmatrix} = \begin{pmatrix} (f_x + f_x^e) \cdot \frac{x_{3D}+x_{3D}^e}{z_{3D}+z_{3D}^e} + (c_x + c_x^e) \\ (f_y + f_y^e) \cdot \frac{y_{3D}+y_{3D}^e}{z_{3D}+z_{3D}^e} + (c_y + c_y^e) \end{pmatrix} \tag{4.29}$$

The final error of the 2D projection is then calculated as:

$$e_{2D} = t_{2D} - t_{2D}^e \tag{4.30}$$

Uncertainty Propagation For the computation of the overall uncertainty information for the 2D projection process, the Jacobian weights are determined as

$$J_{focal} = \frac{\partial e_{2D}}{\partial (f_x^e, f_y^e)} \tag{4.31}$$

$$J_{principal} = \frac{\partial e_{2D}}{\partial (c_x^e, c_y^e)} \tag{4.32}$$

and the result covariance matrix is computed based on the 2×2 input covariances for focal length and principal point error $C_{e_{focal}}, C_{e_{principal}}$:

$$C_{e_{2D}} = J_{focal} \cdot C_{e_{focal}} \cdot J_{focal}^T + J_{principal} \cdot C_{e_{principal}} \cdot J_{principal}^T \tag{4.33}$$

4.3.3 2D Distortion Propagation

Functional Relationship The functional relationship used to model image distortion is based on the approach described by Luhmann [Luhm 05]. The AICON camera calibration software, which is used for Roivis, applies the same model.

Distortion is modelled using radial Δ_{rad}, tangential Δ_{tan} and affine distortion Δ_{aff} components. The corresponding variables are explained in more detail in section 4.5.2.

$$t_{dist} = \begin{pmatrix} x_{dist} \\ y_{dist} \end{pmatrix} = t_{2D} + \Delta_{rad} + \Delta_{tan} + \Delta_{aff} = \begin{pmatrix} x_{2D} + x_{rad} + x_{tan} + x_{aff} \\ y_{2D} + y_{rad} + y_{tan} + y_{aff} \end{pmatrix} \tag{4.34}$$

$$\Delta_{rad} = \begin{pmatrix} x_{2D} \\ y_{2D} \end{pmatrix} \cdot \left(a_1 \cdot (r^2 - r_0^2) + a_2 \cdot (r^4 - r_0^4) + a_3 \cdot (r^6 - r_0^6)\right) \tag{4.35}$$

$$r = \sqrt{x_{2D}^2 + y_{2D}^2} \tag{4.36}$$

$$\Delta_{tan} = \begin{pmatrix} b_1 \cdot (r^2 + 2x_{2D}^2) + 2b_2 \cdot x_{2D} \cdot y_{2D} \\ b_2 \cdot (r^2 + 2y_{2D}^2) + 2b_1 \cdot x_{2D} \cdot y_{2D} \end{pmatrix} \tag{4.37}$$

$$\Delta_{aff} = \begin{pmatrix} c_1 \cdot x_{2D} + c_2 \cdot y_{2D} \\ 0 \end{pmatrix} \tag{4.38}$$

$$\tag{4.39}$$

Including Error Error is added to all components of the distortion.

$$t_{dist}^e = t_{2D} + e_{2D} + \Delta_{rad} + \Delta_{rad}^e + \Delta_{tan} + \Delta_{tan}^e + \Delta_{aff} + \Delta_{aff}^e \tag{4.40}$$

$$e_{dist} = t_{dist} - t_{dist}^e \tag{4.41}$$

Uncertainty Propagation For the computation of the overall uncertainty information for distortion, the Jacobian weights are determined as

$$J_{radial} = \frac{\partial e_{dist}}{\partial(a_1^e, a_2^e, a_3^e)} \tag{4.42}$$

$$J_{tangential} = \frac{\partial e_{dist}}{\partial(b_1^e, b_2^e)} \tag{4.43}$$

$$J_{affine} = \frac{\partial e_{dist}}{\partial(c_1^e, c_2^e)} \tag{4.44}$$

and the result covariance matrix is computed based on the input covariances for the distortion parameters $C_{e_{radial}}, C_{e_{tangential}}, C_{e_{affine}}$:

$$C_{e_{dist}} = J_{radial} \cdot C_{e_{radial}} \cdot J_{radial}^T + J_{tangential} \cdot C_{e_{tangential}} \cdot J_{tangential}^T + J_{affine} \cdot C_{e_{affine}} \cdot J_{affine}^T \tag{4.45}$$

Several assumptions are made to ease the computation. First, the different distortion components are considered as independent and separate Jacobian weights are calculated for radial, tangential and affine distortion. Secondly, the functional relationship for the radial distortion is non-linear. This non-linear step is approximated linearly to allow for an easy error propagation.
The radial distortion parameter r_0 is a constant zero-crossing value and is thus not included in the formula for computing the Jacobian weight J_{radial}.

4.3.4 Final Presentation

As final result, the calculation provides a 2D error and a 2×2 covariance matrix with unit pixels along the x and y axes of the image coordinate system. However, information in pixels is not very valuable for the user and difficult to understand in spatial terms.
The result values are therefore converted back to metric units based on the 3D information available for the scene. The 2D error and standard deviation are projected back to 3D space using the z-distance of the originally selected 3D point for calculation. This computation does not include uncertainty propagation any more as it is only a transformation of units.
The final result is a 2D error in mm and a 2×2 covariance matrix along the x and y axes in a plane parallel to the $x-y-$plane of the image coordinate system.

4.4 Error and Accuracy Presentation

Based on the concept of expanded uncertainty from the GUM, the calculation result is modified once more for reporting it to the user. The measurement uncertainty is multiplied with a coverage factor $k = 2$ to represent a level of confidence of approximately 95%. The resulting measurement error is presented as calculated to inform the user of the discrepancy caused by the tracking system.
Two ways of information presentation are available:

4.4.1 Textual Presentation

The textual presentation uses the GUM approach and states the result for measurement error and expanded uncertainty. As the result is 2-dimensional, the values for x and y direction of the image

Error	Expanded uncertainty
Measurement error in x direction	Expanded uncertainty in x direction
Measurement error in y direction	Expanded uncertainty in y direction

Table 4.2: Elements of the Textual Presentation

coordinate system are stated separately. The four elements of the textual representation are shown in table 4.2 and concrete examples can be found in chapter 6.

4.4.2 Graphical Presentation

There are different ways of representing errors and uncertainty graphically (see for instance Johnson and Sanderson [John 03]). The approach taken for Roivis is based on the visualisation concept described by Hoff et al. [Hoff 00] that uses ellipsoids and elongated cones to represent 3D positional and rotational errors. As the result here is only 2-dimensional, an ellipse is used for graphical representation of the expanded uncertainty. Its dimension is based on the x and y directional values for expanded uncertainty. The directional measurement error result is directly included in the location of the ellipse as it is illustrated in figure 4.8.

4.5 Input Data

To compute uncertainty information for a given AR scene in Roivis, input uncertainty data for the influencing factors identified above must be available. Some information has to be provided by the user, as it is specific to the concrete scenario and data, such as the offset accuracy and the model accuracy. Other information can be provided by the system and is known a-priori, e.g. for tracking and camera calibration.

This section uses both the terms accuracy and uncertainty. In general, the terminology is chosen based on the type of information presented (see section 4.1). However, in section 4.5.1 the research background describes accuracy studies for marker tracking although sometimes the correct term would be uncertainty. For these studies, the terminology from the cited literature is used and not adapted according to the definition above.

4.5.1 Tracking Accuracy

For Roivis, the optical marker-based tracking implemented in the Unifeye SDK is used. The quality of such marker-based tracking systems depends on many influencing factors such as the chosen hardware, environmental constraints and the setup of the marker with respect to the tracking camera. The resulting values reflect the accuracy of the position and orientation of the marker with respect to the camera.

4.5.1.1 Accuracy of Marker-Based Tracking Systems

In the past, several studies have been performed to identify and evaluate the influence of different factors on the accuracy of marker tracking systems.
Zhang et al. [Zhan 02] evaluated four marker trackers, the ARToolKit, the Institut Graphische Datenverarbeitung (IGD) marker system, the Siemens Corporate Research (SCR) marker system and the Hoffman marker system (HOM) with respect to usability, efficiency, accuracy and reliability. The accuracy evaluation was based on the errors in feature extraction and states accuracy results for different rotation angles around the x-axis of the marker and for different regions of marker (ROM).
For the ARToolKit system, two further accuracy experiments have been performed. Both experiments evaluate the relative distance of marker and camera, as well as one angle of rotation. Malbezin et al. placed a marker on the ground and compared the tracking results with physical measurements in an orbit around the marker for different distances (1-3 meters) [Malb 02]. In contrast, Abawi et al. looked at error and standard deviation values for pose estimates [Abaw 04]. The authors conducted an analysis where a combination of criteria is evaluated. High and low error and standard deviation intervals were identified both for different angles and distances and an accuracy function is defined based on these four intervals.

4.5.1.2 Influencing Factors

The presented studies clearly identify the relevance of two influencing factors:

- Distance between camera and marker and
- Viewing angle around x- and y-axis (r_x, r_y).

With respect to the relative position, distance alone does not suffice as influence parameter. Therefore, Zhang et al. already used the region of a marker in an image as indicator, which means the area of the marker in pixels.
This region is a combination of the camera chip size in mm (w,h) and image resolution in pixels (res_x, res_y), the focal length in mm (f) of the camera, the distance in mm (d) between camera and marker and the marker size in mm (s). For a frontal perspective on the marker, the marker area in pixels $(MAiP)$ is computed as

$$MAiP = \frac{f_x \cdot s}{d} \cdot \frac{f_y \cdot s}{d}$$

with

$$f_x = f \cdot \frac{res_x}{w} \text{ and } f_y = f \cdot \frac{res_y}{h}$$

For the accuracy description of the Unifeye SDK marker-based tracking, the parameters $MAiP$ and angle around x- and y-axis are used. To illustrate the influencing viewing angles, figure 4.5 visualises the marker coordinate system. The x- and y-axis of the marker coordinate system describe the marker plane and z points upwards.

Other influencing factors such as environmental conditions or image quality are difficult to measure and can thus not be easily used as input variables for an accuracy function. The current approach is therefore limited to the three mentioned parameters. Nevertheless, these further influencing factors should not be neglected and were included in a general analysis of the Unifeye SDK marker-based tracking, which is described in more detail in section 7.2.

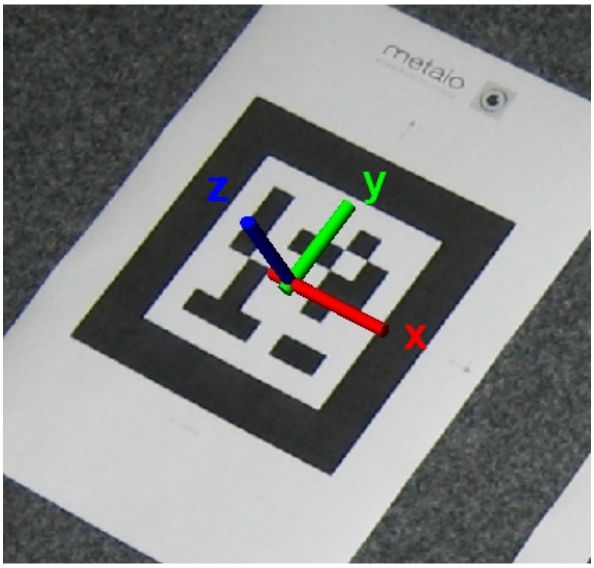


Figure 4.5: Marker Coordinate System

4.5.1.3 Accuracy Function for Roivis

Abawi et al. provided a first step for an accuracy function for marker-based tracking. However, their approach is only based on a few accuracy intervals. The accuracy function for the Roivis factory planning application should be more detailed and should provide information for arbitrary combinations of input values.

Different from the approaches above, the tracking accuracy of the Unifeye SDK marker tracking is not measured in terms of physical experiments, but is analysed using a simulation based approach. This has two main advantages. First, the approach relies on simulated image data (images of markers with known position and orientation and known intrinsic camera parameters) and therefore allows comparing the tracking results with actual correct ground truth data. Second, the simulation process can be automated and thus a huge data set can be created to provide a good base for an accuracy function. Still, the main disadvantage is clearly that simulated image data cannot perfectly reflect the real world.

As the accuracy function cannot be expressed in terms of an actual equation, the simulation data is used to fill a look up table, a tracking accuracy database.

4.5.1.4 Creation and Use of the Tracking Accuracy Database

For data acquisition, the Unifeye ground truth tool was implemented. It allows generating arbitrary camera views of a metaio marker with known marker position and orientation. These views are processed by the Unifeye SDK marker tracking to determine a tracking estimate for the marker position and orientation. The resulting information is then used to fill the accuracy database. Implemented as a look up table the database holds error information filed according to influence factor values. For a set of $(MAiP, r_x, r_y)$, ground truth and estimated feature information of the detected marker corners, as well as full ground truth and estimated position and orientation is stored.

For filling the database with sets, two main constraints were considered. The database should provide tracking accuracy information for a given scene, which is statistically valid. Therefore, the rules of Design of Experiments [Mont 05] are taken into account . This method uses a randomized though structured approach for data generation, which is explained in detail in section 7.2. In addition, the database should provide tracking accuracy information for a given scene, which meets the requirements of the guidelines for expressing the uncertainty in measurement. This constraint requires the database to return enough data sets for each query $(MAiP, r_x, r_y)$ such that a statistical evaluation can be performed.

Based on these constraints, the Roivis tracking accuracy database was created. It is updated every time changes in the marker tracking algorithm are performed to assure consistency in accuracy information and tracking results. More related information on the process of data acquisition can be found in section 7.1.

4.5.2 Camera Calibration Accuracy

The camera calibration accuracy represents the accuracy of the calibrated intrinsic parameters of the camera. Different from the situation above, the intrinsic parameters cannot be compared to ground truth values, but can only be estimated. Therefore, the correct term to be used is calibration uncertainty.

Different camera models are available to approximate real camera projections, differing mainly in their description of the camera distortion. In addition, different methods of calibration are available. Simple approaches use plane chess board patterns, which are just printed on a piece of paper (e.g. Matlab calibration toolbox [Boug 07] or metaio Sextant calibration 3.3.3). More precise approaches rely on pre-calibrated three dimensional calibration boards, which are used in measurement engineering. For the Roivis application, such a high-precision calibration of AICON [AICO 08] is used. The AICON 3D Studio calibration computes a camera model as it is described by Luhmann [Luhm 05] and determines the following parameters:

- Focal length f in mm,
- Principal point (p_x, p_y) as distance in mm from the image centre,
- Radial distortion parameters r_0, a_1, a_2, a_3 (third order polynom),
- Tangential distortion parameters b_0, b_1 and
- Affine distortion parameters c_0, c_1.

Required input parameters for the given camera are the image resolution in pixels and the chip size in mm, which needs to be available in the camera specification.

To determine the uncertainty of the AICON calibration, a set of calibration files is used to calculate a mean and a standard deviation for all the calibration parameters. The Roivis Extended Sextant tool performs this statistical calculation and creates an output binary calibration file (see also section 3.3.3).

AICON 3D studio also provides a residual after calibration. This value describes the remaining error after optimisation and could serve as a better quality information for the intrinsic parameters than the statistical values, which are calculated by the Extended Sextant tool. Thus, in the future, the residual can supersede the current information to improve the overall quality of the process.

4.5.3 Offset Accuracy

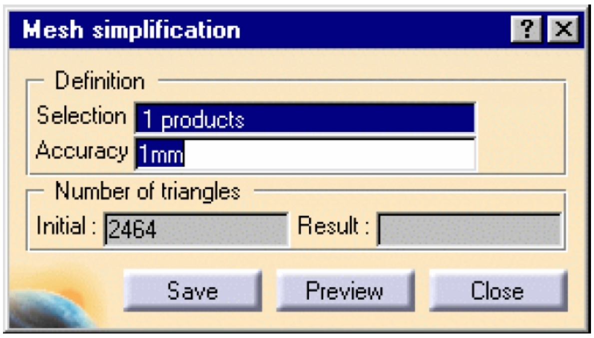
The offset accuracy describes the accuracy of the transformation leading from the marker tracking coordinate system to the model coordinate system (registration offset). As this registration offset is different for each scenario, it has to be determined by the user as one preparational step. Depending on the approach that is used to determine the offset, the corresponding accuracy information has to be retrieved. This retrieval process can be of various kinds. Again there is no ground truth data available, thus, the result is given as uncertainty information.

- If the offset is determined by direct measurement, the offset uncertainty is based on the uncertainty of the tool used for measuring. There are measurement tools, where a concrete uncertainty is available (e.g. measurement arm) and tools, where the uncertainty can only be estimated (e.g. simple ruler).
- If the offset determination is based on a calculation process, which uses certain input data, the offset uncertainty is a function of the uncertainty of the input data and must be calculated according to the propagation rules specified in section 4.1. Again, this input uncertainty can be either known or has to be estimated in some way.

For Roivis, a number of useful approaches to determine the registration offset have been implemented. More information on their nature and ways to determine their uncertainty are presented in chapter 5.

4.5.4 Model Accuracy

Finally, the model accuracy for the used 3D model has to be specified by the user. In industrial scenarios, the 3D models are usually taken from a design database where various stages of a virtual object are available (e.g. different production stages of a product throughout the production line). These 3D models are created using powerful design tools such as CATIA (see section 2.2.2.2 on example software). Such CAD tools can export 3D models in various formats and with various properties. One property is the tessellation of the model, which describes the number of polygons used to represent the model. Depending on the degree of tessellation, the model represents the reality better or worse. This degree of tessellation is thus an uncertainty measure for the virtual model and can be used as input information for the uncertainty calculation in Roivis.
The model uncertainty value is specified in mm and can be set in the CAD software. Figure 4.6 shows the mesh simplification dialog of CATIA.

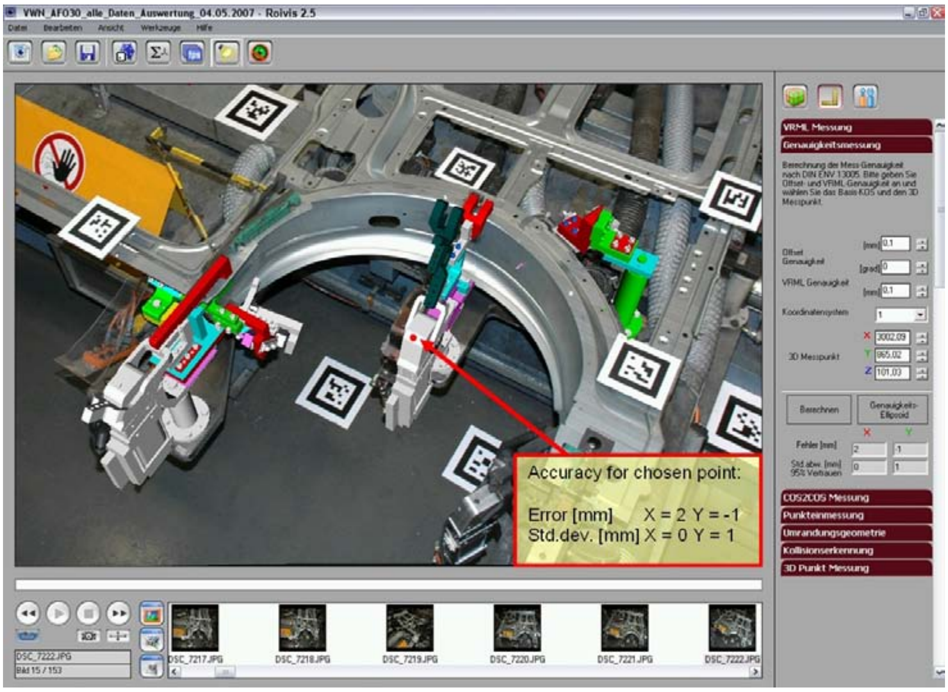


Selection 1 products
Accuracy 1mm
Initial : 2464
Result :

Figure 4.6: CATIA Mesh Simplification Dialog

4.6 Implementation

To calculate an overall uncertainty information for a given scene, the accuracy / uncertainty input information needs to be combined according to the propagation process described above. This uncertainty calculation functionality for Roivis is available through the Accuracy Measurement tool in the measurement category of the Roivis toolbox. The tool in use is shown in figure 4.7.



Berechnung der Mess-Genauigkeit nach DIN ENV 13005. Bitte geben Sie Offset- und VRML-Genauigkeit an und wählen Sie das Basis-KOS und den 3D Messpunkt.

Offset Genauigkeit [mm] 0.1
[grad] 0
VRML Genauigkeit [mm] 0.1
Koordinatensystem 1
3D Messpunkt X 3002.09 Y 865.02 Z 101.03
Fehler [mm] X 2 Y -1
Std.abw. [mm] 95% Vertrauen X 0 Y 1

Accuracy for chosen point:
Error [mm] X = 2 Y = -1
Std.dev. [mm] X = 0 Y = 1

DSC_7222.JPG
Bild 15 / 153

Figure 4.7: Accuracy Measurement Tool in Roivis (Source: Volkswagen AG)

4.6.1 Input for Uncertainty Calculation

The input information is available as described above. The user needs to specify the offset and model uncertainty. In addition, the tracking coordinate system, which shall be used for calculation and a specific measurement point on a 3D model must be selected in advance. Based on this data, the system can retrieve the missing input accuracy/uncertainty information automatically and can combine the data to form the overall error and uncertainty statement for the chosen 3D point.

4.6.1.1 Tracking Accuracy and Error

This data is taken from the tracking accuracy database, using the tracking information for the selected coordinate system. Internally, a query is performed to find representative information in the database for the current AR scene based on the given values for $(MAiP, r_x, r_y)$. As the database cannot contain data sets for each set of input values, an interval search is performed in an area around the stated input values to retrieve at least 50 result sets. Starting with the correct query parameters, the search is step by step expanded to find result sets. The maximum interval size is currently set to ±5° and

around ±5% of the z-distance value. The current database size of around 50 MB is adequate for these intervals.
The result of this query is given by sets of marker corner features with corresponding ground truth information. Before computing an average error for the tracking pose, distortion uncertainty is added to the the marker corner features. That way, the uncertainty of the currently used camera calibration, which influences the tracking result, is included in the process. Each set of tracking corners is then transformed to a tracking pose, which can be compared with the corresponding ground truth to determine the final tracking pose error.

4.6.1.2 Offset Uncertainty

The offset uncertainty needs to be stated by the user as the means of marker positioning are previously unknown and depend on the current application scenario.
If the offset was calculated using tools in Roivis, which also calculate an uncertainty statement for the offset, these values can be copied directly from there. The offset uncertainty must be provided as translational and rotational standard deviation values in mm and degrees respectively.

4.6.1.3 Calibration Uncertainty

Information on calibration uncertainty is available based on the chosen calibration file for the scene, as described above. The Extended Sextant calibration format holds intrinsic parameters, as well as variance information for the single parameters.

4.6.1.4 Model Uncertainty

The model uncertainty is again stated by the user, who chooses the virtual model to be used for the AR scene and is entered as a standard deviation value in mm.

4.6.1.5 3D Measurement Point

Finally, a 3D measurement point must be chosen based on the virtual model to specify the point of interest for calculation. The 3D measurement point can either be entered manually as x, y and z coordinates or can be chosen by clicking on the virtual model geometry in the scene.

4.6.2 Uncertainty Calculation and Visualisation

The information of all influencing factors is combined according to the equations stated above. The result is returned as 2D error and standard deviation values, including a 95% confidence interval, and displayed in the number boxes of the tool.
Besides this numerical statement, the other means of visualisation are available through checkboxes. The uncertainty ellipsoid and an additional textual visualisation in the rendering window can be switched on and off as desired by the user.

4.6.3 Result Interpretation

The process above describes the uncertainty calculation for a point in the scene. As presented in figure 4.1, the virtual overlay (actual) is subject to noise and diverges from its intended (target) position. Thus, any 3D point on a virtual model in the scene differs from its target position. This difference is reflected by the calculated uncertainty information.
The result of this calculation is an error and a standard deviation, which can be interpreted as follows:

- The error values represent a directional error for the visualisation of the selected 3D point in the scene. It is the propagated result of the original marker tracking error, which is a systematic error.
- The standard deviation values represent a 95% confidence interval around the visualisation of the selected point in the scene. In 2D it can be visualised as an ellipse. This ellipse characterises the effects caused by random errors in the process.

Figure 4.8 visualises this concept of error and uncertainty in Roivis. For a chosen point $P1$ in the AR scene, the calculation results in an error e and an expanded uncertainty u. The length of the major and minor axis of the ellipse are fixed through the expanded uncertainty values in x and y direction (u_x, u_y). The error e results in a 2D translation of the ellipse with respect to the originally chosen point $P1$.

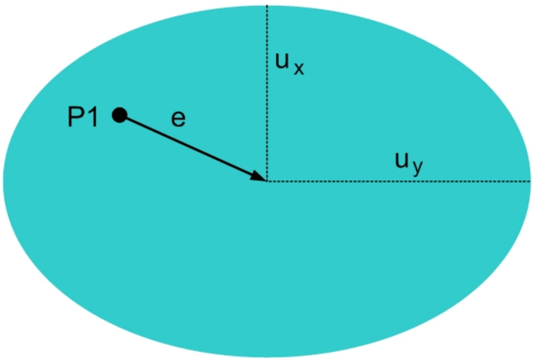


Figure 4.8: Error and Uncertainty Visualisation in Roivis

4.7 Summary

This chapter presented the background and the implementation of one key requirement for Roivis and one of the main contributions of this thesis: the provision of an overall quality statement for a given AR scene.
Based on an ISO standard, concepts for uncertainty calculation and presentation from measurement engineering were introduced, which were then transferred to the Augmented Reality world by regarding the Roivis system as a measurement system. To calculate an uncertainty statement, influencing factors on the final output were determined and a chain of uncertainty was described, which relates the input uncertainties of the different factors to one single output quality information for a selected point in the AR scene. Finally, the practical realisation of the process was outlined, in describing the concrete acquisition of input data and the presentation of the final result.

5 Registration in Roivis

Implemented Approaches and Aspects of Uncertainty

As mentioned in section 3.2, data and process related aspects play an important role for the serviceability and acceptance of the factory planning application. A crucial aspect here is the registration between the real and the virtual world. In section 4.2, the registration offset was introduced as one source of error for the overall registration accuracy. Within the context of Roivis, this offset is needed to align the marker coordinate system with the virtual model coordinate system. Supporting registration therefore requires the consideration of accuracy and usability.

Figure 5.1 presents the different coordinate systems, which are present in a typical industrial Augmented Reality scenario. The scenario is independent from the used tracking system and has the following coordinate systems:

- The tracking world coordinate system, which in the case of Roivis is the origin of the visualisation camera,
- The tracking target coordinate system, which in the case of Roivis is the marker coordinate system and
- The model coordinate system, which is not necessarily aligned with the target coordinate system.

Using the automotive industry as an example, the model coordinate system is mostly the car coordinate system. Digital car bodies and car parts have a specific model coordinate system, which is standardised. Usually, it is located in the middle of the front axle and is right-handed with x pointing to the back of the car and z pointing upwards. When tracking a real car body, the tracking target often cannot be placed in accordance with the model coordinate system as it lies inside the car body. To overlay virtual information on the real car body, it is thus necessary to determine the offset between the target coordinate system and the model coordinate system.

In the following, the task of registration is presented in detail. First, section 5.1 gives a background on general options for registration. Then, the second important contribution of this thesis, the Roivis registration toolbox, is described in section 5.2. Finally, some practical considerations of use are discussed in section 5.3.

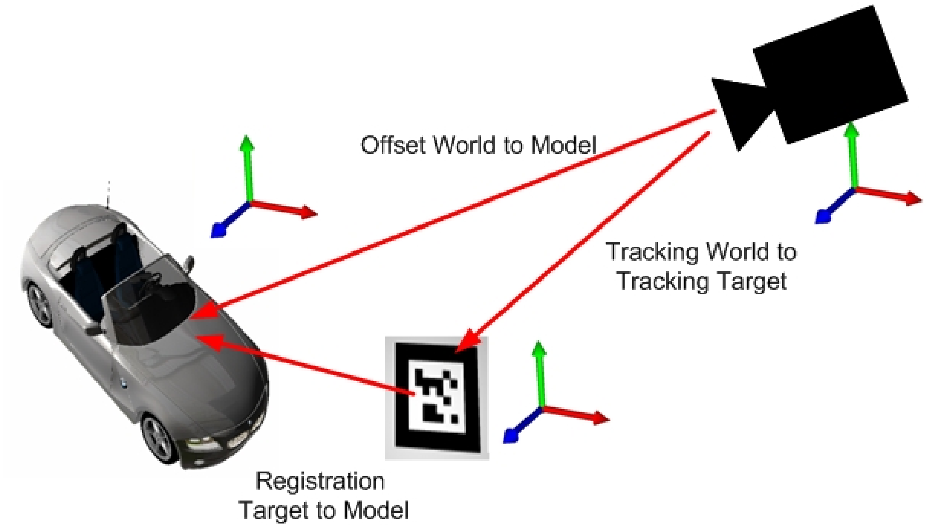


Figure 5.1: Coordinate Systems in an Industrial AR Environment

5.1 Registration Background

Starting from a general point of view, registration means alignment of data sets in some way. More concrete, the data sets shall be transformed into one coordinate system. The approaches to solve this alignment problem highly depend on the kind of data given and the concrete application, which shall be met. Table 5.1 shows some examples for alignment problems in Augmented Reality.

Alignment Task	Data Sets	Application
Registration of two images	2D-2D	Feature tracking
Registration of image to 3D model	2D-3D	Marker tracking
See-through display offset	2D-3D	See-through calibration
Coordinate system transformation	3D-3D	Point-based COS alignment
Offset between two trackers	6D-6D	Hand-eye calibration

Table 5.1: Overview on Alignment Problems in AR

Different data sets can be given due to several causes such as different viewpoints for data acquisition, different times of data acquisition, different sensors for data acquisition or different dimensions of the data sets (list adapted from image registration types [Zito 03]). The goal is to compute a transform model, which maps one data set to the other. The majority of image registration algorithms follows a four step principle to achieve this goal [Zito 03]. These four steps can be generalised for registration approaches:

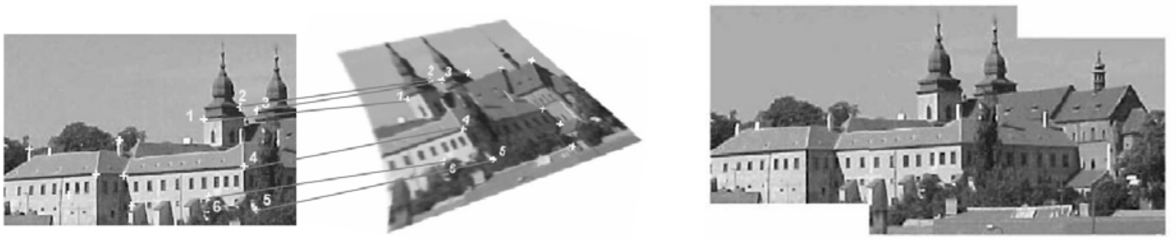
- Feature detection: detection of distinctive objects in the data sets,
- Feature matching: establishment of correspondences between the detected features,
- Transform model estimation: computation of the parameters of the transform model based on the established feature correspondences and

- Data transformation: transformation of one data set to the coordinate system of the other data set based on the computed transform model.

The following presentation of registration approaches is limited to a brief overview, as a detailed description of the different available methods and algorithms would go beyond the scope of this thesis.

5.1.1 2D-2D Image Registration

Image registration is used in various applications in tracking, medical imaging and computer vision in general. Due to the diversity of images to be registered and due to various types of degradations in images, there is no universal method applicable to all registration tasks. An example scenario for 2D-3D image registration is presented in figure 5.2.



(a) Feature Matching (b) Result of the Image Transformation

Figure 5.2: 2D-2D Image Registration (Adapted from [Zito 03])

5.1.1.1 Feature Detection

Feature detection can either be done manually by an expert user, automatically through image processing algorithms or based on a combination of manual and automatic steps. Several kinds of features can be differentiated, such as line features [Ziou 98] or point features [Zhen 99].

5.1.1.2 Feature Matching

Detected features in two images can be matched based on different measures, such as image intensity values, close neighbourhoods, spatial distribution or some symbolic feature descriptors.
A different approach is given by so called area-based matching methods, which do not need specifically detected features. Instead, windows of pre-defined size are used for correspondence estimation. A classical example here is the cross-correlation method, which exploits image intensities directly for the matching task [Prat 91].

5.1.1.3 Transform Model Estimation

The estimation of a transform model for the established feature correspondences consists of two main tasks: the choice of a mapping function and its parameter estimation. The mapping function should meet the properties of the image data, pursuing the goal that after the image transformation, the two feature sets should be as close as possible. Examples for mapping functions are rigid mapping functions, which perform a global mapping such as the shape-preserving similarity transform, the affine transform or the perspective projection model [Hart 03], or non-rigid mapping functions, which include object deformations in their parameters such as elastic registration, level sets registration or optical flow registration [Beau 95].

5.1.1.4 Image Transformation

Finally, the two image data sets can be aligned based on the given transform model. This step is performed using either forward or backward transformation. The forward method transforms each pixel based on the given transformation to the other image space. However, this can produce holes in the resulting transformed image and overlaps with the other data set. Hence, a backward approach is usually chosen based on a regular grid of target points and the inverse of the estimated mapping function. In addition, an interpolation function is applied to avoid holes or overlaps [Lehm 99].

5.1.2 3D-3D Point Registration

The 3D-3D point registration problem aims to optimally align two sets of 3D points by estimating a best 6DOF transformation between them. Figure 5.3 depicts and abstract sketch of this task.

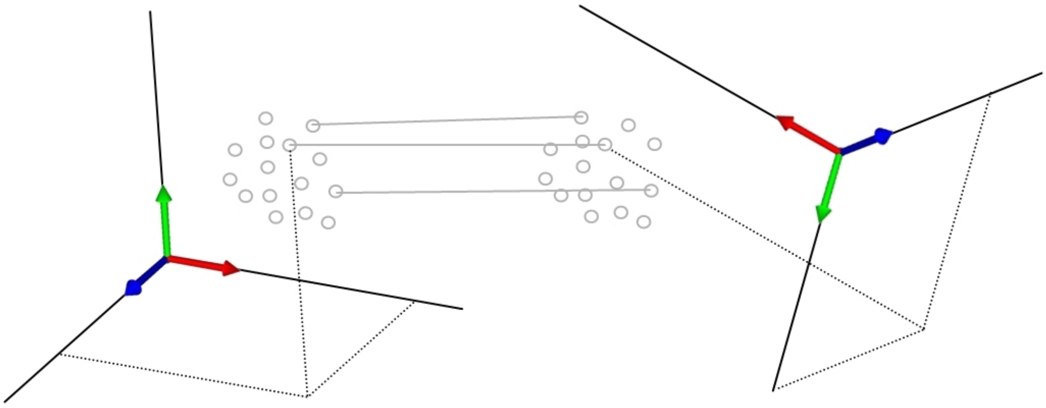


Figure 5.3: 3D-3D Registration for a Point Cloud

5.1.2.1 General Registration Process

The general solution, executes the four step approach.

Feature Detection For the 3D case, the source of feature data is some kind of 3D model (real or virtual), which is based on vertices, edges and faces. Features can thus be corners, lines or planes, which can all be defined based on 3D points.

The detection of those features is therefore a selection from the given representation. This can be done manually by the user or automatically through random choice or based on some pre-defined measure. In the latter case, the aim should be to identify relevant structures, which suit the given task. An example for such an automatised 3D feature selection is for instance presented by Platonov and Langer, who created an algorithm for automatic contour model creation based on polygonal CAD data. The algorithm identifies relevant edges that are suitable for tracking [Plat 07].

Feature Matching and Transform Model Estimation Given two data sets of 3D points, their point-wise correspondences can be known already (e.g. due to the means of detection), can be identified manually by the user or can be calculated automatically. In the former two cases, the transform model estimation is a pose estimation process based on known 3D-3D correspondences. Whereas in the latter case, the correspondences are unknown a-priori and the registration problem in then a simultaneous pose and correspondence problem (SPC). Within this work, the latter case is not used and is thus not explained further.

Transform Model Estimation with Known Correspondences Given a set of known 3D point correspondences, a set of linear equations can be created that includes the two point clouds and the transform model mapping one cloud to the other. Different numerical algorithms are available for solving this set of equations under various constraints. A common approach for linear sets is least-squares minimisation, which finds the best model for mapping data sets by minimizing the sum of squared residuals. In the case of two point clouds, the residuals are the errors between corresponding points after application of the transformation model. This model fits the point cloud problem very well, as the least-squares error metric has a natural relationship to distance in Euclidean geometry. The convenient approach for solving linear least-squares problems is the application of singular value decomposition (SVD). Concrete algorithms are for instance presented by Hartley and Zisserman [Hart 03].

Besides SVD, minimisation problems in general can be solved using iterative estimation methods. These methods can be applied to non-linear and linear problems, which are processed through iterative refinement of the parameters until the error of approximation falls below a pre-defined threshold. Iterative estimation algorithms are for instance the Newton or Gauss-Newton iteration, the gradient descent method or the popular Levenberg-Marquardt algorithm, which is a hybrid between Newton iteration and gradient descent. Again, more details on the algorithms can be found in [Hart 03].

Transformation According to Estimated Model The transformation of one data set to the coordinate system of the other data set can be done forward and backward. As the transform is a 4×4 transformation matrix based on translation and rotation, the matrix is invertible and can be applied for transformation in both directions.

5.1.3 2D-3D Point Registration

2D-3D point registration consists in the determination of a camera model, which maps 3D points in space to 2D points in an image (see figure 5.4).

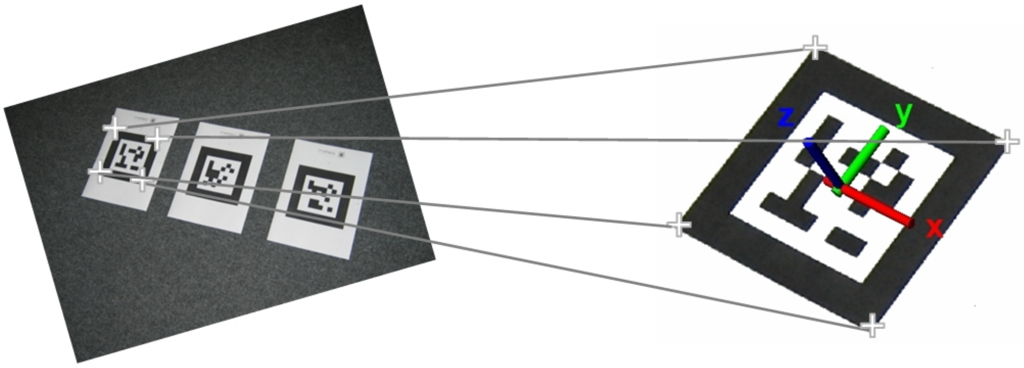


Figure 5.4: 2D-3D Registration

5.1.3.1 Feature Detection

For 2D-3D registration, feature detection both in 2D and 3D is needed and can be performed according to the approaches described above for the 2D and the 3D case.

5.1.3.2 Feature Matching

As in the 3D-3D case, the problem of feature matching and transform model estimation is related through the knowledge on feature correspondences. For unknown correspondences, SPC approaches would have to be used, which are not covered in this work.

Transform Model Estimation with Known Correspondences The model that relates the given 3D and 2D points represents the perspective projection of 3D space onto the 2D image plane, including a coordinate system transformation between camera coordinate system and 3D model coordinate system. Using the pure pinhole model, this function is linear and the transform model can be estimated using linear minimisation approaches as presented for the 3D-3D case. However, real image data is subject to a major non-linear influence factor: radial lens distortion (see for instance Luhmann [Luhm 05]). The radial distortion can be included in the transform model, resulting in a non-linear functional relationship of 3D and 2D points. This relationship can be solved by applying iterative estimation algorithms as presented above.
The transform model includes the projection matrix and a transformation matrix. Depending on the application scenario, some parameters in the transform model might already be known. For instance, marker tracking involves 2D-3D registration with a known projection matrix and aims at computing the transformation matrix only (e.g. Kato and Billighurst [Kato 99]). In contrast, camera calibration algorithms usually compute both projection matrix and transformation matrix (e.g. AICON 3D Studio [AICO 08]).

5.1.3.3 Transformation

Depending on the application, the resulting transform model is used in different ways. For marker tracking, the transform is applied for correctly positioning virtual model data with respect to the visualisation camera.
If the projection matrix was determined, its main use is for image rectification. Based on the calculated distortion parameters, image data can be warped on a pixel basis to compensate for the distortion.

5.1.4 6DOF-6DOF Registration

6DOF-6DOF registration describes the determination of a coordinate system transformation based on sets of 6DOF transformations (see also figure 5.10).

5.1.4.1 Feature Detection

In Augmented Reality, these 6DOF data sets are either measured by tracking systems or they are previously available. Often, they are the results of a preceding referencing task (e.g. 2D-3D registration for marker tracking).

5.1.4.2 Feature Matching

A very common approach for matching 6DOF poses is the application of time stamps. Each data set is equipped with a time stamp reflecting the point in time of data acquisition. Later, these time stamps allow identifying correspondences. A critical issue here is the synchronisation of data sets in order to have comparable time stamps and to avoid mismatches for the registration task.

5.1.4.3 Transform Model Estimation

The transform model is a transformation matrix, which relates the pairs of 6DOF poses to each other. The functional relationship is a simple matrix multiplication, which is linear. Thus, the resulting pose can be estimated using the already introduced algorithms.

5.1.4.4 Transformation

As for the 3D-3D case, the transformation matrix is invertible and allows for forward and backward transformation.

5.2 Implemented Approaches

To support the registration process for the Roivis system, a set of different registration methods was implemented. These approaches are based on available resources and known processes and in many cases their implementation was motivated by the cooperation partner Volkswagen. The focus was laid on methods that rely on given hardware and familiar tasks in the industrial environment and can be integrated easily in the existing AR-based planning process.

On the one hand, the resources available for registration are given by the general data required for the AR process such as images, markers and the digital model data. On the other hand, the industrial application environment offers its own resources through special hardware, as well as software. Measurement engineering is a helpful source here. High-precision measuring hardware and software can be used for the AR-related registration task. Furthermore, the common objects of measurement are of great interest when looking for favourable points in the digital and real world. The reference points used for registration in measurement engineering can also support the AR registration process.

Based on these resources, the following approaches were implemented:

- Registration based on a coordinate measurement machine (CMM),
- Registration based on 2D-3D point correspondences,
- Registration based on 3D-3D point correspondences,
- Registration based on CAD data manipulation,
- Registration based on a manual approach and
- Registration based on 6DOF pose correspondences.

5.2.1 Registration Based on a CMM

5.2.1.1 CMM Measuring Functionalities

With an external coordinate measurement machine, the registration process can be achieved by using the registration functionalities of the CMM. CMMs provide high-precision measurements based on a measuring probe. They are equipped with a measuring software that allows transforming the internal origin coordinate system to an arbitrary location using point correspondences.

5.2.1.2 Registration Process

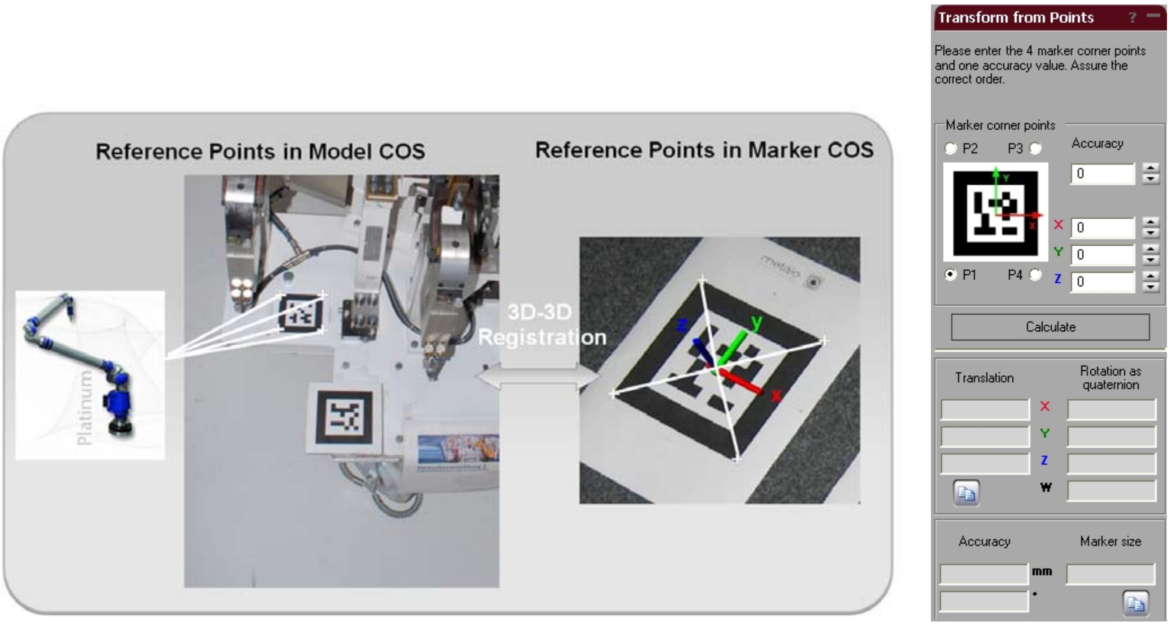
The CMM registration tool implemented for Roivis requires a CMM, which is already registered to the model coordinate system (e.g. the car body coordinate system). This can be achieved using the CMM measuring software as described above. Then, 3D point correspondences between the tracking target coordinate system and the model coordinate system are used to determine the needed offset. Figure 5.5 shows the concept of registration with a CMM and the Roivis CMM registration tool.
The user needs to specify the four marker corner points of a 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. For the Roivis marker tracking, the origin lies in the centre of the marker

$$c = \frac{P1 + P2 + P3 + P4}{4} \tag{5.1}$$

The coordinate axes of the marker are indicated in figure 5.5, z pointing to the observer (see also figure 4.5). Due to nature of the specified points, pairs of points directly identify the direction of the coordinate axes. They are thus used to create base vectors u, v, w, which define the new coordinate system. The transformation matrix T from the marker to the model coordinate system is then related to a change of basis [Haus 07] and is given as:

$$T = \begin{pmatrix} u_x & v_x & w_x & c_x \\ u_y & v_y & w_y & c_y \\ u_z & v_z & w_z & c_z \\ 0 & 0 & 0 & 1 \end{pmatrix}^{-1} \tag{5.2}$$

with $u = \overrightarrow{P1P4}$,
$v = \overrightarrow{P1P2}$ and $w = u \times v$



Please enter the 4 marker corner points and one accuracy value. Assure the correct order.

Accuracy: 0

X: 0
Y: 0
Z: 0

(a) Concept of CMM Registration

(b) CMM Registration Tool

Figure 5.5: Registration Based on a CMM

5.2.1.3 Aspects of Uncertainty

In addition, an uncertainty value for the corner point uncertainty can be specified, which is then used to estimate the uncertainty of the resulting transformation (positional and rotational uncertainty).
The uncertainty of the input data is provided by the positional uncertainty of the CMM, which is usually stated in the machine specification. Given this value, an input convariance matrix C_p can be filled and the resulting transformation uncertainty can be calculated using backward error propagation (see for instance Hartley and Zisserman [Hart 03]).
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 covariance matrix that represents the uncertainty is then given by

$$C_F = (J_F^T \cdot C_p^{-1} \cdot J_F)^{-1} \text{ where } J_F = \frac{\delta F(q_k, p_k)}{\delta(t_x, t_y, t_z, r_x, r_y, r_z)}$$

Not all of the covariance values are presented to the user. Instead, a general positional and rotational standard deviation is calculated based on the trace of the covariance matrix. The corresponding entries of the covariance are averaged and the positive square root is displayed as result.

5.2.1.4 Tool Implementation

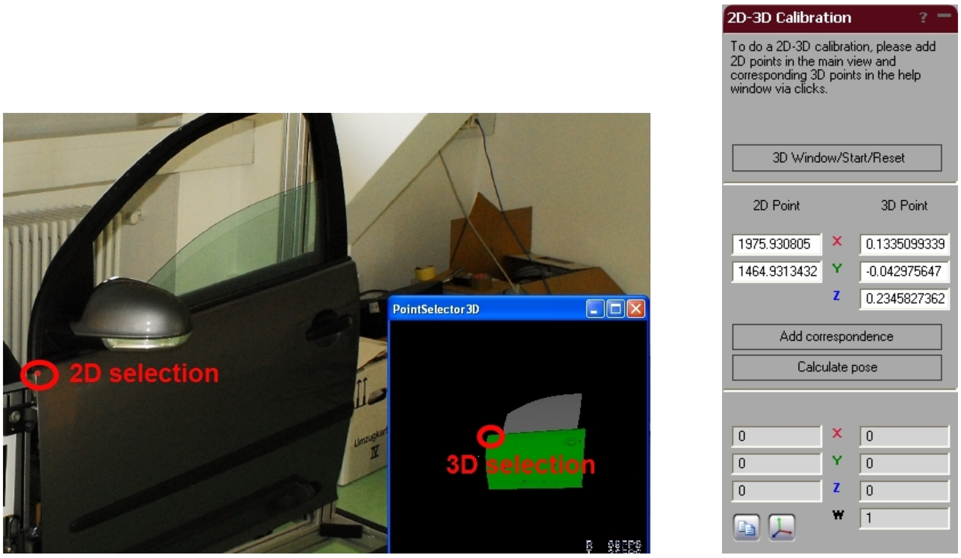
The CMM registration tool is integrated in the Roivis application. The graphical user interface of the tool is shown in figure 5.5. The upper section of the GUI provides the input fields. For each measurement entry, the corresponding marker corner point needs to be selected and the 3D point information is entered in the given fields.
The calculation result is displayed in the fields in the lower section of the tool. The format for the registration offset is given in translation and quaternion representation, which is used in all registration tools. Using the available copy button, the offset information can be copied to the clipboard for further use elsewhere.
If an uncertainty input value was stated by the user, the output uncertainty is calculated together with the transformation result. The copy command will copy both the transformation and the uncertainty result to the clipboard. The information can then for instance be used directly as input data for the Accuracy Measurement tool (see section 4.5).

5.2.2 Registration Based on 2D-3D Point Correspondences

The next option for registration is based on 2D-3D point correspondences, which are provided by the user through clicks in 2D image data and corresponding 3D digital model data. This approach does not require any real world reference such as a marker, as it purely relies on point correspondences selected by the user.

5.2.2.1 Registration Process

Figure 5.6 (a) presents the tool in use. 2D points are selected in the image of the scene and 3D points are chosen in a viewer showing the corresponding digital model. Currently, selected point correspondences are visualised and the user is able to adjust them by simply performing new clicks in the windows. To support this adjustment process, both 2D and 3D window provide a zoom functionality. When the location of a point pair is satisfactory, the correspondence can be stored for calculation.
If at least three correspondences have been added, the point sets can be sent to a camera pose estimation algorithm that calculates the transformation from the camera coordinate system to the model coordinate system.



To do a 2D-3D calibration, please add 2D points in the main view and corresponding 3D points in the help window via clicks.

2D Point		3D Point
1975.930805	X	0.1335099339
1464.9313432	Y	-0.042975647
	Z	0.2345827362

0	X	0
0	Y	0
0	Z	0
	W	1

(a) Process of 2D-3D Registration (b) Registration Tool

Figure 5.6: Registration Using 2D-3D Point Correspondences

5.2.2.2 Aspects of Uncertainty

In this case, no direct uncertainty information can be provided as the resulting uncertainty fully depends on the clicking accuracy of the user. However, to get a feeling for the quality of this approach, this clicking accuracy has been evaluated for sample images. The evaluation is presented in section 7.4.

5.2.2.3 Tool Implementation

The 2D-3D registration tool is structured similar to the CMM registration tool and is also integrated in Roivis. The upper part provides the input section. Selected 2D and 3D points are visualised in the corresponding fields and can also be entered manually (see figure 5.6 (b)).
The resulting 6DOF pose of the camera is presented in the fields at the bottom of the tool. To further use the result, two options are available. The pose can be copied to the clipboard or it can be directly exported as a tracking configuration file. In the latter case, the configuration file contains the direct transformation from camera to model coordinate system and does not require a marker specification.

5.2.3 Registration Based on 3D-3D Point Correspondences

5.2.3.1 Introduction

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 that are known in the 3D digital model and can be tracked easily in the real environment. An example from industry are drill holes, which are manufactured precisely as they are the connecting points between different components. These holes are known exactly in the digital data. Their real counterparts can be identified by using adapters that fix the tracking target to the drill hole. Figure 5.7 depicts a marker equipped with an adapter to fit the drill holes of an align fixture.

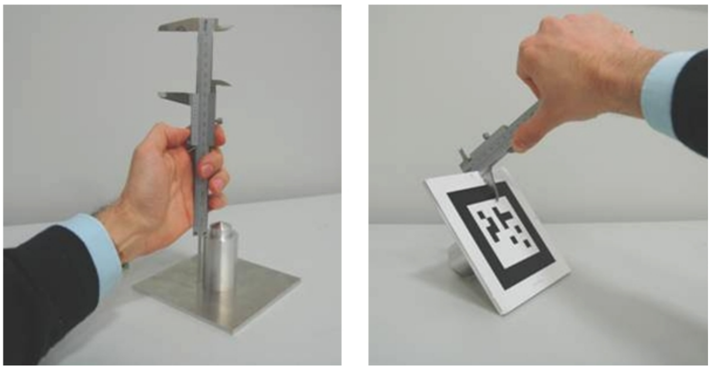


Figure 5.7: Adapter for 3D-3D Registration (Source: Volkswagen AG)

5.2.3.2 Registration Process

The 3D-3D registration 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. Figure 5.8 depicts the concept of this registration process. As input, the tool receives:

- An image folder holding the image set for the real scene,
- Calibration data for the images,
- A text file containing the digital 3D referencing points (one point per line with x-, y- and z-coordinate separated by blanks) and
- Marker configuration data, which lists the adapter markers with their offsets to the specified digital referencing points.

The offset for the markers is required as, due to the adapter plate, the marker origin lies slightly above the drill hole origin and a small translation in negative z-direction of the marker coordinate system is needed to compensate this.

The 3D-3D registration tool then processes the available image data for the configured markers and determines the 3D location of the markers (including offset) in the camera coordinate system. This point set, together with the digital 3D referencing point set from the text file are then sent to a 3D-3D transformation optimisation algorithm. The resulting pose references the camera coordinate system to the digital model coordinate system. Based on this information, the offset from each single marker to the model coordinate system can be calculated.

5.2.3.3 Aspects of Uncertainty

For the 3D-3D registration case, the 3D digital model data is usually given through so called reference points or pass points. In industry, these points are specifically used to define a frame of reference, e.g. the car coordinate system in automotive industry. They are therefore known very accurately. Nevertheless, there are other influence factors, which lead to errors such as manufacturing defects or

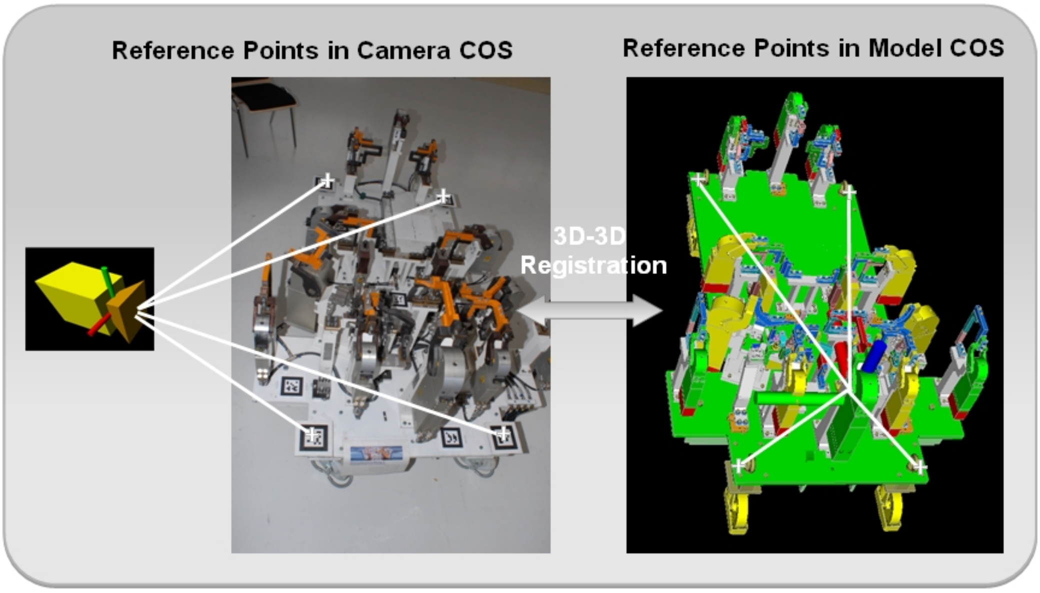


Figure 5.8: Concept of 3D-3D Marker-Based Registration

deformations due to temperature or other external impacts.
Evaluating all those factors would go beyond the scope of this thesis. Thus, for uncertainty evaluation, the quality of the result of the 3D-3D registration process is based purely on the quality of the marker tracking. This uncertainty information is not available directly for a concrete calculation, but in section 7.4 a general uncertainty evaluation for the 3D-3D referencing process based on marker tracking uncertainty is described.

5.2.3.4 Tool Implementation

The tool for 3D-3D registration is not part of the Roivis toolbox, but is implemented as an external tool. The graphical user interface is presented in figure 5.9. Input data needs to be specified as stated above. The output tracking configuration is written to a selected output file.
The implemented version of the tool does not only perform 3D-3D registration, but also executes an optimisation process over all configured markers over all images. More details on this functionality are presented in the section on hybrid approaches.

5.2.4 Registration Based on CAD Data Manipulation

5.2.4.1 Registration Process

The next approach requires some knowledge in the CAD environment. Here, the digital model itself is manipulated to better fit the requirements for its use in the AR scenario. A favourable 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

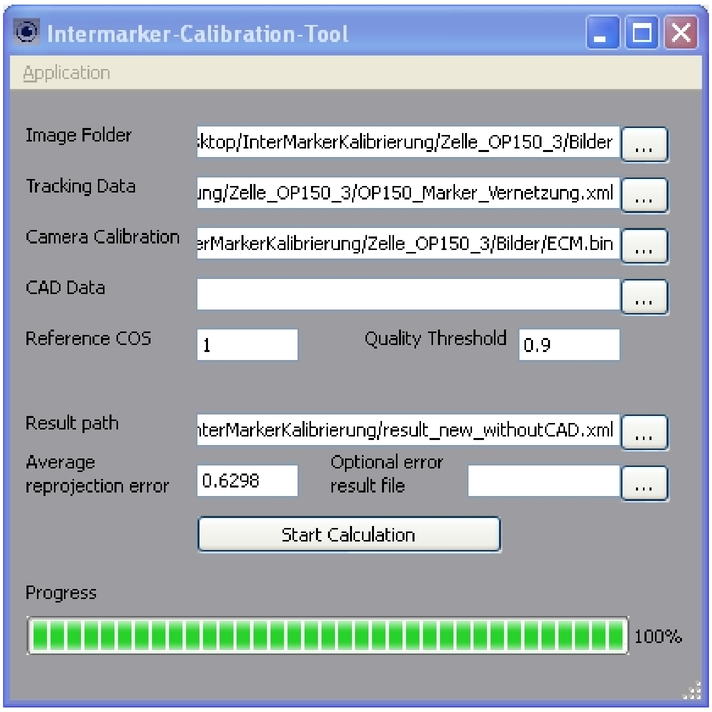


Image Folder: ktop/InterMarkerKalibrierung/Zelle_OP150_3/Bilder

Tracking Data: ng/Zelle_OP150_3/OP150_Marker_Vernetzung.xml

Camera Calibration: rMarkerKalibrierung/Zelle_OP150_3/Bilder/ECM.bin

CAD Data:

Reference COS: 1

Quality Threshold: 0.9

Result path: terMarkerKalibrierung/result_new_withoutCAD.xml

Average reprojection error: 0.6298

Optional error result file:

Progress: 100%

Figure 5.9: Tool for 3D-3D Registration

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.

5.2.4.2 Aspects of Uncertainty

For the CAD approach it is difficult to derive a statement of uncertainty. As the offset is determined in CAD software, the positioning of the coordinate system can be done with sub-millimetre and sub-degree accuracy. However, the quality of the transformation depends on the quality of the digital model, its tessellation and the level of accordance with the real object (e.g. car body). In addition, the quality of the adapter influences the result.

5.2.4.3 Tool Implementation

This approach relies on CAD functionalities, which are available in commercial software products. After the manipulation of the model coordinate systems, further adjustments can directly be performed with the basic object manipulation functionalities of Roivis.

5.2.5 Manual Approach

The registration process between camera and model coordinate system can also be performed manually, based on a favourably positioned marker. To reasonably determine the registration offset, the marker location should already fix several degrees of freedom of the offset. This can be achieved by attaching the marker to a planar location, which is parallel to a plane in the model coordinate system.

5.2.5.1 Registration Process

For manual registration only image data of the scene and the digital model itself is required. The object manipulation functionalities of Roivis are used to estimate the translation and rotation of the digital model. Very helpful in this context are the use of wireframe views of the geometry, as well as clipping plane functionality. Clipping planes can support the determination of the correct distance between model and marker plane (see also figure 7.17), while wireframe views allow performing fine adjustments in translation and rotation.

As a result, the offset from marker to model coordinate system can be determined based on the required translational and rotational manipulations of the digital model.

5.2.5.2 Aspects of Uncertainty

For the manual approach, no input uncertainty can be determined. The resolution for translational and rotational changes can be set for very fine adjustments. However, the result purely depends on visual checks of real and virtual data and can thus also be misleading in case of inconsistencies between the digital and the real environment.

5.2.5.3 Tool Implementation

The manual registration method is based on the object manipulation functionalities of Roivis. For registration only the basic scene creation tools are needed. If a tracking configuration file has to be created based on the determined model offset, the external marker configuration tool can be used.

5.2.6 Registration Based on 6DOF Pose Correspondences

This method determines the registration offset based on poses. Imagine a planning scenario, where one marker is already registered to the model coordinate system. Additional markers can then be added to the scene and can also be registered to the model coordinate system using the tracking information between the markers. That way, a whole chain of markers can be registered step by step based on multiple images allowing to cover large areas.

5.2.6.1 Registration Process

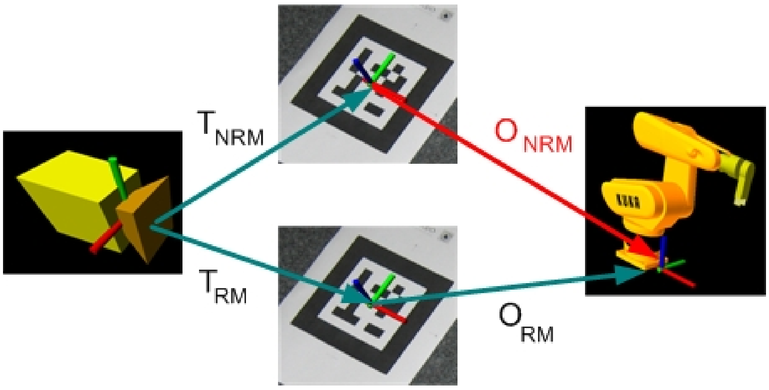
The general 6DOF registration process is based on the idea of concatenating transformations. Given a graph of known 6DOF transformations, missing edges in the graph can be calculated using inversions and concatenations of available transformations. This idea is for instance used and discussed in detail in the work of the FAR group at TU Munich on spatial relationship graphs and graph patterns [Pust 06].

For the concrete case of marker-based factory planning, a scenario with a marker, which is already referenced to the model coordinate system *RM* and a non-referenced marker *NRM* allows performing the following actions:

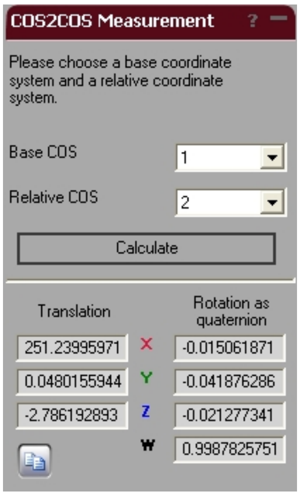
- Create an image showing both the referenced and the non-referenced marker.
- Determine the tracking information for both markers:
  - T_{RM} from camera coordinate system to the coordinate system of the referenced marker *RM*
  - T_{NRM} from camera coordinate system to the coordinate system of the non-referenced marker *NRM*
- The registration offset O_{RM} from the referenced marker *RM* to the model coordinate system is known.
- Then, the offset from the non-referenced marker *NRM* to the model coordinate system can be calculated as O_{NRM}

$$O_{NRM} = T_{NRM}^{-1} \cdot T_{RM} \cdot O_{RM} \tag{5.3}$$

Figure 5.10 (a) presents the graph of transformations for the specified scenario.



(a) Transformation Graph for 6DOF-6DOF Registration



COS2COS Measurement

Please choose a base coordinate system and a relative coordinate system.

Base COS: 1

Relative COS: 2

	Translation		Rotation as quaternion
	251.23995971	X	-0.015061871
	0.0480155944	Y	-0.041876286
	-2.786192893	Z	-0.021277341
		W	0.9987825751

(b) 6DOF-6DOF Registration Tool

Figure 5.10: 6DOF-6DOF Registration

5.2.6.2 Aspects of Uncertainty

For the 6DOF registration process based on one image, the uncertainty for the resulting offset O_{NRM} can be calculated based on the uncertainty of the input transformations O_{RM}, T_{RM} and T_{NRM}. The relationship is linear, thus the propagation is a simple forward propagation based on the Jacobian matrix of the matrix multiplication (see equation (4.15)).

5.2.6.3 Tool Implementation

6DOF registration is directly available within the Roivis toolbox. The graphical user interface is depicted in figure 5.10 (b). The tool design is very simple. The user needs to select a base and a relative coordinate system based on the available tracking configuration for the application. The tool then computes the transformation matrix from the base to the relative coordinate system and presents the results. As for the other Roivis internal tools, the result information can be copied to the clipboard for further use.

5.2.7 Hybrid Approaches

For tracking problems, it can be useful to combine different methods and their advantages. For the presented registration tools, similar considerations led to promising combinations. The following hybrid approaches emerged through experience in the past.

5.2.7.1 3D-3D Marker-Based Registration with 6DOF Support

The marker-based 3D-3D registration computes the offset from the adapter markers to the model coordinate system. Usually, a single image with a sufficient number of visible adapter markers would suffice for 3D-3D registration. However, in general, more than one image is available for a factory planning scene. Therefore, all available image data can be used to optimise the offsets between the available adapter markers and the offsets between the camera poses of the image set.
The implemented optimisation algorithm is not based on poses directly, but relies on the detected marker corner points, which are the base for pose computation. A large state vector is created composed of all transformations between markers (inter-marker offsets) and all transformations from cameras to markers (tracking poses). This state vector is processed by a non-linear optimisation algorithm with the goal to minimise the reprojection error of all marker corners for all given images. The 3D-3D registration process is then executed after this optimisation step. That way, the resulting transformation is optimised with respect to the given images and offers optimal conditions for later planning and analysing tasks based on the same image data.
The described functionality is already implemented in the tool shown in figure 5.9. Note that the graphical user interface includes fields for "Average reprojection error" and "Optional error result file". The average reprojection error of the inter-marker optimisation process, as well as a complete list of the error values are available after calculation to provide the user with additional quality information.

The presented approach is very similar to the computations performed by offline photogrammetric measurement systems. They also rely on image data and determine the orientation of the image network through so called bundle adjustment [Luhm 05]. This similarity to photogrammetric measuring is also mentioned in the further application and evaluation of this registration approach (see section 6.2 and section 7.4).

5.2.7.2 Marker Adapter with CAD-Based Support

The description of the CAD-based approach already indicated that drill holes can be favourable locations for positioning the model coordinate system. However, this implies the use of marker adapters similar to the ones needed for marker-based 3D-3D registration. To avoid the manual rotational adjustment, which was mentioned above, the marker adapter can be constructed in such a way as to fix the marker in all dimensions. An example adapter of such kind is shown in figure 6.6. The adapter was

used for a Roivis analysis in the automotive industry and was attached to the bumper of a car body through two drill holes. Using CAD software, the position and orientation of the marker coordinate system with respect to the drill holes could be determined. That way, the model coordinate system of the digital car model could be transformed as to fit both translation and rotation to the marker coordinate system.
A complete description of the corresponding planning scenario is given in section 6.3.

5.3 Practical Considerations

All presented approaches allow determining registration information for correctly overlaying digital model data with the real environment. However, for actually performing the registration for a concrete scenario, two additional aspects are of importance. First, a registration method needs to be selected from the available toolbox. Second, the result of this registration process must be mapped to a tracking configuration file, which can be loaded in Roivis.

5.3.1 Guidelines for Registration

The presented registration approaches differ in various ways. They offer different computation results and require different input data, resources and knowledge. To provide guidelines for the selection of a registration tool for a concrete application scenario, the different methods have to be compared to each other. Criteria for this analysis can be derived from the general requirements for the acceptance of Roivis: usability and accuracy.
Section 7.4 presents different evaluations performed for the Roivis registration toolbox. These evaluations and the resulting rules of use for the toolbox are another important contribution of this thesis.

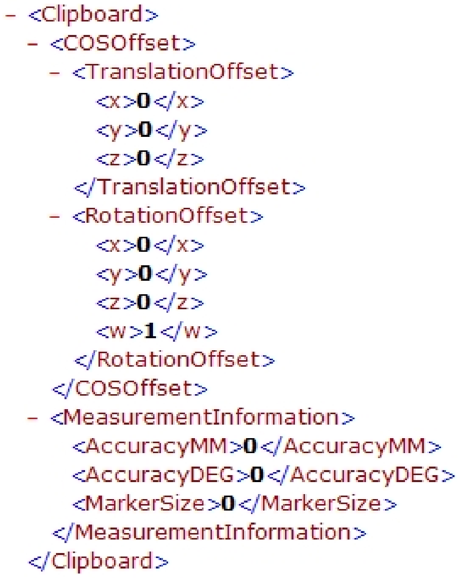
5.3.2 Information Transfer

5.3.2.1 Offset Transfer

The goal of each registration process is the determination of an offset to reference the camera or a marker coordinate system to the model coordinate system. To use these results within Roivis, they have to be mapped to a tracking configuration file, which can be used for AR scene creation. Some tools already present their computation results in terms of such a configuration file. Others only calculate a single offset from a specified marker to the model coordinate system.
In the tool presentation above, the functionality of copying results to the clipboard has already been mentioned. This approach is currently used to transfer information from a tool into a marker tracking configuration. The marker configuration tool provides the functionality to specify a *COSOffset* for each marker, which can be entered manually, but can also be pasted from the clipboard. This offset represents the transformation from the marker coordinate system to a new external coordinate system. By pasting the computed registration offset into the *COSOffset* fields of the marker configuration tool, the specific marker can be referenced to the model coordinate system and thus a marker configuration file is created in a few clicks.

5.3.2.2 Uncertainty Transfer

Different from the other tools, the CMM registration tool also computes a quality information for the result offset. In chapter 4, the Accuracy Measurement tool was introduced. For determining an overall uncertainty statement for the given AR scene, the tool requires offset uncertainty information as input. If the offset is computed using the CMM registration tool, the uncertainty information can be used directly for the Accuracy Measurement tool. Therefore, the Accuracy Measurement tool allows pasting information in terms of uncertainty values for translation and rotation from the clipboard.
Currently, the CMM registration tool is the only tool, which provides an uncertainty information. Nevertheless, the clipboard information structure is open for this kind of data and in case further tools with uncertainty information are implemented, the data transfer is already prepared.



```
- <Clipboard>
  - <COSOffset>
    - <TranslationOffset>
        <x>0</x>
        <y>0</y>
        <z>0</z>
      </TranslationOffset>
    - <RotationOffset>
        <x>0</x>
        <y>0</y>
        <z>0</z>
        <w>1</w>
      </RotationOffset>
    </COSOffset>
  - <MeasurementInformation>
      <AccuracyMM>0</AccuracyMM>
      <AccuracyDEG>0</AccuracyDEG>
      <MarkerSize>0</MarkerSize>
    </MeasurementInformation>
  </Clipboard>
```

Figure 5.11: Clipboard Data for Information Transfer

5.3.2.3 Clipboard Information

For information transfer, the clipboard must hold pose information and uncertainty information. Figure 5.11 shows the XML structure, which holds the clipboard copy and paste information in Roivis. The copy command creates the respective XML node and stores it. Similar, the paste functionality parses the stored XML object for adequate information.

5.4 Summary

In order to meet the second essential aspect for a serviceable application for AR-based factory planning, a registration toolbox was implemented to support the process of correctly registering the real and the virtual world.
This chapter presented a comprehensive overview on the task of registration. After having provided

a general background on registration of data sets in different dimensions, various implemented approaches were introduced by describing their general registration process, outlining relevant aspects of uncertainty and finally discussing the practical implementation of each method for Roivis.
Supporting registration is one of the contributions of this thesis. However, to support the user beyond the simple provision of tools, guidelines for the choice of a registration method with respect to relevant criteria are derived. These guidelines are based on according evaluations for the Roivis registration toolbox, which are presented in chapter 7.

6 Applications

Examples from Industry

In the previous chapters 3, 4 and 5, the general structure of Roivis and its functionalities were introduced, with a focus on the accuracy and registration related features. This chapter presents concrete industrial scenarios and the application of the various tools of Roivis for facing specific problems in factory planning. First, a general introduction to the practical use of the system is described in section 6.1, which outlines the different phases needed for AR-based factory planning and highlights the aspects related to accuracy and registration. Afterwards, two specific planning scenarios from industry are presented: variance comparison at Volkswagen (section 6.2) and interfering edge analysis at Opel (section 6.3).

6.1 Planning with Roivis

This section provides an overview on the practical use of Roivis for factory planning and the necessary steps to prepare, create and analyse a factory planning scenario with the software. It is a collection of experiences of people using the software in practice, mainly from colleagues at metaio and Volkswagen Group Research. Figure 6.1 depicts the different stages.

6.1.1 Preparation of the Analysis

The first phase of the planning process is the preparation. This phase involves the definition of goals for the analysis and the specification of the course of action to achieve them. The course of action determines the acquisition of data for the analysis and the required material and is influenced by the crucial demand for accuracy.

6.1.1.1 Definition of Goals, Involved Data and People

First, the goals of the AR analysis need to be determined. Detailed information from the planners is collected to identify the concrete locations in the factory, which need to be analysed and the concrete kinds of analyses, which shall be performed (e.g. interfering edge analysis or variance comparison).

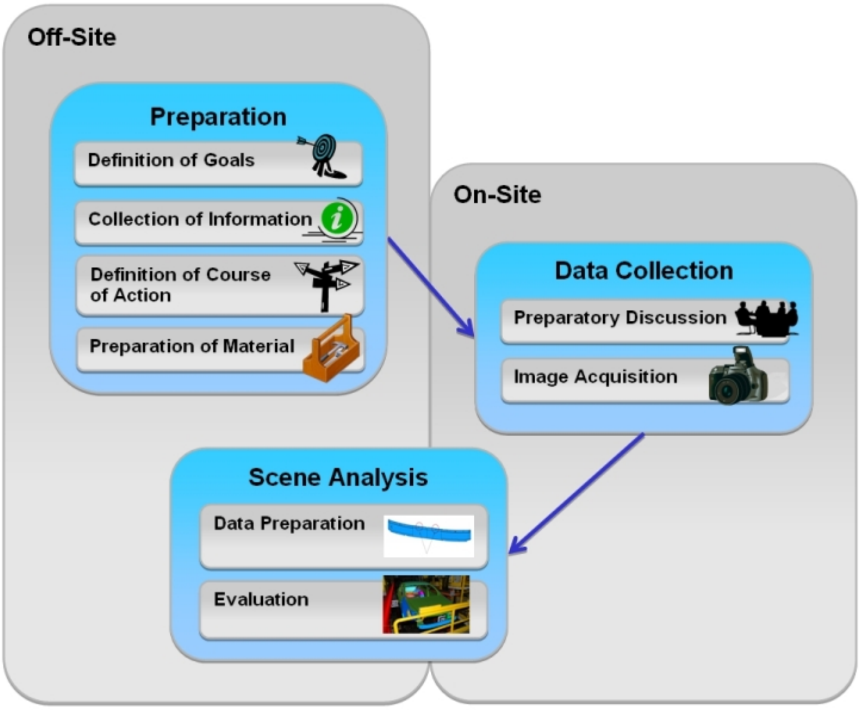


Figure 6.1: Overview on the Practical Use of Roivis

Based on this information, a list of locations can be created including the responsible people, the required virtual models and the desired evaluations.

Besides information collection, another important target of this preparation step is the information exchange with the project engineers, planners and workers on-site. To avoid misunderstandings, it is of great help to talk to the involved people and explain what kind of analysis is planned and how it will be executed in detail. Thereby, possible prejudices against the technology and the analysis can be decreased, as many of the involved personnel do not know Augmented Reality and might not be informed about the concrete aim of the analysis.

6.1.1.2 Collection of Available Data and Information

To allow for optimal preparation of the AR planning, any kind of information on the planning locations is helpful to understand the situation on-site and the required information, which shall result from the analysis. Sketches, photographs, descriptions, CAD data and informations drawn from discussions with engineers and planners are put together.

With respect to the required virtual model data, several aspects must be taken into account. To assure reliable planning results, the correct versions of the models need to be identified (e.g. modelling version, which reflects the planning state needed for the AR analysis or modelling version for the given production step) and converted to the format supported by Roivis. In addition, the scale of the given model and its unit (e.g. millimetres, metres, inches) and tessellation must be known. If the model consists of several parts, the relevant ones should be identified to keep the model size small. Finally, for models that reflect a workflow, the correct workflow position for the analysis needs to be identified (e.g. specific position of a robot arm).

6.1.1.3 Definition of Course of Action

Based on the given information, the scene setup for the on-site data acquisition can be created roughly. Required marker locations and possibilities for attaching the markers are identified and options for registration between the marker and the model coordinate system are considered based on the available approaches, which were presented in chapter 5. The choice of registration method can be based on different constraints. As indicated previously, according evaluations and guidelines are presented in section 7.4. Special demands can arise, if the production line is not stopped during data collection and the markers need to be attached to moving objects in the plant.
In addition, the crucial aspect of accuracy needs to be considered for the scene setup. Section 4.5 introduced the relevant influencing factors. Based on interesting camera perspectives, the marker size and location have to be chosen carefully. On the one hand, the markers need to be positioned such that they optimally describe target objects in the scene. On the other hand, the viewing angle and the marker area in pixels in the acquired image data influence the quality of the planning result.

Besides the planning of a first scene setup, dates and times for on-site data collection need to be found, taking into account the schedules of involved people in the factory, as well as production pauses. If the target object is moving during production, production pauses would ease the collection of image data. Furthermore, security and administrative constraints must be considered. Specific clothes or permissions to take photographs might be required when entering and working in the production environment.

6.1.1.4 Collection and Creation of Needed Material

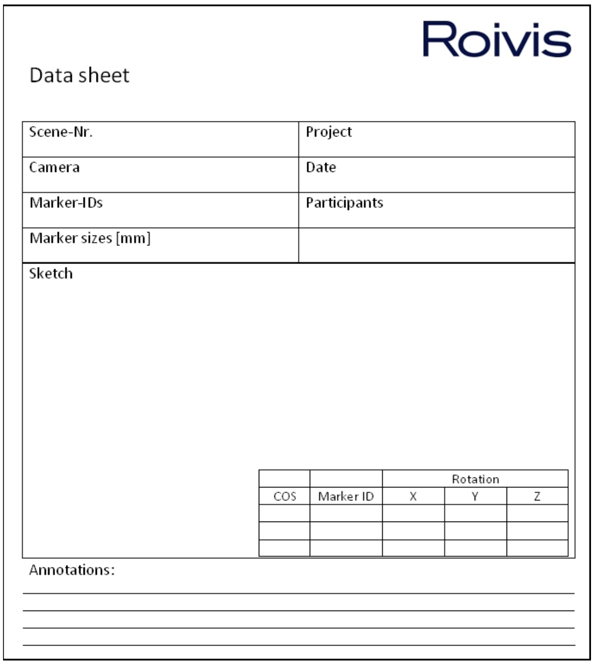
Using the identified means of operation and the restrictions given by the production site, the material needed for data acquisition can be defined.

Markers The markers are prepared including needed adapters or other means of attachment. Different options are given for the choice of marker material. The base can be made from cardboard or aluminium, the former being cheap but easily soiled and rather inaccurate, the latter being robust and accurate, but rather expensive.
Marker material, as well as size have to be chosen based on the given situation.

Camera A high resolution digital camera is used for image acquisition, as recommended for the Roivis system. Extra illumination should be brought to the factory to assure optimal conditions for image acquisition.
The camera needs to be calibrated either just before or right after the analysis to approximate the same environmental conditions during data acquisition and calibration. However, due to the rather cumbersome hardware needed for calibration (i.e. large 3D calibration board), it is often not possible to perform both at the same place.

Other Tools Other helpful tools are a tripod, measurement devices such as laser distance meter, digital level, ruler, adhesive tape and scissors for attaching additional markers (e.g. to map walls or other obstacles). Furthermore, necessary permissions (e.g. for taking photographs or for entering the factory) or specific safety clothes such as shoes or helmets need to be collected.

Finally, a data collection protocol is useful to recall all relevant information for the different analysis locations (markers used, problems encountered, etc.). An example of such a data sheet is shown in figure 6.2.



Roivis

Data sheet

Scene-Nr.	Project
Camera	Date
Marker-IDs	Participants
Marker sizes [mm]	

Sketch

		Rotation		
COS	Marker ID	X	Y	Z

Annotations:

Figure 6.2: Example Data Collection Protocol for Roivis Analysis

6.1.2 Data Acquisition

The actual acquisition of data on-site can be divided in two main parts, the preparatory discussion and the actual execution.

6.1.2.1 Preparatory Discussion

The discussion on-site may be the first time to meet the responsible people from the factory in person. They should again be introduced to the goals and the process of the AR-based analysis and the concrete locations in the plant, which shall be considered. Furthermore, the time planning should be checked once more to assure accessibility to the locations and production pauses if required.
If possible, each location should be visited with the responsible engineers, planners and workers before actually taking shots to assure the correct understanding of problem locations, required measurement results and overall goals for the specific location. In such cases, very often additional aspects come into mind, which can then be included in the data acquisition phase for later evaluation.

6.1.2.2 Actual Execution

The actual execution of collecting image data on-site is performed by at least two persons. One is responsible for marker placement and documentation, the other for image acquisition.

The marker placement should be done as planned in the preparation step, using the identified points of attachment (e.g. drill holes). Sometimes, the planned approach is not possible due to obstacles or security reasons. Then, alternative positions need to be identified and documented accordingly. Markers can also be used to create a reference for additional objects in the scene (e.g. the marker plane can describe a wall or one edge of the marker can describe a real interfering edge).

The positioned markers are documented using the prepared protocol sheets. For each scene (each evaluation), a sketch is made including marker numbers, real object identifiers, position in the plant and any relevant additional information such as offsets, rotations, measurements and the required virtual model for evaluation.

The photographer needs to take the required shots from different perspectives to fully document the real environment via images. The image data must allow successful tracking (sufficient lighting and fully visible markers) and has to show the important views of the scene regarding the planning results. Furthermore, the previously mentioned constraints for accurate marker detection should be considered (marker size in pixels, viewing angle). In case of moving objects, picture series are helpful to see the moving parts in their different locations.

6.1.3 Scene Analysis

As a last step, the collected image data and the virtual model data is combined to create specific AR scenes, each reflecting a problem location that needs to be evaluated. Usually, this task is performed off-site, but if results are required urgently the evaluation can also be done on-site with a shortened preparation phase.

6.1.3.1 Preparation

The given model data is processed for import in Roivis. The correct version is checked, a reasonable tessellation is chosen (e.g. 1 mm) and non relevant model parts are removed to decrease the overall size. Furthermore, an up-to-date camera calibration is calculated using the AICON software and the Extended Sextant tool (see section 3.3.2). Next, the required registration offsets are determined. Based on the course of action and the available data, an approach for calculation is chosen from the registration toolbox (see chapter 5).

Finally, project folder structures are created to store the relevant data in a reusable format.

6.1.3.2 Actual Evaluation

The actual evaluation should be performed soon after the data collection on-site to make sure that the environment can be easily recalled based on the protocols.

Scenes are created based on image data, model data, camera calibration and marker configuration data. For the evaluation, different measures are calculated and analysed, depending on the kind of evaluation to be done and the required results. In general, the resulting data consists of

- Views of the AR scene with and without augmentations (screenshots, as well as scene files),

- Views of the AR scene with different model view states (visible, invisible, wireframe) and clipping planes (screenshots as well as scene files) and
- Calculated measures for collisions, distances and errors.

6.2 Variance Comparison at Volkswagen

In the following, a pilot project of Volkswagen Group Research is presented. The aim of this project was to demonstrate the benefits of AR-based factory planning [Pent 07c]. As a concrete task, variance comparison for an align fixture was executed.

6.2.1 Introduction and Motivation

Car body assembly is a very complex process that requires clamping and joining parts of all kinds of geometries. This is done by numerous mechanical positioning and welding devices. Due to model or technology changes, these devices need to be redesigned to fit the new requirements of the changing model geometries and new production technologies. As described before, it is crucial that the existing planning data is accurate and up-to-date to ensure a successful planning process.

In the scope of a plant extension, an align fixture was analysed with the Roivis system. The extension included the installation of automatic fixture devices with integrated spot welding to reduce the amount of manual work. The concrete project was to analyse an align fixture in which the side plate and the wheel arch of a vehicle are spot welded manually.

6.2.2 Preparation

6.2.2.1 Course of Action

Diligent preparation and high quality input data are essential to achieve results of suitable accuracy. Thus, in the beginning, the concerned align fixture was examined in place and contact with the responsible planner, as well as the construction engineer was established. After discussing the analysing procedure and points of interest for the variance comparison, the access to the actual planning data was provided and a concrete appointment for the analysis was made.

During the in-place examination, it was found that the align fixture offers no accessible reference points, which could be used to register markers to the model coordinate system. Therefore, markers on the align fixture had to be registered with the help of markers attached to the vehicle part, which was clamped in the fixture. This process is supported by the 3D-3D registration method with 6DOF support (see chapter 5). The reference markers for 3D-3D registration to the car coordinate system were attached to known reference points on the vehicle side plate by using according adapters. Additional markers on the align fixture could be registered by the subsequent 6DOF registration step, as align fixture and vehicle part shared the same model coordinate system (car coordinate system).

Again, the similarity to photogrammetric measurement systems can be pointed out (see also section 5.2.7). There, the available image data often also provides known reference points (pass points) and additional unknown measurement points for computation.

6.2.2.2 Marker Adapters

Based on the available digital part geometry, reference points were chosen and measured. Easily accessible drill holes in the side plate were selected for this purpose. Their coordinates and diameters were measured with a CAD tool and documented afterwards. The reference markers should be attached to the drill holes with the help of cylindrical adapters as shown in figure 5.7. For this purpose, adapters with a defined pole length were produced to hold a square plate and an optical marker on the upper side and a small cylinder on the bottom. Using the described adapters, the centre point of a given reference drill hole could be determined. The final registration process to determine the offsets of all used markers to the part coordinate system had to be performed after the image acquisition. It is described below.

The marker adapters were custom-built to fit the needs of the analysis. However, this additional effort was acceptable, because the adapters can be reused since drill hole diameters are standardised.

6.2.2.3 Model and Calibration Data

The acquisition of the needed CAD geometries was the next step of the preparation process. The required input format for Roivis is the VRML 97 standard, which can be easily exported by most of the common CAD tools. The VRML files were taken from the Volkswagen product data management system. Regarding the align fixture, seven geometry files were exported (a ground plate, four common fixture clamps and two fixture-welding-devices), while the vehicle body parts were represented by two geometry files (side plate and wheel arch).

The digital reflex camera Nikon D70 and an external flash unit were used to create image material with an adequate resolution. The camera, which offers a resolution of five mega pixels, was calibrated with the external software AICON 3D and the Extended Sextant, as mentioned in section 3.3.2.

6.2.3 Data Acquisition

After finishing all preparation steps, the work finally continued in the real production line, and images were captured. During a production break, five markers were positioned in the align fixture (encircled orange), and five reference markers were attached to the side plate (encircled green), as shown in figure 6.3.

First, overview pictures were taken, which captured the markers from various positions. These pictures were then used to determine the offsets of the fixture markers via the known offsets of the adapted reference markers.

Then, the vehicle parts were removed from the fixture to get a free view onto the fixture. Finally, detailed pictures where taken from interesting areas, and special attention was paid to the regions in which the new fixture-welding-devices should be installed. As experience has shown, the participation of the construction engineer is recommended during this procedure. This participation ensures that all necessary regions are captured from every needed perspective.

172 pictures were taken during the analysis. 25 pictures (14.5%) were used to register the markers attached to the align fixture.

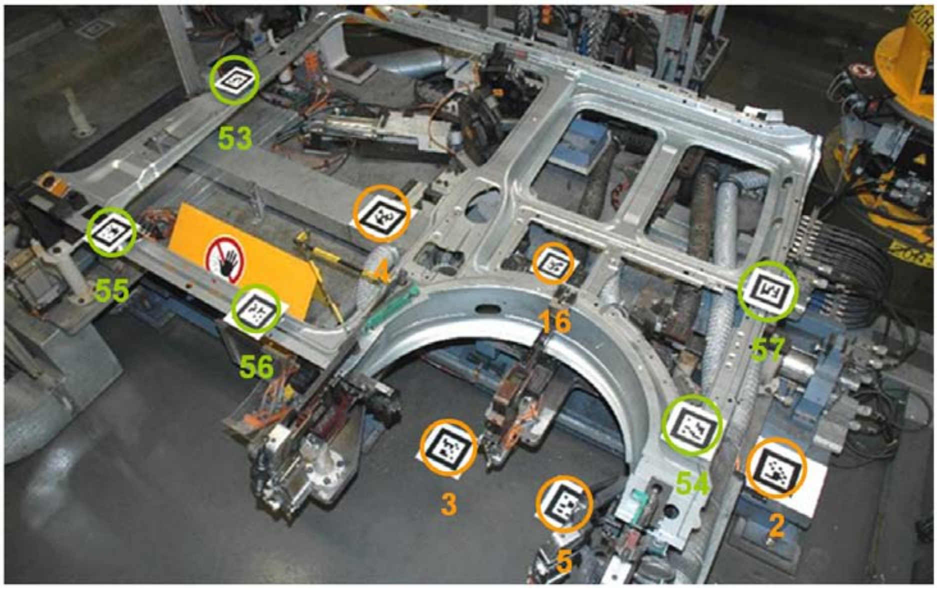


Figure 6.3: Markers on Align Fixture (orange) and Side Plate (green) (Source: Volkswagen AG)

6.2.4 Evaluation and Consequences

6.2.4.1 Preparation

Before the evaluation process could take place, the marker configuration data file was created. This was done using the 3D-3D registration tool provided by Roivis (see chapter 5).The referencing markers (encircled green in figure 6.3) and their corresponding 3D points in the digital model data were used for 3D-3D registration. Based on the resulting transformation from the camera to the model coordinate system, the offsets for each marker could be computed using a 6DOF registration approach. The resulting marker configuration file was used to create the AR scene in Roivis:

- Image data was loaded.
- The calculated Extended Sextant camera calibration file was added.
- The marker configuration file determined through 3D-3D referencing was loaded.
- Finally, the VRML files for the required geometries (fixture and body parts) were overlaid.

6.2.4.2 Evaluation

The data was evaluated in cooperation with planners and the construction engineer. Starting with an optical review, the image data was evaluated iteratively by visualising the different parts of the align fixture (figure 6.4) using different geometry views (see section 3.3.2).

Occlusion view proved to be very helpful while observing scenarios from certain perspectives. The wire frame view enabled an easy comparison of real and virtual objects (see figure 3.6). The use of clipping planes made collision detection possible and helped to estimate distances quickly (see figure 3.7). Measuring functionality was used to verify and document such estimations. An example application of the accuracy measurement documentation is shown in figure 4.7. Due to high-accuracy

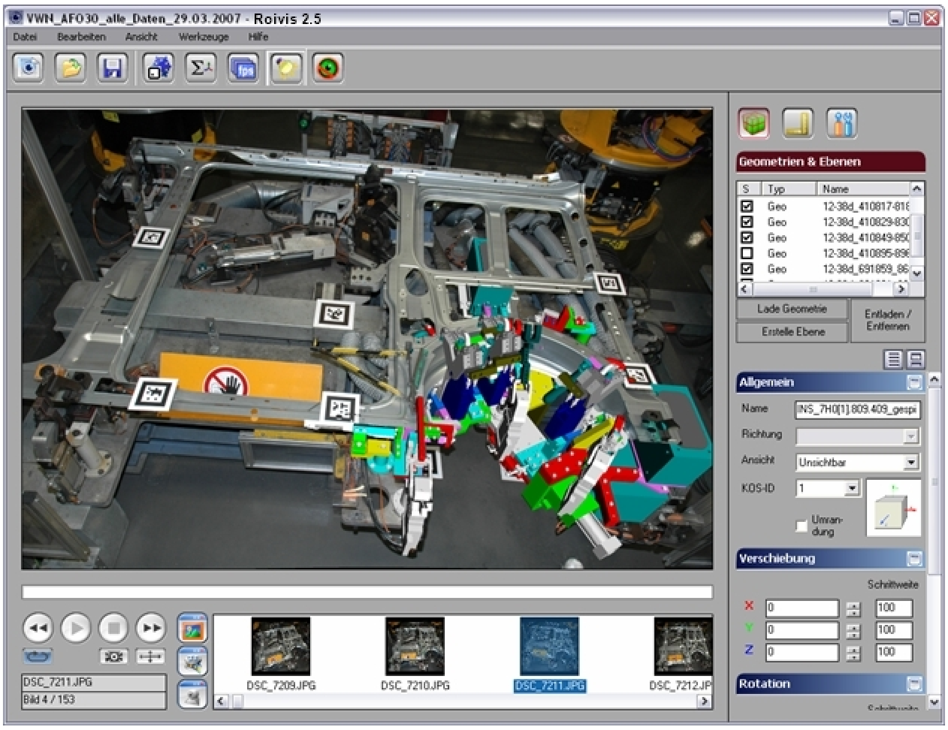


Figure 6.4: AR Scene in the Roivis GUI (Source: Volkswagen AG)

input data, the overall error and standard deviation stayed in the range of 1-2 mm.

It was determined that the digital planning data represented the actual align fixture correctly. This was due to an extensive manual variance comparison, which was performed by the construction engineer before the AR analysis was conducted. The actual state of the planning data could be verified by the AR analysis. An earlier application of Roivis would have decreased the efforts needed for the manual variance comparison and would have reduced the construction costs by 8 %, as stated by planning engineers.
Furthermore, the use of Roivis enabled the consideration of undocumented components, which mostly belonged to the area of supply facilities (more precisely exhaust tubes, terminal boxes and cable channels). An example of such a case is shown in figure 6.5. Since exhaust tubes and cable channels of the analysed align fixture were not represented in the virtual planning data, the construction engineer placed a welding transformer in a tightly packed area. The exhaust tube is marked in red and the area of collision is shown in dashed lines.

6.2.4.3 Review

The goal of a planning process is the achievement of 100 % planning reliability. This means that the plant is built exactly as planned and simulated in the Digital Factory. To ensure 100% planning reliability, a complete and up-to-date digital representation of the real production line is needed. Today, this is rarely available.
Discrepancies between digital planning data and the real world are mainly caused by

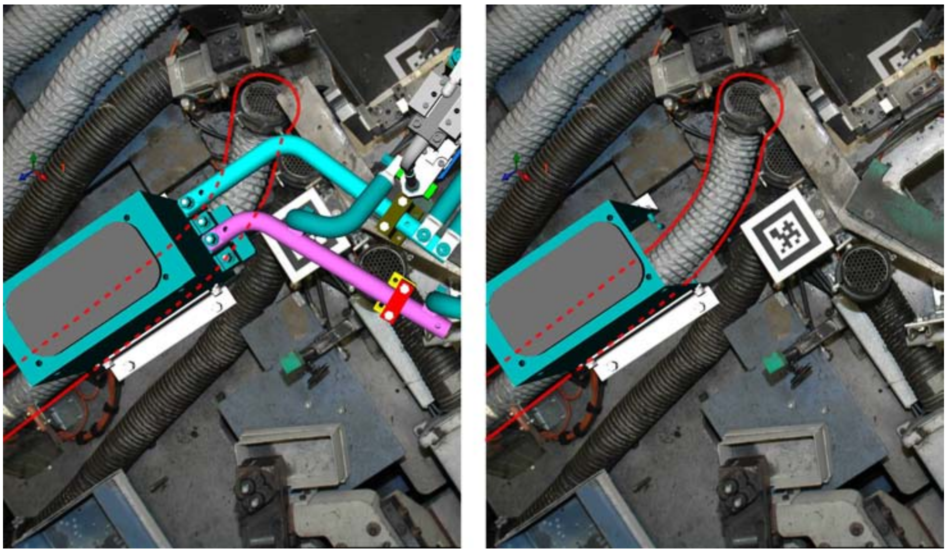


Figure 6.5: Virtual Collision with an Undocumented Exhaust Tube (Source: Volkswagen AG)

- Undocumented changes during the beginning of operation,
- Incorrect assembly of equipment during the beginning of operation or
- Undocumented changes during the operation of the plant.

If these discrepancies are not considered during planning processes, the planning reliability decreases. In the presented pilot case, a planning reliability of 80% was given without the application of Augmented Reality. This denotes that only 80% of the plant extension can be built as planned in the Digital Factory, whereas 20% of the planning must be adjusted retroactively to the actual conditions on-site.

The application of Augmented Reality allows including undocumented or incorrect equipment in the plant conversion as shown in the previous sections. The early detection and consideration of these discrepancies allows increasing the planning reliability. However, for a successful variance comparison it is crucial to have a reliable AR visualisation. Through the provision of a scenario-specific error and uncertainty statement, the quality of the visualisation can be rated and discrepancy checks can be performed accordingly. In the concrete pilot case, the AR evaluation could increase the planning reliability from 80% to 98%. Thus, the variance comparison could save costs during the planning process and allowed an installation on schedule without downstreaming optimisation processes.

6.3 Interfering Edge Analysis at Opel

The second application presents the use of Roivis for a large factory planning study in four factories of Opel around Europe. All in all, evaluations for 84 examination points were performed.

6.3.1 Introduction

As mentioned before, today's factory planning needs to be fast and flexible and has to meet increasing demands for product variations and customised designs as well as fluctuating demands.

Opel has several production sites in Europe, which manufacture cars of the Opel Astra series. The aim of the Roivis analysis was to test these existing production lines for their capability of manufacturing succeeding models of the series, which are already designed, but not yet built. Using interfering edge analysis, the minimum distances to obstacles on all sides of the car should be measured.
Based on the results, information is now available describing

- Where the designed succeeding models can be manufactured, but also
- What general car size limit is given for future productions in the existing factories without any structural alterations.

The evaluation involved all parts of the production chain of a car ranging from analysis in bodyshell work and paint shop to car body storage and final assembly. Therefore, discussions with planners and workers on-site were crucial in order to identify the known bottlenecks in production and to decide on the concrete sets of evaluations to be performed.

6.3.2 Preparation

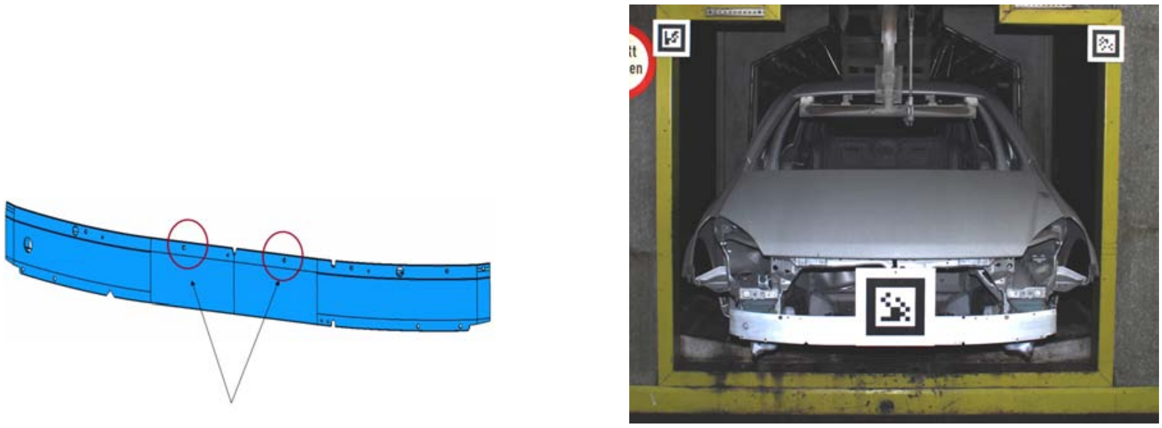
6.3.2.1 Course of Action

Different from the previous application, most of the evaluations for Opel had to be performed during production. The manufacturing process could not be stopped for evaluation, as this would have caused production downtimes. This complicated the acquisition of image data, as the object of evaluation was moving continuously. Thus, the preparation step was very important. The process of marker positioning and image acquisition had to be planned in detail to allow fast execution on-site.
To perform the interfering edge analysis, the virtual model data of the new Astra series had to be registered to the car skid, which transports the car bodies in the production line. During production, real car bodies are mounted on these skids. As the skid fixes the car bodies in a standardised manner, the real car bodies on the moving skid could serve as reference for the virtual new car model. Due to the limited amount of time for data acquisition at each location, one single marker should be used for registration to the car coordinate system. A first analysis of the digital data allowed determining a favourable location for the marker, which could be used throughout the whole evaluation process and was easily detectable in the virtual data and the real world. As for the previous scenario, a special marker adapter was produced. However, as one marker alone had to describe the car body, the adapter should fix the marker in all six dimensions.
At each point of analysis in the different factories, the marker adapter was then attached to the moving car body and images were taken while the production was running.

6.3.2.2 Marker Adapter

To attach the markers to the moving car bodies, two reference points (drill holes) at the front bumper were chosen (see figure 6.6). These points were accessible at all production stages and were easily retrievable in the digital data. A special adapter was designed, which could be attached to the car body using the reference points. Through the 3D structure of the drill holes, the adapter was then fixed rigidly in all six dimensions.

For registration of the marker coordinate system to the car coordinate system, the required offset information was extracted from the available digital data by performing according measurements in a CAD tool.



(a) Reference Points for the Marker Adapter

(b) Marker Attached to Moving Car Body (Source: Opel)

Figure 6.6: Marker Adapter for the Opel Scenario

6.3.2.3 Model and Calibration Data

3D data was provided by Opel. As the evaluation points were spread across the whole production process, it was very important to have the correct versions of the digital models available for the different planning steps. For each evaluation site, the 3D data had to reflect the current manufacturing stage of the car.
Similar to the first application example, a digital reflex camera was used for image acquisition, the Nikon D200. Again an Extended Sextant camera calibration was created (see section 3.3.2).

6.3.3 Data Acquisition

6.3.3.1 Preparatory Discussion

For data acquisition at the different production sites, preparatory meetings with the responsible people of the factory were held. The specific locations of evaluation were discussed in detail and the important goals for the evaluation were clarified. Afterwards, the actual image acquisition was started.

6.3.3.2 Image Acquisition

Two people from metaio performed the data acquisition. At each location, the static environment was tagged with markers. That way, obstacles or general objects of interest in the scene were equipped with a 3D reference, which could be used for collision detection or general distance measurement. Subsequently, the main object of interest, the car body, was tagged. As the car was moving in most cases, one person had to attach the marker adapter to the moving car body, while the other person prepared to take a series of pictures as soon as the field of view was clear. All relevant perspectives had to be included and the setup was documented in detail to provide optimal conditions for later evaluation.

6.3.4 Scene Analysis

6.3.4.1 Preparation

3D Model Data For the Opel scenarios, several manipulations in the digital model data were performed using CAD software in order to ease the scene analysis. The model data was cored to remove all irrelevant data inside the car bodyshell. Furthermore, the degree of tessellation of the models was set to 1 mm. Both operations reduced the data size of the models and made them easier to handle for the Roivis application. Finally, the model coordinate system was moved to the marker coordinate system using the manipulation functionality of the CAD system. The offset was retrievable through the specific structure of the marker adapter and the known locations of the reference points.

Configuration Data The marker configuration was created based on the scenario protocols. The reference marker for the car and the additional markers for obstacle representation were included in a tracking configuration file. As the 3D model data was manipulated, no additional referencing offset had to be included in the configuration file.

The camera calibration was already available and could be used directly for scene creation.

Scene Creation For each evaluation scenario, a set of Roivis scenes was created to reflect the identified problems. For each possible collision and for each interesting distance measurement, specific scenes were saved.

The main results of each scenario could then be documented through screen shots and concrete measurement values for presentation purposes.

6.3.4.2 Evaluation

As the number of evaluated scenarios is very large, only exemplary results can be presented here. The main goal for the scenarios was to perform interfering edge analysis and to determine the available clearance around the car body for the known bottleneck locations.

The following scenario shows one part of the paint shop of the Opel factory in Antwerpen. In the actual Roivis evaluation, virtual car models of a new Opel series were visualised. However, these models are confidential and cannot be published here. Therefore, the following pictures show virtual overlays of a currently produced Opel Astra.

Visualisation of the Scenario The first step for each evaluation was the general visualisation of the scenario. Figure 6.7 shows the Roivis scene with the detected marker coordinate systems and the loaded 3D model of the car body. Through the comparison of real and virtual car body, the dimensions of new series with respect to the current state of production could be presented.

Distance and Accuracy Evaluation Next, clipping planes were added to the scene to get a 3D representation of relevant obstacles in the environment (see section 3.3.2 for more details on clipping planes). These planes were bound to the available markers in the scene and required translations with respect to the marker origin were taken from the scene protocol.

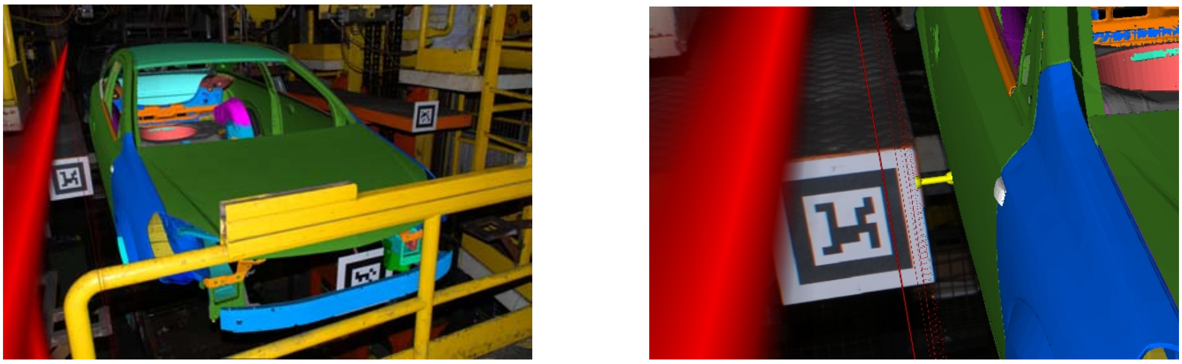
Once the clipping planes were positioned, measurable objects for the obstacles were available. The

(a) Roivis Scene with Tracked Coordinate Systems

(b) Roivis Scene with Loaded 3D Model

Figure 6.7: Basic Visualisation of a Scene in the Paint Shop (Source: Opel)

distance measurement tool could now be applied to determine the shortest distance between a point on the car body and a clipping plane. Figure 6.8 depicts this process. The resulting distance for the given case was measured as 73.1 mm.



(a) 3D Representation of Obstacles Through Clipping Planes

(b) Distance Measurement Based on the Clipping Plane

Figure 6.8: Measuring Tasks for a Scene in the Paint Shop (Source: Opel)

Given this distance measurement, the question of its reliability needed to be answered. To determine a quality statement for this measurement, the accuracy measurement tool was used. The VRML uncertainty was set to 1 mm based on the chosen degree of tessellation. The two points selected for distance measurements were:

- On the car body relative to the car model coordinate system: (2224.56, 864.13, -69.91)
- On the clipping plane relative to the clipping plane coordinate system: (1188.78, -90.00, 229.20)

Table 6.1 presents the uncertainty calculation results for two different input settings of offset uncertainties.

Offset Uncertainty: 1 mm and 0.1°				
Scenario	Error x [mm]	Error y [mm]	Std.dev. x [mm]	Std.dev. y [mm]
Car point	-1	2	8	12
Plane point	1	-1	3	4
Offset Uncertainty: 5 mm and 0.5°				
Scenario	Error x [mm]	Error y [mm]	Std.dev. x [mm]	Std.dev. y [mm]
Car point	-1	2	37	59
Plane point	1	-1	11	14

Table 6.1: Uncertainty Values for the Distance Measurement

6.3.4.3 Review

With the AR-based approach, the required evaluations could be performed using real image data of the different production lines and virtual model data of car bodies, which are not yet produced. For registration again a hybrid and adapter-based approach was applied (see also chapter 5). The choice was based on the special nature of the evaluation, characterised mainly through the limited amount of time for each scenario. The special marker adapter for two reference points was the easiest and most flexible solution for the given case. It could be used for all scenarios in all four factories.

In addition, due to the modification of the 3D model data, the determination of the registration offset was transferred to a CAD software measurement task. This step could have been avoided and the offset could also have been added to the marker configuration file. However, the main advantage of this approach was the reduction of rotational error for the scene analysis. Rotational error increases with the distance along which it is propagated. Due to the movement of the coordinate system, this distance could be reduced.

The results of the interfering edge analysis are included in future factory planning tasks at Opel. The distribution of the manufacturing tasks for future cars among the available production sites can be based on the knowledge about maximum clearance in the different factories. In addition, fluctuating demands for specific car models can be handled through outsourcing or reallocation of manufacturing tasks.

Again, the reliability of the AR visualisation is crucial for the usefulness and applicability of the planning results. Through the calculated error and uncertainty values, according thresholds can be added to the measured distances to provide a security buffer for consequential decisions.

6.4 Summary

This chapter presented concrete examples of application, underlining the serviceability of Roivis for AR-based factory planning. First, the general process of preparation, creation and analysis of factory planning scenarios with the system was described, highlighting the accuracy and registration related tasks. Afterwards, the execution of two specific planning tasks from automotive industry was discussed.

The first example presented a variance comparison task at Volkswagen. There, Roivis allowed detecting several discrepancies between digital data and the real world and could thereby increase the overall planning reliability by 18%. In the second example, Roivis was applied for interfering edge analyses at four factories of Opel around Europe. Based on the determined data on maximum clearance in the different shop floors, production quota for the new Opel Astra series could be allocated. In addition, valuable information for future allocation or outsourcing of manufacturing tasks is now available.

7 Evaluation

Analysis of Tracking, Registration and Complete System

The previous chapters presented various aspects of AR-based factory planning. Roivis with its general functionalities and the features related to accuracy and registration were introduced. The overall goal for the development process of Roivis is the creation of a productive and beneficial application for industrial use. In this context, the analysis of the system components according to different criteria is a required and valuable indicator.

This chapter describes different evaluations performed for the Roivis system to analyse the accuracy and usability of system components, as well as the overall system productivity. At the beginning, section 7.1 presents a general background for evaluation. Afterwards, the underlying marker tracking system is analysed with respect to accuracy (section 7.2) and robustness (section 7.3). Section 7.4 then discusses aspects of uncertainty and usability for the Roivis registration toolbox. Finally, a general analysis of Roivis in terms of productivity is performed in section 7.5.

7.1 Evaluation Background

As mentioned above, the evaluations performed for Roivis comprise accuracy, usability and productivity related aspects. This section therefore introduces concepts for according analyses. First, the Design of Experiments approach is presented, whose concepts are applied to evaluate the accuracy of the metaio marker-based tracking system. Furthermore, available requirements for rating success and productivity of industrial AR applications are described. Finally, usability and usability evaluation approaches are briefly introduced, which are applied to the registration toolbox later in this chapter.

7.1.1 Design of Experiments

7.1.1.1 Statistics

In section 4.1, concepts on error and uncertainty were introduced. Mean and standard deviation were described as parameters, which conveniently characterise a distribution, the normal or Gaussian dis-

tribution. Given such normal distributions, there are many good analysing techniques available.
Section 4.1 also presented the central limit theorem (CLT). According to the CLT, averages from a set of samples from a distribution will be distributed approximately normally, even if the parent population is not normally distributed. The use of such averages thus makes the analysis more secure.

7.1.1.2 Fundamentals of Experimentation

Design of experiments (DOX) is basically the use of particular patterns of experiments. These patterns allow to generate a lot of information about some process, while minimizing the number of actual experiments to get this information [Del 97]. The quality of the resulting information depends on the quality of the input data and the analysing techniques applied. DOX creates high-quality data in minimum quantity to provide a good base for various analyses. The resulting data can be used to estimate what affects a process, but also to separate effects that are significant from those that are meaningless.
Section 4.1 also introduced the fact that every measurement is subject to errors - random or systematic. These variations cannot be eliminated altogether, but the aim is to minimise them. Then, it will be much easier to identify the effects of changes in data on changes in the process. The Design of Experiments approach provides four main defences against this so called scatter [Del 97]:

- Scientific rigour: Be meticulous about every detail and carefully monitor and weigh every factor.
- Randomisation: Randomise the order of the different runs of experiments to avoid side effects.
- Blocking: Create subgroups of experimental conditions to ease comparison.
- Replication: Repeat the same experimental setup more than once.

7.1.1.3 Preparation of Experiments

Based on the fundamentals just presented, experiments can be prepared in a few steps:

- Have a clear understanding of the problem and the goal of the experiment.
- Include all concerned people in a meeting and have a brainstorming on
  - The list of all possible factors that are likely to effect the process,
  - The range of control factors (minimum and maximum values) and
  - The number of factors and their levels (intermediate steps between minimum and maximum values).
- Pick the appropriate experimental design and plan the experiment in full detail.
- Execute the experiment as planned.

7.1.1.4 Experimental Designs

The most basic pattern of experimental design is the full-factorial pattern. It involves every factor at every level and permits a detailed analysis of effects and interactions of factors. However, for complex experiments with many factors and levels, this can be very time and cost consuming.
A compromise is given by the so called fractional-factorial approach, where only a subset of all possible combinations is regarded. Various designs are available within the fractional patterns. Simple

patterns look at two levels for each factor. To measure non-linear factor effects, at least three levels of a factor are needed, which leads to more complex ways of analysing data [Del 97]. Furthermore, to be able to identify the influence of each parameter on the output, the factor that should be analysed has to be varied in a controlled way (design factors) while all other influence factors are randomly chosen (allowed-to-vary factors) [Mont 05].

7.1.2 Acceptance and Usability Evaluation

The goal for the development of Roivis was to create a productive and successful AR application for industrial use. To evaluate the current state of the application according to these aspects, some indicators are required.
This section introduces background on acceptance and usability aspects, which shall provide the information basis for this evaluation.

7.1.2.1 Acceptance of IAR Applications

For rating the acceptance of an industrial Augmented Reality application, two approaches are outlined here. General requirements for "killer applications" and a maturity classification for Augmented Reality applications based on specific characteristics are presented.

Requirements for "Killer Applications" According to Navab, killer AR applications for industrial environments provide better solutions than traditional approaches. They can convince a large number of customers and create noticeable financial benefit for industry [Nava 04]. Navab identifies three main criteria for successful, marketable applications:

- Reliability: The application needs to be robust and accurate and has to provide reproducible solutions.
- User friendliness: The application must be safe and easy to setup, learn and use and should be customisable.
- Scalability: The application should be scalable beyond simple prototypes to be distributed in larger numbers.

Maturity Classification of Industrial AR (IAR) Applications Another approach to define the requirements needed for a successful and accepted IAR application is given by Regenbrecht [Rege 06], who presents an AR application maturity continuum. This classification system consists of three main types of applications: demonstration systems, prototype systems and productive systems (see figure 7.1).

Besides this graphical representation, lists of main characteristics of the three application types are stated. Demonstration systems focus on technology, are characterised by a high amount of uniqueness and require investments. In contrast, productive systems focus on usability and user acceptance, are actually applied in the field and are profitable. In-between those two stages, Regenbrecht places so called demonstration systems, which are already close to real use, but still require technology-friendly environments, as they do not yet comprise the amount of usability and robustness needed for a productive application. Table 7.1 summarises the characteristics for the three different systems.

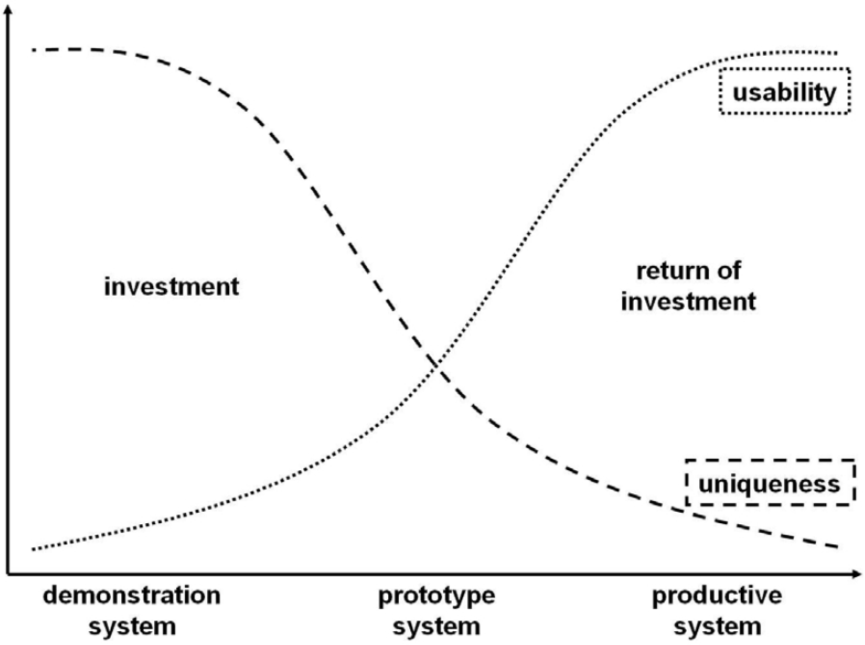


Figure 7.1: Types and Maturity of Applications [Rege 06]

7.1.2.2 Usability Basics

Both collections of requirements presented in the previous section emphasise the user and the usability of the system. An application will only be accepted if it satisfies the user's needs and integrates well with the working process of the user.
Usability and usability evaluation is a large field of research. Various standards and methods are available to describe what usability is and how to measure it adequately.

Definitions An international standard defines usability as the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specific context of the user [ISO 98].
Other approaches describe usability as a combination of factors, including ease of learning, efficiency in use, memorability, error frequency and severity and subjective satisfaction [Heal 08].

Evaluation Approaches In 1995, Jakob Nielsen, a leading head in the field of usability, presented results of an evaluation on usability inspection methods. The two methods, which were rated as most beneficial, were user testing and heuristic evaluation [Niel 95].
For user testing, representative users are selected. They are asked to perform representative tasks and are observed to see what they do, where they succeed and what difficulties they have. Two main groups of users can be distinguished: Novice users, which are new to the system and expert users, which are experienced with the system.
Heuristic evaluation involves having a small set of evaluators examine the interface and judge its compliance with recognised usability principles. Such principles ("heuristics") are for instance the

Demonstration System	Prototype System	Productive System
unique in some way		
focused on technology	focused on application	focused on user acceptance
not targeted for real use	close to real use	addresses real users
	robust in core functionality	robust and reliable
hardly ever replicated	applied more often	frequently applied
uses prepared data	uses real-world data	uses existing data chains
laboratory-like environment	technology-friendly environment	applied in the "field"
requires investment		has to be profitable
follows no standards		uses standards
targeted to customers	targeted to customers and users	targeted to users
	some documentation	full documentation
	first usability investigations	well-designed and tested

Table 7.1: Characteristics of the Three Application Types [Rege 06]

visibility of the system status, user control and freedom, error prevention or consistency of the interface [Niel 94].

7.1.3 Evaluation of Roivis

In the next sections, the basics presented above are applied to important aspects within AR-based factory planning with Roivis. An analysis of the metaio marker tracking system is presented based on concepts of DOX. Furthermore, the implemented registration approaches are compared to each other based on accuracy and usability related criteria. Finally, section 7.5 aims to respond to the question whether AR-based factory planning is a killer application and whether Roivis can be considered as real productive industrial AR system.

7.2 Tracking Accuracy Evaluation

The first and most important component in the process of creating an AR scene with Roivis is the marker tracking. It provides the reference to the real world. On top of this reference, further offsets are added to position virtual objects correctly with respect to the real environment. Errors in this first component propagate through all further steps in the chain and can thus cause large uncertainties for the final overlay.
Therefore, the evaluation of marker tracking accuracy is a crucial aspect for the reliability and acceptance of Roivis and a fundamental contribution of this thesis (see also [Pent 06b]).

7.2.1 Design of Experiments Approach

7.2.1.1 Goal of the Experiment

The experiments performed for the tracking accuracy evaluation should analyse the effects of specific influence factors on the accuracy of the metaio marker-based tracking system in terms of translational and rotational error. In addition, an actual accuracy information should be calculated through comparison of tracking results with known correct values.

7.2.1.2 Planning the Experiment

Examples for application of the theory on Design of Experiments are usually taken from nature. Natural processes are analysed such as some physical constant, which is measured. For this scenario, influence factors are given by the whole surrounding environment - temperature, hardware equipment and so on. In addition, the true value for the measurement result stays unknown and thus, the measurement error cannot be calculated, but needs to be estimated based on statistical methods.
For marker tracking evaluation such experimental studies have been presented in section 4.5.1. Different from these approaches, this tracking evaluation aimed to really determine a tracking error by comparing tracking results with actual ground truth data. This ground truth data was generated using an image simulation application. Given this simulation based testing environment, the possibilities for experiments were of a different kind. Thus, the DOX concepts presented above were not always reasonable for this scenario. Nevertheless, they were used as far as possible, in order to ensure a structured approach for testing.

Experimental Design Pattern Using the simulation based environment, different influence factors could be varied at different levels with no effort. Nevertheless, the number of runs should be limited in some way to keep the amount of data in a range, which can still be reasonably analysed and stored.
The experiment followed a fractional-factorial approach. Different sets of experiments were performed where one factor was manipulated in a controlled way using pre-defined levels, while all other influence factors were set to random values within their ranges. An overview on the settings of the experiment is given in table 7.2.

Influence Factors The influence factors chosen for evaluation were based on sources from literature and internal brainstorming meetings at metaio. As described in section 4.5.1, the marker area in pixels in the image as a value of distance and camera parameters (*MAiP*), as well as the viewing angle around x- and y-axis (r_x, r_y) were chosen as factors. It is important to note that the viewing angles also influence the actual marker area in pixels in the image. To avoid this dependency, the parameter *MaiP* is calculated assuming a front view on the marker.
With respect to image simulation, different marker areas and different viewing angles were created by manipulating the camera pose with respect to the marker. Some of the camera pose entries have direct effects on the marker area and the viewing angles, others do not. Therefore, the factors chosen for the experiment can be divided in actual control factors and other factors.

- Control factors
  - z-translation (t_z) (effects size of the marker in the image)
  - Focal length and resolution $(f, (res_x, res_y))$ (effect size of the marker in the image)
  - x- and y- rotation (r_x, r_y) (effect viewing angle)
- Other factors

- x- and y- translation (t_x, t_y) (do not effect *MAiP* or the viewing angle, but determine location of the marker in the image)
- z- rotation (r_z) (does not effect *MAiP* or the viewing angles)

Rotation Settings

r_x in °	r_y in °	r_z in °
$[-65;65]$	$[-65;65]$	$[-180;180]$

Translation Settings for Camera 1: $res = (1024,768)$, $f = 1030$

t_z in mm	t_x in mm	t_y in mm	Number of Sets
$[-500;-1000]$	$[-100;100]$	$[-50;50]$	2000
$[-1000;-1500]$	$[-400;400]$	$[-300;300]$	2000
$[-1500;-2000]$	$[-800;800]$	$[-500;500]$	2000
$[-2000;-2500]$	$[-1000;1000]$	$[-800;800]$	2000
$[-2500;-3000]$	$[-1400;1400]$	$[-1000;1000]$	2000
$[-3000;-3500]$	$[-1600;1600]$	$[-1200;1200]$	2000
$[-3500;-4000]$	$[-1800;1800]$	$[-1400;1400]$	2000

Translation Settings for Camera 2: $res = (3008,2000)$, $f = 2190$

t_z in mm	t_x in mm	t_y in mm	Number of Sets
$[-500;-1000]$	$[-200;200]$	$[-150;150]$	2000
$[-1000;-1500]$	$[-600;600]$	$[-400;400]$	2000
$[-1500;-2000]$	$[-1000;1000]$	$[-600;600]$	2000
$[-2000;-2500]$	$[-1800;1800]$	$[-1100;1100]$	2000
$[-2500;-3000]$	$[-2100;2100]$	$[-1400;1400]$	2000
$[-3000;-3500]$	$[-2500;2500]$	$[-1500;1500]$	2000
$[-3500;-4000]$	$[-2700;2700]$	$[-1700;1700]$	2000

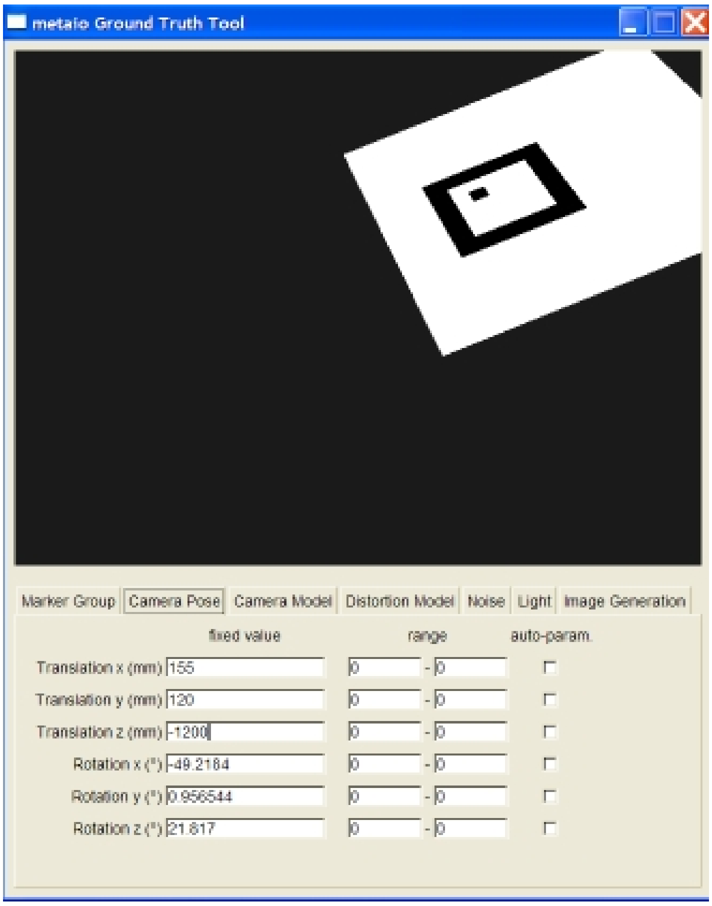
Table 7.2: Ranges for the Factors of the Tracking Accuracy Experiment

Ranges and Levels The ranges of the factors were based on the constraints of a successful marker tracking. Section 7.3 points out that the marker tracking is sensitive to partial occlusion of the marker. Therefore, the marker needed to be fully visible in the image to get a tracking pose. In addition, not only the marker edges, but also the internal marker pattern had to be detectable to assure successful marker classification. These aspects limit the ranges of all parameters. Furthermore, some control factors are not independent from each other. z-translation, focal length and resolution of the camera together define the marker area in pixels as described in section 4.5.1. To avoid these dependencies during the experiment, focal length and resolution were set to fix values and only the z-translation was manipulated. For closeness to reality, representative values were used to set focal length and resolution. The ranges for the identified factors, including the constraints of camera parameters, are presented in table 7.2. The levels for the z-translation were created on an increment base of 100 mm, the levels for the angles were created on an increment base of 5°.

7.2.2 Experimental Environment

7.2.2.1 Simulation of Ground Truth Data

For data acquisition, a tool was implemented in C++ using OpenGL combined with an FLTK graphical user interface. It allows the generation of arbitrary camera views of a metaio marker. These views are then processed by the metaio Unifeye SDK tracking component. The eight corners, which describe the inside and outside boundary of the thick black border of the marker are extracted to estimate the marker pose in the current view. For each image the given ground truth information on the marker position and the camera are stored in an XML file together with the tracking results. These files are then used in the statistical analysis. Furthermore, the system allows specifying fixed values or ranges for parameters and selecting the controlled and the random parameters. Increments can be specified to allow for arbitrary levels of the different factors. Figure 7.2 depicts the graphical user interface.



	fixed value	range		auto-param.
Translation x (mm)	155	0	0	☐
Translation y (mm)	120	0	0	☐
Translation z (mm)	-1200	0	0	☐
Rotation x (°)	-49.2184	0	0	☐
Rotation y (°)	0.956544	0	0	☐
Rotation z (°)	21.817	0	0	☐

Figure 7.2: Ground Truth Tool for Data Simulation

Data was created, based on the plan described above. Following the blocking concept, data sets with controlled values of the viewing angles and random other values were computed, as well as data sets with controlled values of the z-translation and random other values.

7.2.2.2 Analysis

In the analysis step, the resulting data files of the data generation were processed. Each file consists of general information on the simulated camera (focal length, resolution values), ground truth information on the eight marker corners (four corners for each border square of the black area) and the camera pose (6DOF translation and rotation) and the tracking results for the corner detection and the camera pose. The data was imported in MS Excel and analysed and visualised as diagrams. For the corner error, the 2D sub-pixel differences between ground truth data and tracking result for the eight corners were averaged. The pose error was computed as averaged sum for each of the 6DOF parameters (translation in $x-$, $y-$, and $z-$direction, rotation angle around $x-$, $y-$ and $z-$axis) separately and combined for an overall translation and rotation error. The translation error describes the Euclidean distance between ground truth and tracking translation and the rotation error is given by the averaged angular error.

7.2.3 Results

The results of this tracking accuracy experiment are presented in the following. In general, the simulation-based experiment supports the results of other studies performed for marker tracking accuracy (see Abawi et al. [Abaw 04] or Zhang et al. [Zhan 02]). In addition, due to the simulation-based approach with a large number of samples, the results offer information in more detail and allow the creation of an error function with much higher resolution than previous studies.

7.2.3.1 Effects of the Marker Area in Pixels $MaiP$

The size of the marker in pixels in the image has a similar effect on translational and rotational error of the tracking result. In both cases, the experiments showed that a large marker leads to better results. Figures 7.3 and 7.4 depict a graphical representation of the experimental results. The curves allow several conclusions for the effects of the marker area in pixels and thus for the relationship of distance between camera and marker, marker size, focal length and camera resolution:

- Both translation and rotation error decrease rapidly in the beginning ($MaiP \leq 10000$ pixels).
- After a certain threshold is reached, larger marker sizes do not lead to considerable improvements anymore ($MaiP \approx 40000$ pixels).

7.2.3.2 Effects of the Viewing Angle r_x, r_y

The viewing angle mainly has an effect on the rotational accuracy. Figures 7.5 and 7.6 show examples for the influence of the rotation angle. The main aspects, which can be identified are:

- The viewing angle does not have a strong influence on the translational error, front views of the marker ($r_x/r_y \approx 0$) lead to slightly better detection of the z-translation.
- The viewing angle does have a strong influence on the rotational error. Front views of the marker lead to larger errors than views from the side.

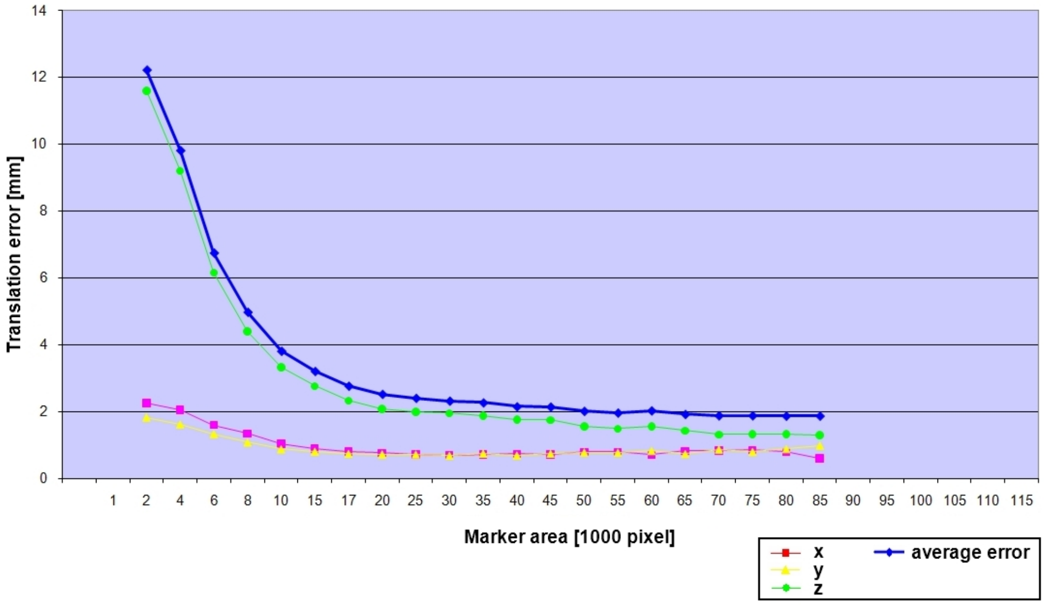


Figure 7.3: Effects of *MaiP* on the Translational Error

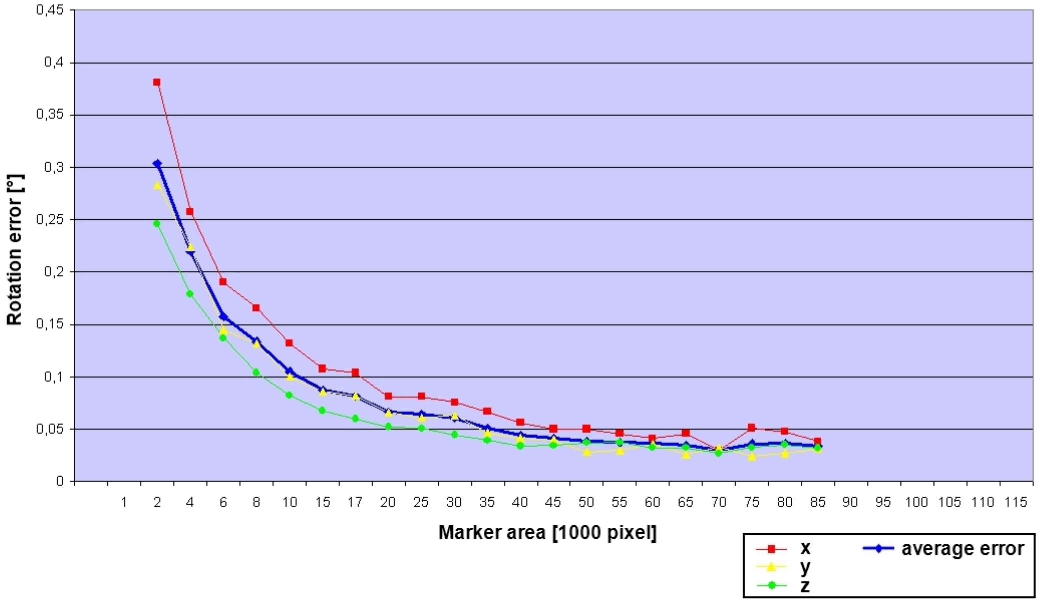


Figure 7.4: Effects of *MaiP* on the Rotational Error

Figure 7.5: Effects of the Viewing Angle r_y on the Translational Error

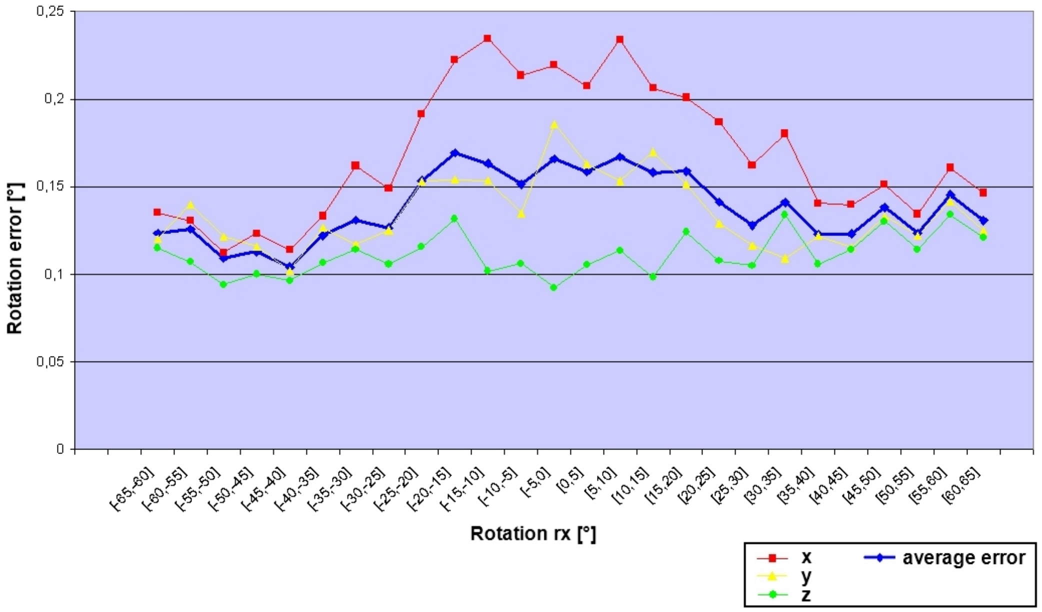


Figure 7.6: Effects of the Viewing Angle r_x on the Rotational Error

7.2.3.3 Factor Independent Results

Besides the analysis of the effects of specific influence factors on the tracking result, the curves also allow stating some general results for marker tracking accuracy:

- The translational error is mainly caused by an error along the z-axis.
- The rotational error is more evenly distributed about all axes with less influence about the z-axis.

7.2.4 Applications for the Experimental Results

In the context of Roivis and for the metaio marker tracking in general, the data collected through this experiment has several important areas of application.

7.2.4.1 Guidelines for Marker Tracking Scenarios

First, guidelines for marker tracking scenarios can be derived based on the identified effects of the analysed influence factors. The experiment detected favourable as well as disadvantageous situations for marker tracking accuracy. When planning a marker tracking scenario, this information can be included to optimally design the layout of markers and camera, as well as the choice of markers (size) and camera (intrinsic parameters).

Viewing Angle To limit additional tracking errors through unfavourable viewing angles, camera and markers can be positioned keeping figure 7.6 in mind by avoiding front view shots.
Front views provide a slightly better detection of the z-translation. However, rotational errors increase over distance whereas translational errors stay constant. Therefore, it is more important to keep the rotational error as small as possible.

Marker Area in Pixels The identified effects of the marker area in pixels for the image size allow conclusions on the setup of markers and camera. If high accuracy is required, a high-resolution camera should be used. In addition, a reasonable marker size s can be calculated for a known maximum distance of camera to marker z_{max}.

$$s \approx \frac{s'_x \cdot z_{max}}{f_x} \approx \frac{s'_y \cdot z_{max}}{f_y} \tag{7.1}$$

$$f_x = \frac{res_x \cdot f}{w} \tag{7.2}$$

$$f_y = \frac{res_y \cdot f}{h} \tag{7.3}$$

with $s'_x = s'_y = \sqrt{40000}$[1] the edge length of the marker in the image in pixels and f_x, f_y the focal length in pixels, which can be determined based on camera focal length in mm f, camera resolution in pixels (res_x, res_y) and camera chip size in mm (w, h) (see figure 7.7).

---

[1] Threshold identified in section 7.2.3.1.

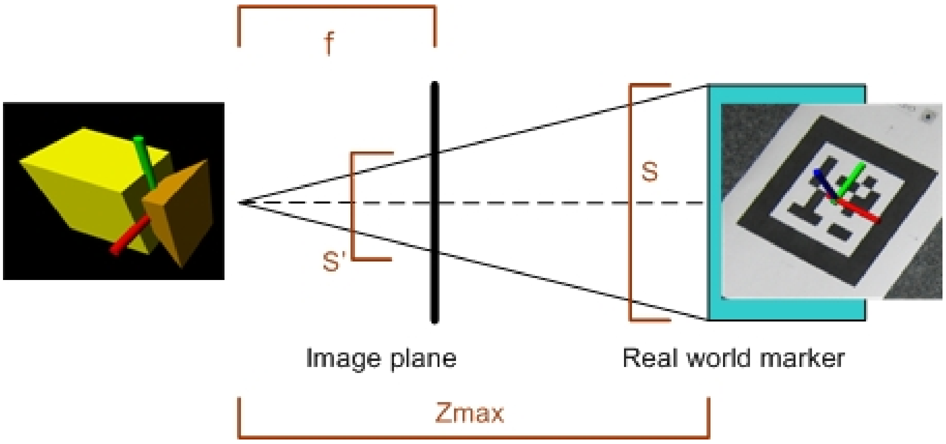


Figure 7.7: Determination of a Reasonable Marker Size

7.2.4.2 Quality Assurance

Another aspect is the possibility to perform quality assurance tests using the experimental approach described before. Any modification or update in the marker tracking algorithm can be evaluated against the previous version by means of translational and rotational error. Thus, the quality of the tracking result can be evaluated and modifications will only be brought into productive use, if they at least keep the standard of the previous version.
Figure 7.8 presents a comparison of two marker tracking algorithms. Subfigure (a) depicts the translational tracking error for the marker tracking implemented in the metaio Unifeye SDK 2.4, whereas subfigure (b) shows the same curve for data sets created based on the metaio Unifeye SDK 3.0.

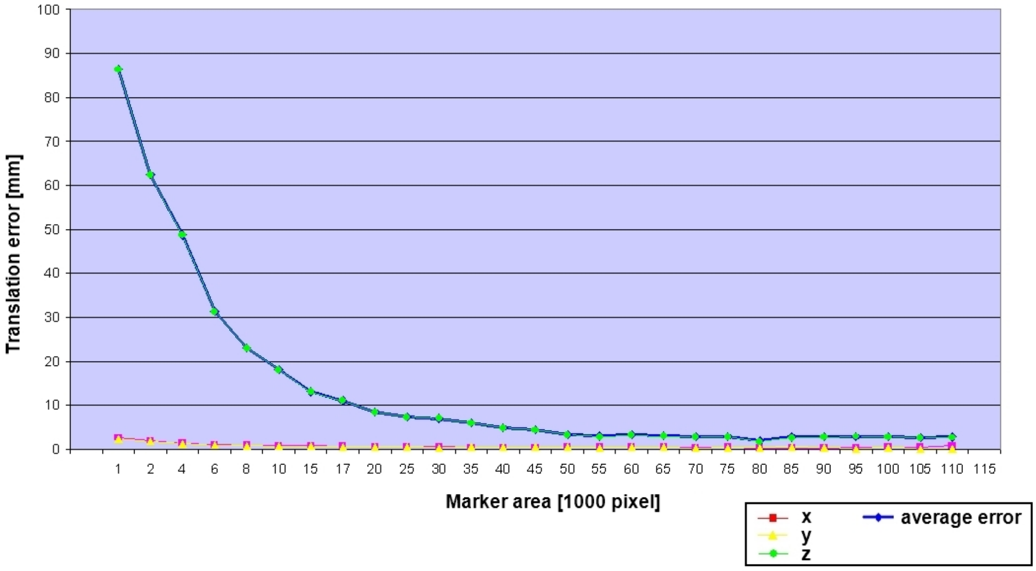
Naturally, given appropriate input information, similar tests for accuracy comparison can be performed with other marker tracking algorithms or tracking systems in general.

7.2.4.3 Tracking Accuracy Database for the Uncertainty Calculation

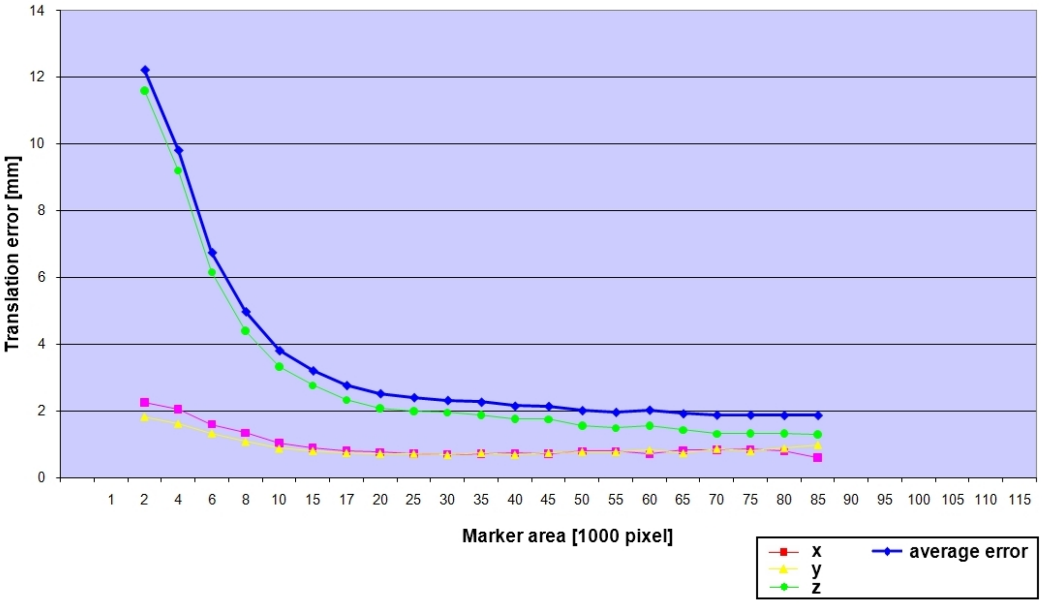
Finally, the main application of the results within Roivis is the tracking accuracy database for the uncertainty calculation, which was already presented in section 4.5.1. The data sets created for the tracking analysis are stored in a look up table using keys consisting of the influence factors $(MaiP, r_x, r_y)$. For error and uncertainty calculation, queries are performed on the look up table and data sets, which are representative for a given scene, are extracted and used to calculate a mean error and standard deviation for the marker tracking. This statistical information is then used as input data for the further propagation process.

7.3 Tracking Robustness Evaluation

In addition to the accuracy of the tracking system, robustness is another important criterion for tracking systems in general. Some basic studies have been performed to evaluate the robustness of the metaio marker tracking with respect to noise, illumination and partial occlusion. Full details can be found in [Ulbr 08].



(a) Translational Error for Unifeye SDK 2.4



(b) Translational Error for Unifeye SDK 3.0

Figure 7.8: Comparison of Different Version of a Marker Tracking Algorithm

In contrast to the accuracy evaluation approach above, these evaluations are based on a one-factor-at-a time pattern, which does not allow to identify dependencies between the influence factors. The results below show that the effects of the different influence factors are very consistent. Thus, the information gathered using on these simple experiments was considered as sufficient.

7.3.1 Noise

To analyse the effects of noise on the tracking, the ground truth tool was expanded with the functionality to add noise to the simulated image data. As the real camera noise is the result of several independent noise components (thermal noise, shot noise, quantification noise [Kida 03]), the combined noise influence can be approximated using a normal distribution.

Noise of different standard deviations has been created to evaluate the marker tracking. Due to the application of according filters and thresholds in a pre-processing step of the tracking, the noise did not influence the resulting tracking pose.

Figure 7.9 shows the translational error for Gaussian noise of different standard deviations (σ = 0, 5, 10 and 15). Camera poses were chosen randomly and the results are visualised according to marker area in pixels. All four curves show the same tendency and do not differ distinctly in values.

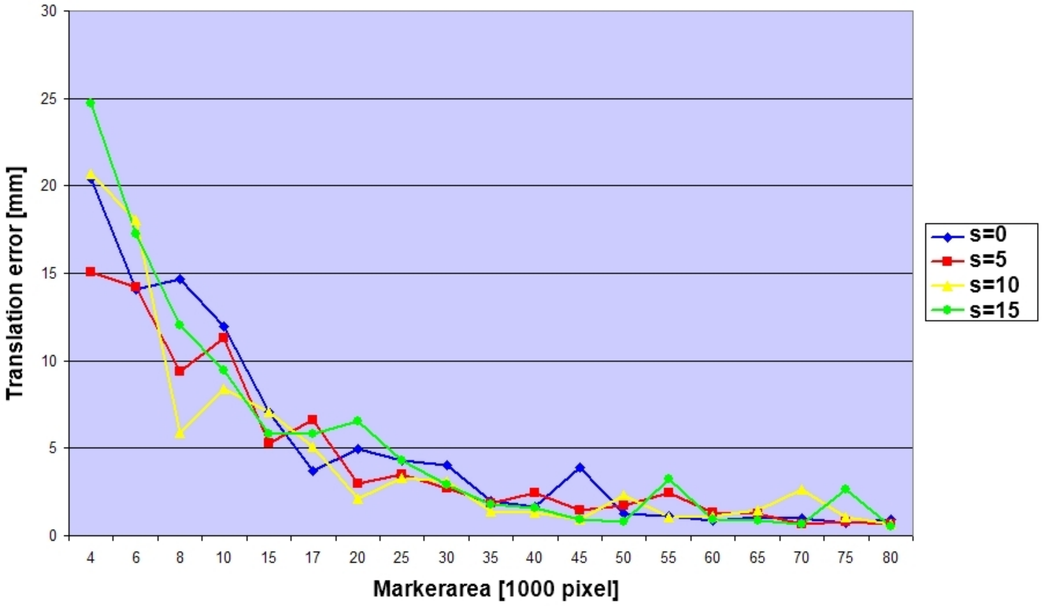


Figure 7.9: Translation Error for Different Noise Intensities

7.3.2 Illumination

For testing the effect of illumination, video sequences were created, where the illumination of the environment was continuously changed from dark to very bright and back. The tracking results for the video sequence were very successful, as the threshold algorithm implemented for the metaio marker tracking could cope very well with the different lighting conditions. Even when parts of the marker were illuminated and parts were still dark, the algorithm was able to detect the marker.

7.3.3 Partial Occlusion

Finally, partial occlusion is a factor that influences the outcome of marker tracking algorithms, as well as optical tracking systems in general. The metaio marker tracking currently does not support partial occlusion. To obtain a valid tracking pose, the full marker has to be visible in the tracking image. Fully visible in this case means that the black marker border must not be occluded at all. The inner data matrix pattern, which is required to distinguish different markers from each other implements an error correction. Therefore, parts of the pattern may be occluded or disturbed in some other way (e.g. dirt) and the marker will still be identified correctly. More details on the implementation of such error correcting matrix patterns for markers can be found in the work of Fiala [Fial 04].

7.4 Registration Evaluation

As mentioned before, the marker tracking lays the base for the creation of AR scenes in Roivis. However, this reference to the real world often does not suffice to position virtual objects correctly and an additional registration offset is needed. The registration approaches presented in chapter 5 provide process support for the determination of this additional offset. For the overall overlay accuracy, the reliability of the registration process is thus as important as the reliability of the tracking. In addition, the usability of the different registration approaches directly influence the acceptance of the overall system. Only when the user is able to achieve the desired goal with reasonable effort, the application will be used steadily.

This section presents the results of a comprehensive evaluation of the Roivis registration toolbox with respect to uncertainty and usability criteria, which is the first of its kind to the best of our knowledge. To achieve a comparable and valid evaluation of the different available approaches, all processes were applied to the same industrial example scenario: a test facility at Volkswagen (see figure 7.10).
In the following, this analysis is described in detail. For usability evaluation, expert reviews were performed to rate the required time and knowledge, as well as the complexity of the different registration processes. In addition, the necessary resources and their costs were documented. Finally, uncertainty was evaluated based on available information, such as direct calculations and estimations based on randomised sample data.
In the end, the discovered information is summarised to provide an important additional contribution for the Roivis registration toolbox: guidance for the choice of a registration method based on usability and uncertainty constraints.

7.4.1 Overview on the Setup

The test facility is a welding fixture with mechanical clamps, which retain a car underbody during robot spot welding. Performing factory planning tasks for this test facility requires the positioning of digital model data with respect to the model coordinate system, in this case the car coordinate system. As markers cannot be position in accordance with the car coordinate system, an additional registration step must be performed. To test and compare all available methods for this task, the following steps were performed:

- Registration based on a CMM: Registration of a marker to the model coordinate system using an external measurement tool, i.e. the FARO Platinum measurement arm,

Figure 7.10: Evaluation Environment for the Registration Approaches (Source: Volkswagen AG)

- Registration based on 3D-3D point correspondences using 6DOF support: Registration of a set of markers to the model coordinate system using 3D-3D point correspondences, which are determined through adapter markers and their corresponding digital CAD points and additional 6DOF registration of further markers in the scene,
- Registration based on 2D-3D point correspondences: Registration of digital model data to one specific image using 2D-3D point correspondences in image and model data,
- Manual registration: Registration of digital model data to one specific marker using manual pose adjustments and
- Registration using a CAD-based approach: Registration of digital model data to one specific marker by directly manipulating the CAD data.

The next sections explain each of these processes in more detail and outline the properties of each approach based on the previously listed criteria. As the tools and their means of functioning have already been presented in chapter 5, the description focuses on the basic steps required to compute registration information and prepare an AR planning scene.

7.4.2 Registration Based on a CMM

For registration based on a coordinate measurement machine, a FARO Platinum measurement arm with 3.7 meters working range was used in combination with the FARO measurement software [FARO 08].

7.4.2.1 Registration Process

To register a marker to the car coordinate system, the following steps were necessary:

Marker preparation and image acquisition First, the test facility had to prepared with a marker and a set of images was collected for the AR visualisation in Roivis.

Setup of the Measurement Arm Next, the FARO measurement arm had to be setup. The arm was fixed on a tripod and positioned with respect to the testing environment in such a way as to be able to reach all reference drill holes of the facility with the FARO tool tip. In addition, the tool tip was calibrated to be able to collect valid point measurements with the arm. Unfortunately, only a spherical tip was available which downgraded the accuracy of point measurements.
Given a calibrated tool tip, the measurement arm could be registered with respect to the car coordinate system. Point correspondences were collected to perform a transformation of the coordinate system based on 3D-3D correspondences. Three reference drill holes of the testing facility were measured (see figure 7.11(a)). Their corresponding point set in model coordinates was given through the reference point descriptions available right next to the drill holes. If no such coordinate plates had been available, the data would have had to be extracted from the company construction data base.
Using this set of 3D-3D correspondences of points in the current FARO coordinate system and the car coordinate system, the FARO measurement software computed the transformation between the two coordinate systems and set the car coordinate system as new origin coordinate system of the FARO measurement arm.

Determination of Marker Corner Measurements in the Car Coordinate System After the FARO arm was registered in the car coordinate system, the registration of the marker to the car coordinate system could be performed. To do this, the four corners of the marker were measured with the FARO arm (see figure 7.11(b)).

(a) Drill Hole Measurement with the FARO Arm (b) Marker Corner Measurement with the FARO Arm

Figure 7.11: Registration Using a Coordinate Measurement Machine (Source: Volkwagen AG)

Calculation of the Marker Offset Using the Roivis CMM Registration Tool Based on these measurements, the transformation from the marker to the car coordinate system could be calculated. The measured corner points were entered in the Roivis CMM registration tool and the calculation was performed. The resulting offset was copied to clipboard and used in the marker configuration tool to create a tracking configuration for the marker including the computed registration offset.

Creation of a Roivis Scene Finally, a Roivis scene was created based on the results of the calculation. An image of the registered marker was loaded together with a corresponding camera calibration. Then, the tracking configuration file was loaded in Roivis, as well as the digital model of the testing facility. After scaling the model with factor 1000 (due to different units in Roivis (mm) and the export system (m)), the virtual data was correctly overlaid with its real counterpart.

7.4.2.2 Aspects of Uncertainty

For the FARO registration process, the Roivis CMM registration tool could compute an uncertainty information for the concrete measurement scenario. The FARO arm has a positional standard deviation of 0.1 mm. This information was entered in the corresponding input field of the Roivis tool. For the concrete registration example, with a registration marker with an edge size of 100 mm, the result values were stated as 4.0 mm positional and 0.2° rotational uncertainty. The mathematical background for this computation is explained in section 5.2.

7.4.2.3 Aspects of Usability

Resource Requirements and Costs For the registration process based on a coordinate measurement machine, the measurement hardware and software needs to be available as well as an expert user to perform the first calibration and registration operations. The FARO arm is a powerful measurement tool. In addition to the costs for the hardware and software, a training for the user is required, which sums up to a price of approximately € 50,000 to € 60,000. Although the tool is very expensive, there are various other areas of application for such a measurement machine. Therefore, the system might already be available in the factory and can thus be easily used for this AR registration task.

Time Effort and Process Complexity Table 7.3 sums up the time effort and complexity for the single steps of the registration process. The complexity is measured as low for general AR-related tasks and high for expert tasks.

Step	Time Effort	Complexity
Marker and images	2 min	low
Setup	17.5 min	high
Marker corner measurement	5 min	high
Marker offset calculation	3 min	low
Scene creation	2 min	low

Table 7.3: Time and Complexity for the CMM Registration Process

General Aspects The result of the CMM registration process is a transformation offset for the marker coordinate system, which was registered. Thus, the result can only be used for views on the testing environment that show the registered marker. To include other marker coordinate systems, the 6DOF registration process has to be applied in addition to this method.

Besides this limitation, the approach has the great advantage of automatically providing an uncertainty information for the result of the offset computation. The uncertainty values can be directly transferred to the Accuracy Measurement tool for performing calculations there.

7.4.3 Registration Based on 3D-3D Correspondences

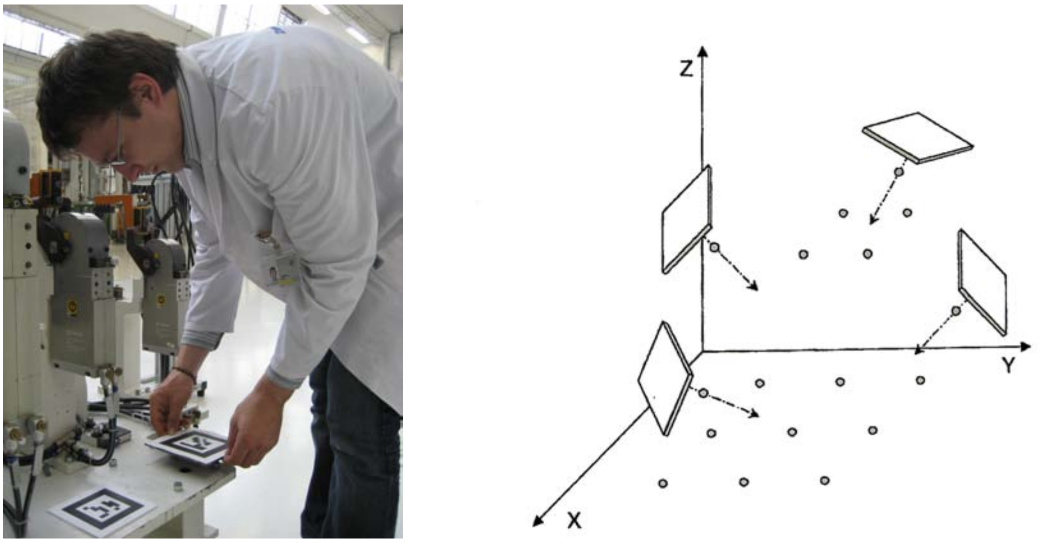
For the marker-based registration approach, marker adapters similar to the ones shown in figure 5.7 were used. Four such markers were attached to the four reference drill holes available on the testing facility.

7.4.3.1 Registration Process

To determine the registration information, the following steps were performed:

Creation of Adapter Markers Before the registration process could be started, adapter markers had to be manufactured. However, this is an off-line procedure, which only needs to be done once, as the adapter markers can be reused. The adapters were manufactured to fit the drill hole specifications as well as a reasonable marker size. In the example here, markers of 100 mm size were used.

Positioning of the Adapter Markers and Image Acquisition In the beginning, the adapter markers were attached to the available drill holes (see figure 7.12(a)). In addition, several other markers for the inter-marker calibration step were placed all over the testing environment. Then, a set of images was acquired from different viewing angles and different distances in order to cover the whole testing environment.



(a) Positioning of Adapter Markers (Source: Volkswagen AG)

(b) Example Configuration for Image Acquisition [Luhm 05]

Figure 7.12: Registration Using 3D-3D Correspondences

The connection of this approach to photogrammetric measuring (see section 5.2.7), can provide helpful guidance here. The measurement points (in this case the markers) should be arranged in a 3-dimensional way. Furthermore, recommendations for camera perspectives can be taken from photogrammetry literature. Figure 7.12 (b) depicts an example configuration for four camera positions.

Performing the 3D-3D Registration To perform the registration process with the 3D-3D registration tool, the needed input data for the calibration tool was prepared. A tracking data file was created, which configured all available markers in the scene including the offsets from the adapter markers to the drill hole reference points. These offsets were known based on the manufacturing specification of the adapters and describe the distance from the marker plane to the actual location of the reference point. In the given case, a negative z-translation of 25 mm was required. Furthermore, a CAD text file was created, holding the drill hole reference points in car coordinates.

Based on this data, the calibration could be started. Using the collected image data, corresponding calibration, tracking configuration and CAD data, the tool optimised the transformations between all available marker coordinate systems over all images and referenced all markers to the car coordinate system based on the given 3D-3D correspondences. The result was given as another tracking configuration file.

Creation of a Roivis Scene Again, a Roivis scene could be created based on image, calibration, tracking and virtual model data.

7.4.3.2 Aspects of Uncertainty

For this registration method, uncertainty information could not be calculated as easily as for the CMM-based case. To get an idea on the quality of the result, two different approaches were analysed. First, a quality statement could be computed by assuming some uncertainty of the input data. Then, the resulting pose uncertainty could be estimated based on a set of noisy input samples. Second, the optimisation process performed during the inter-marker calibration provided some feedback on the quality of the result. These residuals could also be analysed.

Estimated Pose Uncertainty from Noisy Input Samples The pose estimation was based on point correspondences for the four reference drill holes. The marker translation values were randomised based on the uncertainty information available from the marker tracking evaluation (see section 7.2). The 3D model data, as well as the adapters were assumed to be perfect. In the latter case the accurate manufacturing process of the adapters and the standardised drill holes assure that the adapters can be tightened down with negligible error.

For the randomisation process, the actual tracking values for an example image were used as input information. Gaussian noise was added to the samples, where the standard deviation for each of the reference points was extracted from the available marker tracking uncertainty graphs. A set of 20 samples was created. Figure 7.13 presents the resulting pose uncertainty based on the noisy input measurements.

Optimisation Error During the inter-marker calibration, two optimisation processes were performed. First, the offsets between all markers were optimised based on the reprojection error for all given images. And second, the 3D-3D registration computation was performed through an optimisation algorithm. In both cases, the optimisation algorithm did not only return the result values, but also an error vector, which could be used for a quality statement.

For the optimisation of the inter-marker transformations, the resulting pixel reprojection errors are

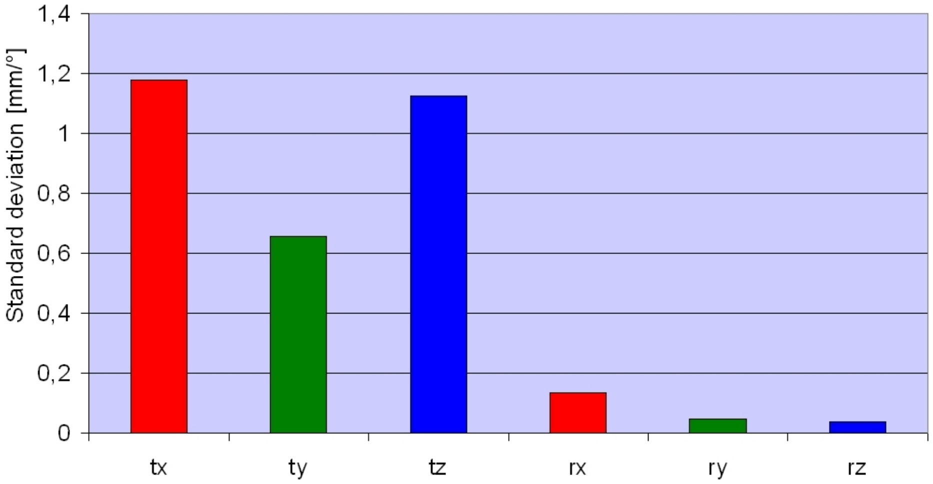


Figure 7.13: Estimated Uncertainty for the 3D-3D Registration Process

visualised in figure 7.14. Each curve represent the residual error for the four reference points after optimisation for one image of the set. As the diagram shows, the error stayed in a range of 0-1.5 pixels and only the distant COS4 was optimised slightly worse.

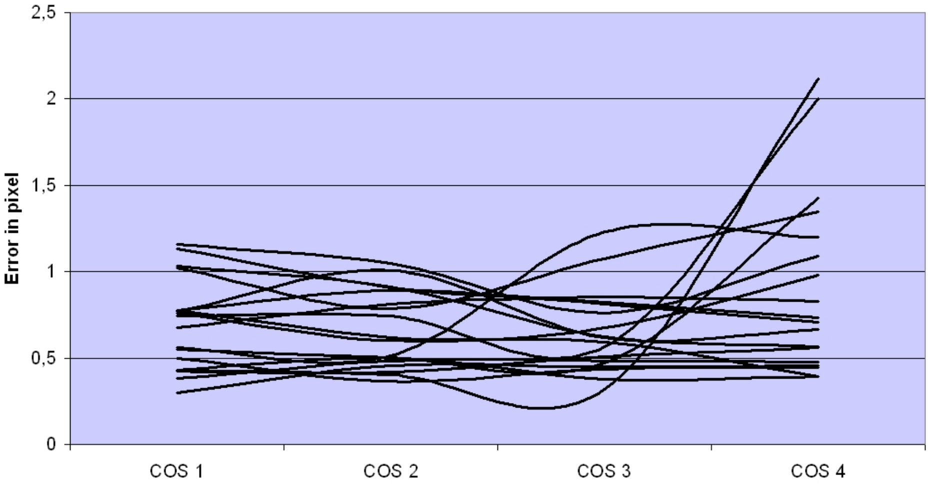


Figure 7.14: Residual Gap After Inter-Marker Optimisation

For the 3D-3D point optimisation process, the residual error for the four reference points was very small with an average of 0.002 mm.

7.4.3.3 Aspects of Usability

Resource Requirements and Costs The 3D-3D registration approach is based on Roivis registration software. The main external resource needed are the adapters for the markers. Such adapters have to be manufactured and can be estimated with costs of approximately €1,600 for a set.

Time Effort and Complexity As for the previous section, time and complexity are summarised in table 7.4. Complexity of the steps is rated as low for easy tasks and medium for tasks, which require some experience. Tasks of the latter kind are the marker placement and the acquisition of image data. Here, the views needed for evaluation, accuracy aspects for marker tracking, as well as favourable photogrammetric perspectives should be considered when collecting data.

Step	Time Effort	Complexity
Adapter marker creation	offline	–
Marker positioning (4 markers)	4 min	medium
Image data acquisition (≈ 20)	10 min	medium
Inter marker calibration		
- input tracking data	5 min	low
- input cad data	2 min	low
- calibration execution	4 min	low
Scene creation	2 min	low

Table 7.4: Time and Complexity for the 3D-3D Registration Process

General Aspects The result of the process is a tracking configuration file, which provides registration offsets for all available markers, optimised for the given image data set. Different from the CMM-based approach, all available markers are now registered to the car coordinate system and can be used for visualisation. This offers more flexibility in terms of viewing points.
A disadvantage in comparison to the CMM-based approach is the missing information on the accuracy of the result. However, some quality information can be stated based on the results of the optimisation process.

7.4.4 Registration Based on 2D-3D Correspondences

Next, the registration process through 2D-3D point correspondences was evaluated. As presented in section 5.2, the point correspondences are collected through mouse clicks in 2D image and 3D virtual model data. For the given example here, the referencing drill holes were used. Thereby, only the 2D points were selected via clicks, as the corresponding 3D data was directly available through the coordinate plates.

7.4.4.1 Registration Process

Only a few steps were needed for the registration process:

Image Acquisition No markers had to be positioned here and only a single image had to be acquired for the registration.

Creation of a Roivis Scene To prepare for the correspondence collection, a Roivis scene was created. The image for which the offset should be calculated was loaded together with a calibration file. No tracking configuration was required as the correspondences were chosen manually.

Determination of the Offset Using the Roivis 2D-3D Registration Tool Given the Roivis AR scene, the 2D locations of the drill holes in the image were selected via mouse clicks and the corresponding 3D car coordinates were entered directly in the respective fields of the 2D-3D registration tool. Four correspondences for the four drill holes were collected to calculate the registration offset. The result was a transformation from the camera coordinate system directly to the car coordinate system. The pose was exported to a tracking configuration file, which was then loaded automatically.

Updating the Roivis Scene After the new tracking configuration was available, the virtual model data could be loaded.

7.4.4.2 Aspects of Uncertainty

As for the 3D-3D case, uncertainty information could not be calculated directly for this approach. Nevertheless, some estimation could be done based on assumptions on the uncertainty of the input clicks.

User Clicking Study The quality of clicks on image data was analysed through a small user study with 9 users. They were asked to select a specific point in different images, a marker corner point, based on the same conditions as available within Roivis (zoom only up to an image size of 2000x2000 pixels due to renderer limitations). The following images were used:

- Image 1: camera image with resolution 640x480
- Image 2: camera image with resolution 3008x2000
- Image 3: simulated image with resolution 3008x2000

The measured clicks of the test users were compared with the corner detection of the metaio Unifeye SDK marker tracking for image 1 and 2 and with the true corner values for the simulated image 3. The resulting mean errors and standard deviations are visualised in figure 7.15.

Pose Uncertainty Estimation Based on this click error, the pose uncertainty could be estimated. As for the 3D-3D case noisy data samples were generated by applying a Gaussian error to the measured values. Again, only the 2D pixel points were randomised and the 3D data was assumed to be perfect. Figure 7.16 depicts the resulting uncertainty for the 2D-3D registration pose.

However, this estimation has to be handled carefully. The input clicking accuracy may not be representative for the application scenario. Depending on the image selected for performing the clicks, the drill holes are visible better or worse. A marker corner is the intersection of two edges and can thus be reasonably located, even in case of noise. In contrast, a drill hole is a black circle in an image whose centre is not necessarily as easy to identify. Furthermore, due to larger distances a click error of one pixel has a larger impact on the final pose error than for a closer shot.

7.4.4.3 Aspects of Usability

Resource Requirements and Costs This approach does not require any special resources and causes no additional costs. Roivis provides all necessary tools.

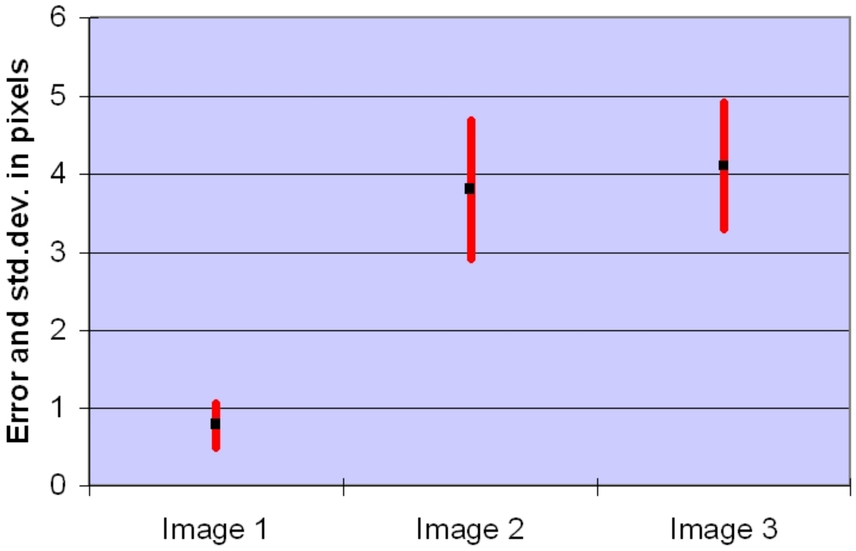


Figure 7.15: Error and Standard Deviation for the User Click Test

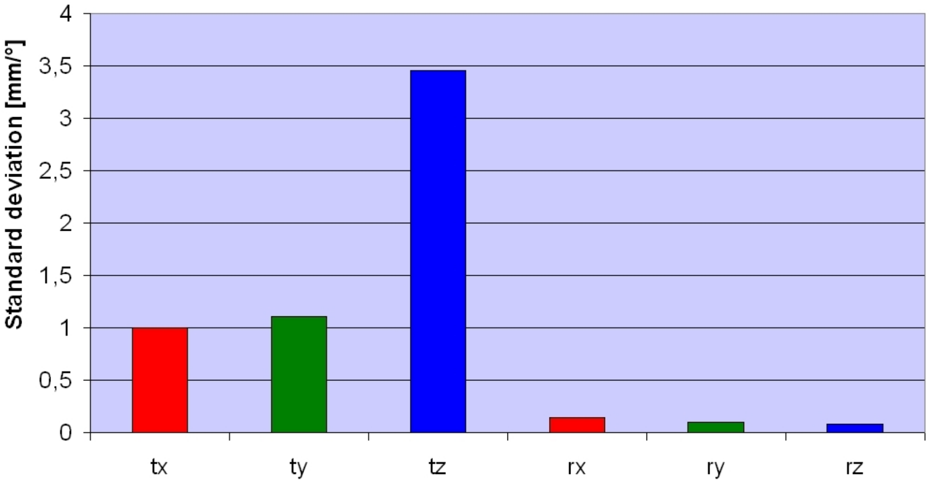


Figure 7.16: Estimated Uncertainty for 2D-3D Registration

Time Effort and Complexity Time effort and complexity are listed in table 7.5. The complexity is low throughout the process as none of the steps requires special knowledge.

Step	Time Effort	Complexity
Image acquisition	1 min	low
Scene creation	2 min	low
Offset determination (4 correspondences)	4.5 min	low
Scene update	1 min	low

Table 7.5: Time and Complexity for the 2D-3D Registration Process

General Aspects The process of 2D-3D registration is very fast. However, the result cannot compete with other approaches in terms of accuracy. Using the car coordinates directly improves the quality of the 3D input data, but the 2D clicking accuracy still depends on the carefulness of the user. In addition, the resulting information can only be used for the specific image. To transfer the knowledge to other images, additional markers in the image could be registered to the car coordinate system based on the 6DOF registration approach.

The main advantage of the method is the fact that it does not require any markers. In case an AR scene shall be created based on image data that does not provide markers for tracking or only shows markers, which are not registered to the car coordinate system, the simple click approach can provide a first initialisation of the transformation. Improvements can then be done using manual adjustments.

7.4.5 Registration Using a Manual Approach

The manual approach for registration relies on the object manipulation methods available in Roivis. The user positions the model correctly with respect to a chosen coordinate system using the visual feedback provided by Roivis.

The manual approach is only reasonable, if some prerequisites are given. An available coordinate system in the scene should be usable for manual adjustment. This is for instance given, if a marker plane is parallel to the one of the coordinate system planes of the model coordinate system. In this case, the rotational offset is limited in the sense that for two axes only simple 90° or 180° rotations are required.

7.4.5.1 Registration Process

For manual determination of a registration offset the following steps were performed during evaluation:

Marker preparation and image acquisition The first important step was the selection of a marker location based on the idea described above. The chosen location should keep the offset determination as easy as possible.

For the given scenario, a marker was placed on the ground plane of the test facility and images were acquired accordingly.

Creation of a Roivis Scene Afterwards, a Roivis scene could be created. Image data, camera calibration data and a tracking configuration file, which described the positioned marker were loaded. Then, the 3D model data was loaded and bound to the chosen marker coordinate system.

Rough Positioning Based on the created scene, a rough positioning process could be started. The effort for this positioning step depends on the discrepancy between marker and model coordinate system. For the concrete application case, first, the digital model had to be scaled by factor 1000. Then, the model was rotated around the z-axis by 90°. That way, the rotational offset was already determined approximately.

For the translational offset, the z-distance between marker plane and model plane could be estimated using a clipping plane. Figure 7.17 shows the use of the plane. The clipping plane was positioned on the marker and set to clip away the parts of the model, which lay below the marker plane. That way, the z-translation could be estimated such that the ground plane of the digital model and the marker plane coincided.

The missing translational offsets for x- and y-direction could now be determined through visual comparison of the real test facility in the image and the digital model.

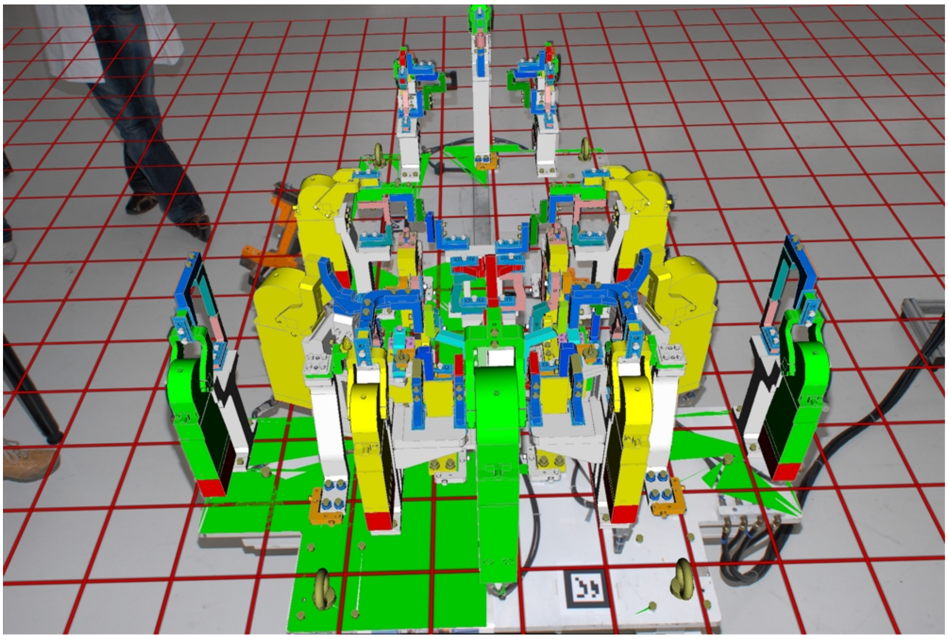


Figure 7.17: Manual Adjustment Using a Clipping Plane (Source: Volkswagen AG)

Fine Tuning Given this rough offset, there was unlimited possibility for fine tuning. For the rough translation and rotation values, increments of 10 mm and 5° were used. These could be decreased to values of 1 mm and 0.1°.

To be able to determine a reasonable offset, the test facility was regarded from different viewing angles. Based on different images, the single offsets values could be adapted such that the virtual model fitted better and better its real world counterpart.

However, due to limitations in tracking accuracy, fitting the model best to one image could also result in worse overlays in another image.

7.4.5.2 Aspects of Uncertainty

With respect to uncertainty, no valid statement can be given. The resulting offset is depending partly on the marker tracking quality but more importantly on the carefulness with which the user performs the manual adjustment. The choice of translation and rotation values can be done with sub-millimetre and sub-degree accuracy, but the final parametrisation depends on the user.

For the evaluation, the registration started with the selection of a ground plane, which is assumed to be parallel to one model coordinate system plane. However, the available reference points indicated a slight rotation of the test facility ground plane. It was negligible here ($\approx 0.001^\circ$), but it might be of importance in other cases.

In addition, the real test facility was used as a reference, although it was unknown how well the virtual model reflects the real facility.

7.4.5.3 Aspects of Usability

Resource Requirements and Costs This approach also does not need any special resources and causes no additional costs. Only the general scene creation and manipulation tools of Roivis are used.

Time Effort and Complexity Time effort and complexity are listed in table 7.6. The complexity is low for scene creation and rough adjustment. The choice of marker and the fine tuning require some experience in this area.

Step	Time Effort	Complexity
Marker and images	2 min	medium
Scene creation	1 min	low
Rough adjustment	3 min	low
Fine tuning	7 min	medium

Table 7.6: Time and Complexity for the Manual Registration Process

General Aspects The main advantage of this method is that it can be performed by simply using the basic manipulation tools of Roivis. No additional measurements need to be done. A rough offset can be determined very fast. After that, improvements can be performed at will to reach the desired degree of accuracy.

However, this idea of improvements at will can also be seen as the big disadvantage. No statement about the reliability of the result is possible. As mentioned above, the variance between real and virtual model can be a major problem and can lead to wrong results.

In general, the method is limited in application, as it is bound to the availability of a suitable marker location.

7.4.6 Registration Using a CAD-Based Approach

For the CAD-based approach, the model coordinate system was moved to a location, which allowed to easily position a marker target in the real environment. The registration effort was thus transferred to CAD software.

7.4.6.1 Registration Process

For the test facility, the following steps were performed:

Marker Preparation and Image Acquisition First, a favourable location for positioning the marker had to be identified. In the concrete case, a drill hole was chosen. As marker adapters were already available, the marker coordinate system could be linked to the drill hole location based on the already known adapter offset. After fixing the adapter marker to the drill hole, images were acquired.

Model Manipulation Next, the digital model data was manipulated. The model coordinate system was moved from its original position to the specified drill hole. This process was eased by the fact that the drill hole location was known exactly in the car coordinate system. Thus, the values for coordinate system translation were available directly.

Roivis Scene Creation Based on the modified digital model data, a Roivis scene was created. Image data, camera calibration and marker configuration for the adapter marker were loaded. The digital model was bound to the drill hole marker. Due to the model manipulation, model and marker coordinate system already shared the same origin. In contrast, the marker coordinate system axes and the model coordinate system axes were not yet in accordance. Thus, some additional rotational adjustments were needed for correct overlay. The final registration offset could then be determined as a combination of the CAD translation and the rotational adjustments in Roivis.

7.4.6.2 Aspects of Uncertainty

For the CAD-based registration, the uncertainty of the model manipulation in digital space could be neglected. As the translation values were known, the origin was moved correctly to the drill hole centre. The pose uncertainty for the registration offset was thus depending on the marker tracking uncertainty, as well as the marker adapter positioning.

7.4.6.3 Aspects of Usability

Resource Requirements and Costs For the CAD-based approach, a marker adapter was needed. In addition, CAD software was applied by an expert user who, is able to perform the task of coordinate system movement. The price of CAD software can vary from freeware such as Blender [Blen 08] to expensive design tools (e.g. CATIA [Dass 08], FactoryCAD [Siem 07b]). The software used for the concrete case has a license price of around €1,000.
The involvement of CAD software is listed here, as it is explicitly required for the registration process. Although all factory planning tasks require CAD data for virtual overlay, the users of Roivis do not generally have to be experienced with CAD software, but only use the model data as it is provided by the design database or by the responsible people from the design department.

Time Effort and Complexity Time effort and complexity are listed in table 7.7. The complexity is low for data acquisition and scene creation, whereas the CAD task requires expert knowledge.

Step	Time Effort	Complexity
Adapter marker creation	offline	–
Marker and images	2 min	low
CAD manipulation	6 min	high
Scene creation	2 min	low

Table 7.7: Time and Complexity for the CAD Registration Process

General Aspects The result of the process registered the adapter marker to the model coordinate system. Disadvantageous in this case was the use of only one marker for registration. That way, rotational variability around the z-axis of the marker coordinate system stayed, which had to be compensated by manual adjustments.

Beneficial in this case would be the application of marker adapters, which fix the marker in all six dimensions with respect to the test facility (e.g. by using an adapter for two drill holes similar to the application 6.3).

7.4.7 Overall Comparison

For an overall comparison of the different approaches, the information collected for usability is summarised and the registration offsets for all approaches are compared with each other.

7.4.7.1 Usability Overview

The properties of the different approaches are shown in table 7.8. The overview lists costs, resources and result information as stated above and the summarised time effort and complexity. The CMM and 3D-3D marker based approach are the most time consuming methods and require extra resources. In contrast, the manual and the 2D-3D point based approach are cheap and fast in execution. Finally, the CAD based approach is fast, but rather complex and due to the requirement of an adapter and CAD software also costly.

Approach	Time Effort	Complexity	Costs	Resources	Result
2D-3D	$\approx$ 10 min	low	–	–	1 pose
3D-3D CMM	$\approx$ 30 min	medium-high	€ 50,000	CMM	1 pose
3D-3D marker	$\approx$ 30 min	medium	€1,600	adapters	>1 pose
manual	$\approx$ 15 min	low-medium	–	–	1 pose
CAD	$\approx$ 10 min	medium-high	€1,500	CAD SW, adapter	1 pose

Table 7.8: Usability Overview

7.4.7.2 Uncertainty Overview

For an uncertainty evaluation, three different approaches were used.

Comparison of the Offset Values First, the same marker offset was computed through each approach to allow for a statistical evaluation of the measured results. Figure 7.18 presents an overview. The standard deviation of the different results for one specific marker offset is visualised. It is important to note that for the 2D-3D approach, an additional 6DOF registration step had to be performed to compute the specific marker offset.

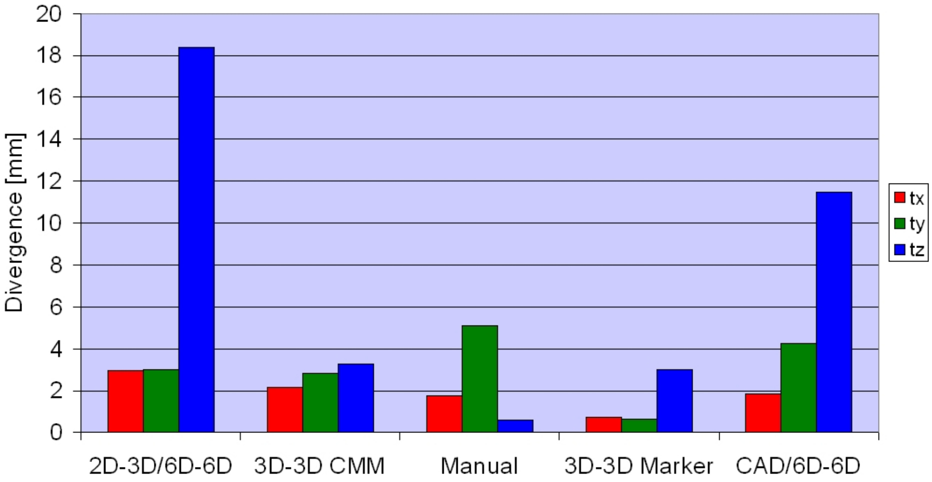


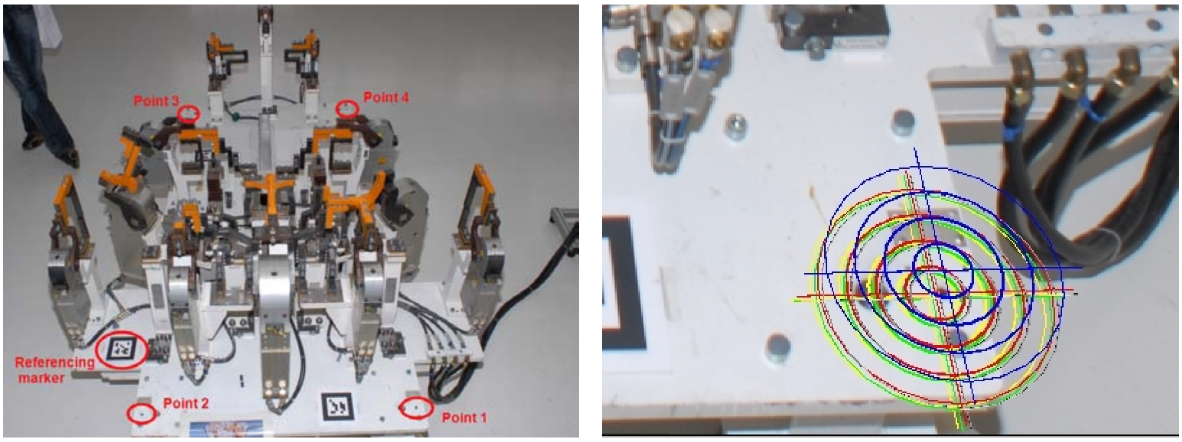
Figure 7.18: Divergence of the Registration Results from the Measured Mean (Translation Only)

The direct comparison shows the closeness of the CMM, the manual and the 3D-3D marker-based approach. The CMM based approach was likely to be the most accurate approach, but here it had to suffer from an inappropriate tool tip and a rather small registration area with a marker size of only 100 × 100 mm. The large divergence for the CAD based method can be derived from the applied marker adapter. The adapter did only fix the translational offset. Thus, small rotational errors led to a translational discrepancy. Finally, the click-based approach shows the largest divergence from the mean, clearly caused by the uncertainty of the user clicks in the image.

Comparison of the Visual Overlay As a second criterion for comparison, the virtual overlays of the different approaches were compared to each other. Line crosses for the four referencing drill holes were superimposed onto real image data (see figure 7.19). The discrepancies indicate the quality of the different approaches. The following colour coding is used:

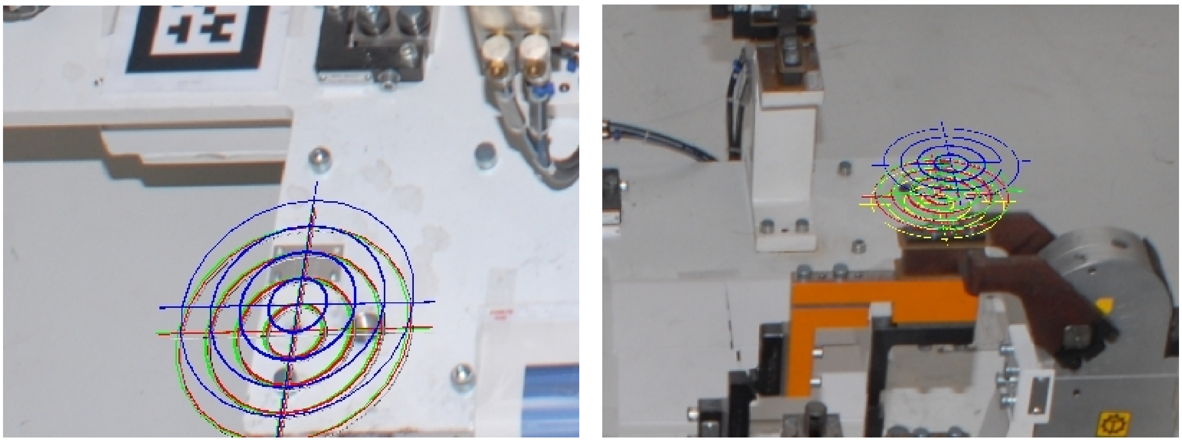
- Blue: 2D-3D approach,
- Green: 3D-3D CMM-based approach,
- Red: 3D-3D marker-based approach,
- Silver: manual approach and
- Yellow: CAD-based.

The visual comparison is in accordance with the results of the direct offset comparison. The CMM (green), the manual (silver) and the 3D-3D marker-based (red) approach provide the best overlay. The large deviation of the 2D-3D approach (blue) is visible in all images. The divergence of the CAD based approach (yellow) can be seen well for the distant drill hole in figure 7.19 (d).



(a) Overview on the Location of Relevant Points

(b) Overlay for Drill Hole 1 (Point 1)



(c) Overlay for Drill Hole 2 (Point 2)

(d) Overlay for Drill Hole 4 (Point 4)

Figure 7.19: Visual Comparison of the Different Registration Results (Source: Volkswagen AG)

Comparison of the Estimated Uncertainty Values Finally, the pose uncertainty estimation performed for the different approaches could be used as a third mean of comparison. Table 7.9 lists the results. All standard deviation values represent a confidence interval of approximately 95%, which corresponds to a coverage factor $k_p = 2$ (see also section 4.1) .

Approach	Translation [mm]	Rotation [°]
2D-3D	$(2.0, 2.0, 7.0)$	$(0.2, 0.2, 0.2)$
$3D_{CMM}$	$(1.9, 2.4, 1.8)$	$(0.3, 0.3, 0.1)$
$3D_{Marker}$	$(2.4, 1.2, 2.2)$	$(0.2, 0.2, 0.2)$
Manual	–	–
CAD	$(1.4, 1.4, 3.4)$	$(0.1, 0.06, 0.06)$

Table 7.9: Pose Uncertainty Overview

The indicated results can only be of limited use. For the CMM-based approach a serviceable uncertainty could be calculated. In contrast, all other values are based on assumptions. Thereby, not all relevant influencing factors were considered. For the 3D-3D marker-based approach and for the CAD based approach the uncertainty of the applied marker adapters was not included, as it is unknown. Furthermore, the click based 2D-3D approach relies on the quality of the input data provided by the user. The diligence with which the point correspondences are selected can hardly be generalised for arbitrary scenarios.

7.4.7.3 Guidelines for Use

Based on the overall evaluation, some guidelines for general use of the registration toolbox for AR-based factory planning can be derived. Most approaches can compete well with each other and depending on the importance of the presented criteria, different methods are favourable. The user can thus prioritise with respect to uncertainty, time, costs, output information, resources etc.

Usable Methods With respect to usability, the simple approaches, which do not require any additional HW or SW are rated best. No expert knowledge is needed and the registration process can be performed very quickly. However, the 2D-3D approach is only valid for the given image and the manual approach puts some constraints on the marker positioning process and requires consistency between the real world and the digital data, which often is not the case. Furthermore, both approaches cannot guarantee good accuracy.
Thus, they can be used for rough registration, but should be avoided when other methods are applicable.

Accurate Methods The CMM and the 3D-3D marker-based approach provide very accurate results. The CAD method can be of similar quality when used in combination with an adapter that fixes the marker in all dimensions (see also 6.6).
The CMM approach has the advantage of providing a concrete uncertainty statement with the registration result, but requires expensive hardware and software. The 3D-3D marker-based approach allows referencing multiple markers to the model coordinate system using bundle adjustment. Given adequate input data (i.e. photogrammetry oriented marker positioning and image acquisition), the

result is of very good quality. However, both approaches are rather time consuming. Finally, the CAD method offers the advantage of reduced error propagation paths through elimination of the registration transformation, but as for the CMM approach, expert tools are required to perform the registration.

As mentioned in chapter 5, the hybrid approaches of 3D-3D marker-based registration with 6DOF support and adapter-based registration in general have emerged as very beneficial in the past. Especially, the former method is estimated to hold great potential. It is easy to use and provides accurate results. However, execution times still need to be reduced. Therefore, according improvements of the existing tools are planned by using more application specific software and hardware.

7.5 Roivis Acceptance and Productivity

After having presented the Roivis system in all its detail, having seen concrete example applications from industry and having looked at various evaluations of accuracy and usability aspects, it is time to return to the original goal stated at the beginning of this thesis. This work aimed to present the path of exploration, development and testing on the way to a productive industrial AR application for factory planning. In order to evaluate the current state of Roivis, this section first recapitulates and sums up the criteria for productivity and success presented in section 7.1. Then, some facts about Roivis and its use so far are presented. Finally, based on this information, Roivis is evaluated for productivity and its potential as a "killer application".

7.5.1 Criteria for Productivity and Success

Section 7.1 introduced the requirements stated by Navab and Regenbrecht for success and productivity of industrial AR applications. Both agree that a productive system has to be robust and reliable, well-designed and user-friendly, frequently applied and profitable. Furthermore, to really become a killer application, the application has to convince a large number of customers and be better than traditional approaches.

7.5.2 Roivis: Facts and Figures

Roivis is the result of an iterative process and has been expanded in functionality step by step (see section 3.1). The product Roivis is available for several years now. The first official version was released in Mai 2006. In the same year, the idea of an intuitive interface for factory planning by means of AR technology also convinced the jury of the innovation award ”Sachen machen”. In December 2006, Roivis won the Dassault Systèmes innovation award.

To analyse the sales figures for Roivis, a differentiation is necessary as there are two ways of selling AR-based factory planning with Roivis:

The Software Roivis On the one hand, the software Roivis can be sold. This includes a software package for the Unifeye SDK and the Roivis graphical user interface, as well as a Nikon digital photo camera and a corresponding Extended Sextant calibration. The customer is fully equipped with hardware and software to perform AR-based factory planning. Training sessions are offered based on concrete industrial scenarios to make the user familiar with the detailed process of use.

The Service Roivis On the other hand, the service Roivis can be sold. Here, the task of factory planning based on Roivis is executed by staff from metaio. They acquire image data in the shop floor, they perform the evaluation with Roivis and prepare the results for presentation to the customer. The customer has to define the specific locations for evaluation, describe the concrete problem and provide the required digital data for planning.

At current stage (Mai 2008), both the software and the service Roivis are approximately equal in sales volume. Both have been sold equally often for about the same average price[2]. However, a big difference is given in the number of customers. The service product Roivis has been sold to ten different customers. In contrast, the software product Roivis has only been sold to two different customers and one of them is the Volkswagen Group, cooperation partner in the development of Roivis.

7.5.3 Productivity of Roivis

To analyse Roivis in terms of productivity, the properties of table 7.1 are regarded, both for the Roivis software product, as well as for the Roivis service product.

7.5.3.1 Roivis Software Product

With respect to the degree of maturity for the software product Roivis, the following situation is given.

Addresses Real Users Roivis as a system addresses real users. It is intended for unknown users in the field of factory planning, which do not necessarily have a background in Augmented Reality.

Well-Designed and Documented The user interface has been designed keeping usability issues in mind [Purs 06]. The implementation includes multiple languages (currently German and English are supported) and provides a detailed documentation both of the graphical user interface of Roivis, as well as the underlying AR system Unifeye SDK.

Integrated into Existing Data Chains An integration of Roivis into existing data chains is currently not realised. Roivis requires digital image data of the factory with registered markers. Furthermore, corresponding 3D model data in VRML 97 format is required. This format can be exported by most CAD tools. Thus, for data acquisition, the shop floor needs to be prepared with markers, which have to be registered accordingly and a model export step is needed to have the digital data in correct format.
The output information provided by the system is given in terms of visual feedback through AR overlays as well as measurement results. Based on the results, decisions on planning tasks are made, which do not require subsequent data transfer.

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[2] Concrete sales figures are known, but cannot be published here.

Robust and Reliable Robustness and reliability have been of great importance during the development phase. Marker-based tracking has been chosen to provide a stable and accurate approach for AR-based factory planning. Furthermore, a quality statement is available for the visualised AR overlay.

Applied in the Field Roivis has been frequently applied with real-world data, mainly from automotive industry.

Profitable with a Market The problems of factory planning and the helpfulness of AR in this case have been presented before. There is a market for AR-based factory planning. However, to really have a productive system, the number of customers still has to increase.

Uses Standards and Fits Technological Environment The main standard integrated in Roivis is the applied digital model format, VRML 97. Furthermore, Roivis is intended for use with standard hardware and software components (see section 3.3).

Targeted to User Acceptance Roivis is targeted to real users. Through the close cooperation with Volkswagen Group Research, many relevant requirements for acceptance by planners could be integrated in the development of Roivis. However, the aim to create a software, which is applicable to various different planning problems can limit the acceptance of the system by end users from planning departments. They want to have an application, which specifically meets their needs and is tailored to their concrete planning problems.

7.5.3.2 Roivis Service Product

When regarding the service product Roivis, many of the properties above are no longer of importance. The system is used by experienced users only and the customers receive the final evaluation results. Thus, mainly the aspects related to acceptance and profitability are of interest.

Addresses Real Users The service Roivis also addresses real users. Due to the fact that the actual software use is performed by experienced staff at metaio with knowledge in the field of AR-based factory planning, the users of the service only need to provide information from their own field of competence. They have to identify the planning problems, which shall be evaluated and have to provide the necessary digital model data.

Profitable with a Market The sales figures presented above, assure the marketability of Roivis as a service product. The service solves the same problems as the software product.

Targeted to User Acceptance In this case, user acceptance is very high. Through the flexibility of the service product, customers are not bound to buy a software product but can use its functionality whenever it is required. In addition, they can rely on the experience and knowledge of the service team, which assures good quality of the results. However, due to the time consuming nature of the process, the service might not be an acceptable solution in case of time pressure. Furthermore, the service is costly in comparison to a software license. One service project could already justify the purchase of a license, as the costs are equal in average.

7.5.4 Killer Application Potential of Roivis

In order for an application to be rated as killer application, additional criteria need to be met besides the productivity of the system. The application must be better than traditional approaches and must convince a large number of customers.

7.5.4.1 Comparison to Traditional Approaches

Both, the software and the service product Roivis sell AR-based factory planning. The competing traditional approaches for factory planning have been introduced in section 2.2. The main areas of application for Roivis are interfering edge analysis, concept planning and planning workshops, as well as variance comparison and part verification. For all these tasks, AR-based factory planning offers great advantages with respect to traditional approaches.

Interfering Edge Analysis Traditional approaches of interfering edge analysis are costly and time consuming. Mock-ups of future products have to be built and sent through the shop floor. Besides the task of creating the mock-ups, the production line has to be stopped for preparing the product skid with the mock-up.
Using AR-based interfering edge analysis offers several benefits:

- No mock-ups have to be built at all.
- The digital model itself is used for analysis, therefore no discrepancies between the evaluation model and the future real model are given.
- The production line does not necessarily have to be stopped for evaluation.
- AR provides the results of the interfering edge analysis in a direct way, as the collisions can be actually seen.
- Despite collision detection, the AR-based analysis provides distance measures for maximum clearance, which might not be determinable using the mock-up approach (e.g. unreachable measures).
- The data can be reused for future evaluations.

Concept Planning and Planning Workshops Traditional approaches for concept planning and planning workshops have to rely on the available data in the company design database. Therefore, the planning is limited to 2D printings of the planning objects or purely virtual 3D views of the objects on a 2D screen or maybe in a CAVE environment. However, the connection to the future real environment in case of re-planning and plant extension is missing completely.
Through AR-based planning, several advantages are given:

- The connection between the real and the digital world is provided. That way, distances and dimensions can be visualised better than in a purely digital environment.

- Different from mock-up based planning, the actual designed digital model data is used.
- In contrast to purely 2D print based planning, a 3D view of the planning objects is provided.
- The results can be documented in an intuitive way.

Variance Comparison and Part Verification Finally, the comparison of virtual and real data is improved through AR. This field of application is perfectly targeted for the technology as the two objects of evaluation are brought together in one single environment. Traditional approaches require visual evaluation based on step by step comparison. This comparison still needs to be done in the AR environment, but the approach offers very important benefits:

- Virtual and real data are directly overlaid and thus no context switch between virtual and real world has to be performed.
- Using the documentation functionalities of the system, the results of the evaluation can be presented in a more intuitive way.
- The scenes can be reused for future evaluations. If evaluations shall be performed in regular time intervals, only new image data has to be acquired.

7.5.4.2 Customer Conviction

All the advantages, the availability of a market and the profitability of the system do not suffice for a killer application if the system does not convince the customers to buy it.

Both the service and the software Roivis have been sold several times in the past two years. However, the number of customers is still very limited. The available sales figures show that the service currently convinces far more customers than the software product does.

7.5.5 Review

Overall, both the service and the software product Roivis can be considered as productive systems, which have been sold successfully in the past. Both approaches meet most of the properties for productivity described above and are more mature than simple demonstrator or prototype applications. However, the customer figures indicate the clear trend towards the service Roivis and with only two customers for the software product Roivis, the system itself cannot be rated as killer application.

The main weakness of the software product is the fact that it is an expert tool. Too many functions and too many tools overwhelm end users from planning departments. In order to address those end users, the software package Roivis has to be tailored to specific planning tasks. This concerns mainly the preparation process and the Roivis toolbox with its functionality for registration and tracking configuration. The process of creating an AR scene for an industrial scenario is still very time consuming, in particular when using registration approaches that assure better accuracy (see section 7.4). Marker positioning and registration are rather cumbersome tasks, which require experience and therefore limit the ease of use of the planning system.

To face this weakness, the provision of application specific software and hardware can be helpful. Such improvements are planned for the promising planning task of variance comparison using the hybrid 3D-3D marker-based registration approach. Besides these concrete plans, a future step could be the complete avoidance of artificial markers and the consequential registration process to further fasten and ease the planning process. Such an approach is for instance presented in the work of Georgel et al. [Geor 07]. The authors describe an AR system for discrepancy checks that relies on factory specific referencing geometries (anchor plates) for tracking instead of artificial markers (see figure 7.20). The detection of those anchor plates in images is not yet fully automatised and the tracking accuracy does not reach the quality of marker-based tracking. In addition, the limited availability of those plates reduces the working environment, which can be tracked. Nevertheless, the approach is very promising as its process is adapted to the industrial environment and avoids manual registration. Thereby, preparation times can be reduced considerably.

Figure 7.20: Tracking Based on Factory Specific Referencing Geometries [Geor 07]

In contrast, the Roivis service product provides a valuable alternative for customers, which do not want to invest into the software product. Instead, they can benefit from the experience and knowledge of the staff at metaio. The AR-based planning tasks are executed by Roivis expert users and the customers can rely on the quality of the planning results. Through service projects, the functionality of Roivis and its benefit can be presented to interested clients. They can experience AR-based factory planning and convince themselves of its potential and serviceability. In fact, the second customer of a Roivis software license besides Volkswagen bought the system after a successful service project.
Furthermore, metaio as service provider can benefit from the service projects and derive new requirements for specific application scenarios that can help to further improve the software product.
However, the service product also has a major disadvantage. Using Roivis as a service requires time for preparing the offer, agreeing on a date, acquiring data, performing the evaluations and presenting the results. Thus, the goal of fast and flexible AR-based factory planning is hardly achievable for a company when relying on the AR service [Bosc 08].

Overall, both the software and the service product are productive applications, but neither of them can be considered as killer application. Roivis is profitable and offers many advantages with respect to traditional approaches. However, it is no "killer application", as the limited number of customers indicates.

7.6 Summary

This chapter discussed several evaluations, which were performed in the context of Roivis. The results provide valuable information about the previously introduced processes on accuracy and registration, as well as the overall factory planning system.

First, some general background on evaluation methods and criteria was presented. Then, these concepts were applied to different analyses. The marker-based tracking system used in Roivis was reviewed with respect to its accuracy and robustness. Furthermore, the registration toolbox introduced in chapter 5 was evaluated for its accuracy and usability, in order to derive guidelines for the application of the different approaches.

Finally, the overall goal of productivity was analysed. Based on available sales figures and practical experience, achievements and weaknesses both for the service and the software product Roivis could be deduced.

8 Conclusion

Summary of Results and Outlook on Future Steps

The aim of this thesis was to present the path of exploration, development and testing on the way to a productive industrial application for Augmented Reality based factory planning. Factory planning is a beneficial area of application for Augmented Reality, as the technology can provide an intuitive interface between the real world and the Digital Factory.
Through the continuous improvement of the Roivis system, a valuable and serviceable industrial AR application has been created. This thesis presented the results of a work that is still in progress. Roivis is further developed, as each application in industry allows drawing new conclusions for enhancement.

This chapter summarises the achievements of this work and presents an outlook on future steps in the field of AR-based factory planning.

8.1 Achievements

Driven by the idea of an easy, fast and affordable possibility for factory planning, the Roivis system was created through an iterative development process. Step by step, important requirements for success and acceptance of the application were derived and realised. Two critical aspects were identified, which are highlighted in this thesis: accuracy for the overall system and process support through a comprehensive registration toolbox.
Furthermore, the degree of maturity of Roivis and its status as a productive industrial AR application were analysed, in order to put the developments in an economic context.

8.1.1 Accuracy

With respect to accuracy, this thesis introduced two main contributions. The idea of regarding the AR system as a measurement system was followed by introducing concepts from measurement engineering. Chapter 4 presented the patent-registered [Pent 07d] approach of combining relevant influencing factors for an industrial AR environment to determine an overall quality statement for the given scene. Furthermore, the concrete determination of input data for this uncertainty propagation process was described. Section 7.2 discussed the approach of a simulation based evaluation of the input marker tracking accuracy. The resulting data fills the tracking accuracy look-up table for the overall uncertainty calculation, but also provides guidelines for the setup and configuration of marker tracking scenarios, as well as quality assurance in case of algorithmic modifications.

8.1.2 Registration Support

Registration support was realised through a comprehensive toolbox offering various methods for registration between real and virtual world. The toolbox was created, keeping the resources and processes in the factory in mind. Chapter 5 presented the different approaches, pointing out the underlying mathematical concepts, as well as the concrete implementation for Roivis.
To facilitate the choice of a favourable method based on the given application scenario, the toolbox was evaluated for its usability and accuracy. Section 7.4 presented this comparison and the resulted guidelines.
The combination of registration methods with corresponding guidelines of use is another important contribution of this thesis.

8.1.3 Productive IAR

Finally, the main aim of this thesis was to give insight into the the general path of development and use of Roivis. Chapter 3 presented the identified requirements and in the following their implementation was described. Through the integration of accuracy and registration related features, the existing application could be considerably improved, resulting in a flexible and reliable system for AR-based factory planning. Chapter 6 presented two example scenarios from industry - interfering edge analysis and variance comparison - to show the concrete process of use.
To rate the degree of maturity of the current system, section 7.5 analysed Roivis with respect to its productivity and killer application potential. Here, the software product Roivis and the service product Roivis were distinguished. For the current status of the system, both the service product and the software product are productive in use and have been applied frequently in industry. However, the number of customers for both products clearly points out the advantages of the service.

8.2 Future Work

The Roivis system, as it was presented in this thesis will not be the last iteration of the application. Several further possibilities of improvement have been identified and for some of them the process of implementation has already started.

8.2.1 Usability

Roivis has been created as an application, which shall be flexible in use and applicable to many factory planning scenarios. However, this flexibility resulted in a large set of tools and functionalities, which can be overwhelming for users who are not familiar with Augmented Reality. For successfully performing factory planning tasks with Roivis, experience is often critical and a lot of knowledge on the available functionalities is required to actually perform AR-based factory planning fast and easy, as it was intended in the beginning.

There are two options for further pursuing the development of Roivis. One possibility is to continue addressing expert users in the field through a comprehensive AR system, which cannot only be applied for factory planning, but also for various other AR related tasks. The other option is to narrow the scope of Roivis and create specific solutions targeted for concrete industrial problems. An example of the latter case is AR-based variance comparison for automotive industry, based on the process of use presented in section 6.2. All required functionality is available, but the creation of an AR scene still needs preparatory steps for marker positioning, image acquisition and the subsequent use of the marker configuration tool, a text editor, the 3D-3D marker-based registration tool and finally Roivis itself. To further ease this process, intermediate steps could be automated and integrated more closely into the Roivis application. Concrete plans for the future are the creation of application specific hardware (such as a fixed set of pre-defined marker adapters including a tracking configuration file), as well as more ergonomic and application targeted software. In addition, the available usability studies based on expert review will be enlarged through comprehensive user studies to verify the current approach and identify further requirements for improvement.

Both developments are promising. The latter approach of targeted solutions can make the software product Roivis more attractive for industrial end users, whereas the former comprehensive system provides the perfect AR toolbox for the successful factory planning services.

8.2.2 Accuracy

Besides usability, accuracy was identified as a crucial criterion for success. Based on the experience through industrial applications, the system accuracy is considered as sufficient. In addition, the available quality statement provides helpful support when rating the reliability of the visualised AR overlay.

However, the current implementation of the system, as well as its uncertainty calculation module are targeted exclusively to marker-based tracking. The uncertainty propagation chain presented in chapter 4 relies on the information available through the marker tracking uncertainty database. Currently, other tracking systems cannot be integrated easily in this chain. Thus, for openness towards future tracking system developments, this interface should be modified in order to provide a more flexible integration of tracking system uncertainty.

A concrete approach for factory planning that is based on another kind of tracking system has already emerged. Section 7.4 introduced the CMM-based registration process using a FARO measurement arm. This mechanical device cannot only be used for registration, but can also serve directly as a tracking system, which provides accurate real-time pose information. Equipped with a visualisation camera, the FARO arm offers a new solution for AR-based factory planning, as shown in figure 8.1. The promising system has already been successfully applied for several variance comparison tasks. Thereby, the registration of real and virtual world can be based on the referencing functionalities of the FARO measurement software and an additional Hand-Eye calibration between the FARO arm and the visualisation camera allows for correct AR overlays.

Figure 8.1: AR-Based Factory Planning Using a FARO Measurement Arm (Source: Audi AG)

8.2.3 Closer to the Digital Factory

Finally, a future step of AR-based factory planning can support the process of closing the gap between the real production plants and the Digital Factory. Through the AR planning process, image data and corresponding camera pose information are available, which can serve as input for a 3D reconstruction algorithm (see also section 2.2.3). Thereby, 3D point clouds can be computed, which offer a digital representation of the real factory. Volkswagen Group Research already tested this approach together with the University of Kiel [Koch 98]. The resulting point cloud can be loaded in a Roivis scene to provide additional information on the surrounding environment and to support the process of collision detection [Pent 07c]. Further evaluations of this approach are planned to gain more experience on the potential of this kind of information merging.

Concluding, Roivis and the developments around Augmented Reality based factory planning are work in progress. The contributions described in this thesis helped to further improve the system and create a reliable approach for factory planning, which is applicable to many industrial planning problems. However, the practical use of the system also revealed weaknesses, which need to be covered to convince users and customers and assure the success of Roivis on the factory planning market. In addition, other promising developments and applications in the field of AR-based factory planning still need to be further evaluated and expanded. Thus, the path of exploration, development and testing continues!

Glossary

2D	2-dimensional.
3D	3-dimensional.
accuracy	Closeness between results of a measurement and the real values of the measurand..
ActiveX	Component object model developed by Microsoft for Windows platforms (see also `http://msdn.microsoft.com/en-us/library/aa751972(VS.85).aspx`).
AICON 3D Studio	Analysing software for 3D measurements, which is used for camera calibration in Roivis, by AICON 3D systems [AICO 08].
align fixture	Device to align and fix a vehicle part in a specific location, e.g. for robot spot welding..
AR	see Augmented Reality.
Augmented Reality	Technology which enhances the user's view of the real world through superimposition of virtual information.
base vector	One of a set of linearly independent vectors in a vector space such that each vector in the space is a linear combination of vectors from the set.
bundle adjustment	Method that computes the simultaneous spatial adjustment of multiple images in a global coordinate system under consideration of measured image points [Luhm 05].
CAD	see Computer Aided Design.
central limit theorem	Statement on the statistical nature of sums and averages of random variables (see section 4.1).
CIM	see Computer Integrated Manufacturing.
CLT	see central limit theorem.
CMM	Coordinate measurement machine.
Computer Aided Design	Use of computer technology to aid the design of a product.
Computer Integrated Manufacturing	Method of manufacturing in which the entire production process in controlled by computers.
Cos	Coordinate system.

C#	Object-oriented programming language developed by Microsoft as part of the .NET initiative (see also `http://msdn.microsoft.com/en-us/vcsharp/default.aspx`).
Design of Experiments	Approach for performing experiments such that a lot of information can be generated based on a minimized number of experiments.
Digital Factory	Comprehensive network of digital models, methods and tools, including simulation and 3D/VR visualisation, which are integrated through continuous data management [Digi 08].
DOF	Degrees of Freedom.
DOX	see Design of Experiments.
extrinsic camera parameters	transformation parameters from a world origin to the camera coordinate system.
Factory planning	Systematic planning of factories, dealing with problems of planning, realising and putting factories in operation.
GUI	Graphical user interface.
GUM	Guide for the expression of uncertainty in measurement [Guid 99].
Hand-Eye calibration	Process of determining the relative transformation between the coordinate system of a camera ("eye") and the coordinate system of an attached external tracking system ("hand").
Head Mounted Displays	Visualisation devices worn on the head or as part of a helmet with a small display in front of one or each eye.
HMD	see Head Mounted Displays.
IAR	see Industrial Augmented Reality.
Industrial Augmented Reality	Application of Augmented Reality technology to industrial scenarios.
intrinsic camera parameters	internal parameters of the camera: focal length, principal point, distortion .
Jacobian (matrix)	Matrix of all first-order derivatives of a vector-valued function.
metaio	Company that designs, develops and markets Augmented Reality solutions (see also `http://www.metaio.com`).

pinhole model	Camera projection model that maps points in space X on the image plane, where the line joining X with the camera projection centre C meets the image plane [Hart 03] .
pose	Position (translation) and orientation (rotation).
precision	Closeness between successive measurements of the same measurand carried out under the same measurement conditions.
quaternion	Non-commutative extension of complex numbers described by a 4-dimensional vector which provide a convenient mathematical notation for representing rotations in 3D space.
registration	Alignment of data sets; in the context of this thesis the determination of a transformation from camera or marker coordinate system to the model coordinate system.
residual	Difference between an estimated (adjusted) and the observed value.
Roivis	AR-based factory planning application, by metaio.
singular value decomposition	Useful matrix decomposition, which is for instance applied to solve over-determined systems of equations [Hart 03].
skid	Frame which aligns and fixes a car body during the manufacturing process.
SPC	Simultaneous pose and correspondence problem.
SVD	see singular value decomposition.
trace	Sum of the diagonal values of an $n \times n$ matrix.
tracking	Process of estimating and following the pose of an object over time.
transformation	4×4 matrix which represents a coordinate system transformation in 3D space.
uncertainty	Characterises the dispersion of the values that could reasonable be attributed to the measurand.
Unifeye SDK	Software development kit for rapid and easy development of Augmented Reality applications, by metaio.
Virtual Reality	Technology which allows a user to interact with a computer-simulated environment.
VR	see Virtual Reality.

VRML	Virtual Reality Modeling Language, a standard file format for 3-dimensional interactive vector graphics (see also `http://www.web3d.org/x3d/specifications/vrml/`).
XML	Extensible Markup Language, simple and flexible text format (see also `http://www.w3.org/XML/`).

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