AN INTEGRATED AUGMENTED REALITY METHOD TO ASSEMBLY SIMULATION AND GUIDANCE

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A THESIS SUBMITTED

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

NUS GRADUATE SCHOOL FOR INTEGRATIVE SCIENCES AND ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

2016

Declaration

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Wang Xin

2016-01-06

Acknowledgements

I would like to express my sincere gratitude to my supervisors, Professor Andrew Nee Yeh Ching and Associate Professor Ong Soh Khim, for the continuous support of my PhD study and related research, for their patience, motivation, and immense knowledge. Their patience and support helped me overcome many crisis situations and finish this thesis. I could not make it today without their effort. They care for students' welfare and well-being, and set up an excellent research environment for us. I appreciate all their contributions of time, ideas, and funding to make my PhD experience productive.

I also would like to express my sincere appreciation to every member in the ARAT Lab, Dr. Zhang Jie, Dr. Shen Yan, Dr. Fang Hongchao, Dr. Niu Sihong, Dr. Wang Zhenbiao, Dr. Billy Saputra, Dr. Zhu Jiang, Dr. Jiang Shuai, Dr. Ng Laixing, Dr. Zheng Xin, Dr. Andrew Yew, Dr. Yu Lu, Dr. Yan Shijun, Dr. Yang Shanshan, Zhao Mengyu, Huang Jiming, Li Wenkai, Terence Siew, and Miko Chang. You have been great colleagues and best friends.

I would like to thank NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, for providing me with the research scholarship and the kind assistance and advice.

Last but not least, I would like to thank my parents, for giving birth to me in the first place and supporting me spiritually throughout my life.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AF	Assembly Feature
AFS	Assembly Feature Surface
AIM	Assembly Information Management
AMS	Assembly Motion Simulation
AOG	Assembly Operation Guidance
AR	Augmented Reality
ARAMS	Augmented Reality assisted Assembly Motion Simulation
ARAOG	Augmented Reality assisted Assembly Operation Guidance
ARKF	Augmented Reality Kernel Functions
ARTE	Augmented Reality based Task Environment
ARTR	Augmented Reality Tracking and Registration
VR	Virtual Reality
CAD	Computer Aided Design
CARAGM	Cognition based interactive Augmented Reality Assembly Guidance Module
CCD	Charge-Coupled Device
CCH	Component Contact Handling
CMOS	Complementary Metal-Oxide-Semiconductor
CV	Computer Vision
DOF	Degree Of Freedom
EBHI	Enhanced Bare Hand Interface
GPU	Graphics Processing Unit

HCI	Human Computer Interaction
HMD	Head-Mounted Display
HHD	Hand-Held Display
IARAE	Integrated Augmented Reality Assembly Environment
IMU	Inertial Measurement Unit
KLT	Kanade-Lucas-Tomasi tracker
MBT	Model-Based Tracker
MGDE	Minimum Geometric Datum Element
OAIM	Ontology-based Assembly Information Model
OATP	Ontology for Assembly Tasks Procedure
OWL	Web Ontology Language
PDM	Product Data Management
RD	Rotation Directions
RFID	Radio-Frequency Identification
SLAM	Simultaneous Localization And Mapping
SMF	Source Media Files
STL	STereoLithography file format
SWRL	Semantic Web Rule Language
TD	Translation Directions
USR	Unit Sphere Representation
VRML	Virtual Reality Modeling Language
XML	Extensible Markup Language

Abstract

Much research effort has been devoted to improving the efficiency of mechanical assembly for decades, due to the combinatorial complexity and the great impact it has on the modern industry, especially the topics of assembly motion simulation (AMS) and assembly operation guidance (AOG).

For the AMS, enterprises are often faced with the need to modify and/or update the existing product, imposing additional constraints from the presence of the existing real components for the traditional pure virtual AMS. Therefore, in this research, an AR-based AMS system (ARAMS) is proposed and implemented to incorporate the interaction between real and virtual components, so that users can obtain a more immersive experience of the assembly simulation in real-time and achieve better assembly design. A component contact handling (CCH) strategy is proposed to model all the possible movements of virtual components when they interact with real components. A novel ontology-based assembly information management (OAIM) approach is proposed to access and modify the information instances dynamically corresponding to user manipulation. To support the interaction between real and virtual components, a hybrid marker-less tracking method is implemented. A method is proposed to calculate the resultant forces exerted on virtual components from contacts with real components and manipulation from the user's hands (forces and torques applied, etc.) during an assembly process. In addition, two interaction tools, namely, bare-hand interface and hand held tool, are provided to enable users to manipulate virtual components intuitively.

For the AOG, in order to improve the usefulness and effectiveness of the state-of-the-art AR assembly guidance systems, it is imperative to integrate human cognition support to deliver the most appropriate modality and amount of information so that the users can receive and process it effortlessly. In this thesis, a novel human Cognition-based interactive Augmented Reality Assembly Guidance Module (CARAGM) is proposed to investigate how AR can provide various modalities of guidance to assembly operators for different phases of user cognition process during assembly tasks. An intuitively enhanced bare-hand interface (EBHI) is integrated to facilitate the interaction between the user and the rendered contents.

An integrated augmented reality assembly environment (IARAE) is developed to implement both ARAMS and CARAGM. For evaluation purposes, a set of tests have been conducted and presented. The tests results demonstrate that the ARAMS is effective, intuitive and efficient, and specifically, with the proposed physics-based force/torque calculation during AMS, ARAMS generates physically plausible motions for the reference components manipulated by the user's bare-hands. For the CARAGM, the users can perform tasks more quickly and accurately as compared with the other two baseline systems, and the users evaluate CARAGM as intuitive, effective and easy to use.

1. Introduction

This chapter begins with a brief introduction to two important research topics in mechanical assembly, namely, assembly motion simulation (AMS) and assembly operation guidance (AOG). The introduction includes definition of AMS and AOG, their impact on product development process, and existing approaches to these two topics. Following this, the research motivation and objectives of this research are outlined. Finally, the organization of this thesis is presented.

1.1 Manual assembly in manufacturing engineering

1.1.1 Assembly motion simulation

Generally, a product designer starts with sketches of components in an assembly, and proceeds to the computer-aided design (CAD) workstation to construct detailed 3D models for both assembly and components. These CAD files are transmitted to the manufacturing and assembly departments to optimize the manufacturing and assembly processes of the final product. Usually, it is at this stage that technicians encounter assembly issues which lead to requests for design changes. Sometimes, the changes are large in number, causing considerable postponement and additional development cost before the release of final product. It is now widely accepted that the later the changes occur in the product development cycle, the more expense they cost (Boothroyd et al., 2011). Therefore, not only is it imperative to take assembly issues into account during product development, it is important to consider the potential assembly issues as early as possible because over 70% of the final product costs are determined during design stage (Figure 1-1).

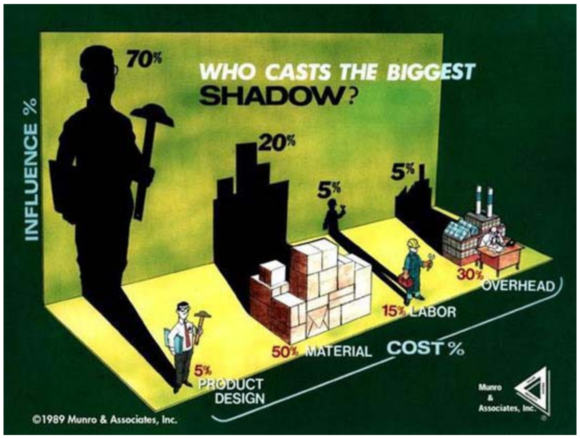


Figure 1-1 Who casts the biggest shadow? (adapted from Munro and Associates, Inc. **http://leandesign.com/history-of-lean-design/**)

Assembly Motion Simulation (AMS) has become a critical step at the product design stage to handle assembly issues. In AMS, details of assembly constraints and relationships, which describe how different components will be assembled, are formalized (Whitney, 2004). A well-designed assembly can improve production efficiency and product quality, reduce cost and shorten the product's time to market. The primary objective of AMS is to simulate the assembly process and validate assembly sequences, including all the required human and machine interaction. When AMS tools are implemented to validate assembly process digitally, the component installation time and assembly operation try-out costs can be minimized, and the productivity can be increased.

1.1.2 Assembly operation guidance

Mechanical assembly operation requires special engineering techniques to ensure cost-effectiveness and on-time assembly of products in a logical sequence of steps. In modern manufacturing, there are still a significant number of assembly operations that require manual human effort, especially for products which are highly customized or with high complexity (Samy, 2011). For example, in automobile production, the assembly of body and chassis are typically automated, while the final assembly of internal and electrical devices is usually manual. In manual assembly, the majority of operations are conducted by trained assembly operators applying established procedures, which are generally organized into sequences of basic tasks, e.g., assembling a particular component to another, according to documented instructions. The procedures are important because, if the steps are taken out of order, it could result in missing components, and the operator would have to disassemble the product to put the components in place. During the assembly process, human operators are located at the center of manual assembly systems. They execute assembly operations by using their manual skill, senses, and intelligence, supported by many tools and devices. Due to a growing demand for flexible and customized production, interfaces designed to optimally support operators in manufacturing become increasingly important (Leu et al., 2013; Stork and Schubo, 2010; Michalos et al., 2013; 2015).

1.2 Overview of existing technologies in mechanical assembly

1.2.1 Existing technologies in AMS

AMS is a critical step and should be considered at all stages of the product design process. Expert assembly planners typically use modern commercial CAD systems, with which, the 3D CAD models of the components to be assembled are displayed on computer screens to aid the planner to determine a component's geometric characteristics and assembly features for a new product (Seth et al., 2011). Although this is the most commonly used approach, there are limitations. Firstly, users are required to identify constraint information between the mating parts by selecting the mating surfaces, axes and/or edges manually; this is a complicated task for complex assemblies. It is difficult to foresee the impact of individual mating specifications on the other aspects of the assembly process with such part-to-part specification techniques. Secondly, most CAD software lacks direct interaction between users and the components, such that users cannot manipulate the components with their hands naturally.

Virtual Reality (VR) technology plays a vital role in simulating advanced 3D human computer interactions, especially for mechanical AMS (Seth et al., 2011), allowing users to be completely immersed in a synthetic environment. Many VR systems have been proposed successfully to aid assembly activities, e.g., CAVE (Cruz-Neira et al., 1992, 1993), IVY (Kuehne and Oliver, 1995), Vshop (Pere et al., 1996), VADE (Jayaram et al., 1997, 1999, 2000a, 2000b; Taylor et al., 2000), HIDRA (Coutee et al., 2001, Coutee and Bras, 2002), SHARP (Seth et al., 2005, 2006), etc. However, even though most VR systems are designed to simulate the assembly process in a realistic fashion, they still have some limitations. First, while the physical relations between the users and/or objects in the virtual environment are eliminated, the users' realistic experience is lost, thus decreasing the fidelity and effectiveness of the VR assembly process. Another limitation is that the users cannot move around and interact naturally with the virtual environment as they would in a real environment. The users are constrained to a fixed position or a limited space, and the interaction methods they use are through external devices (e.g., data glove, haptic devices, etc.). Furthermore, the VR experience may not be highly convincing as it is not easy to fully and accurately model the actual working environments which are critical to the manufacturing processes. Although there are advanced approaches to accelerate the computation process (e.g., graphics processing unit (GPU) based acceleration: http://www.nvidia.com), the real-time performance remains a challenge.

Augmented Reality (AR) technology can overcome these limitations as it does not need the entire real world to be modelled (Ong et al., 2008), thus reducing the high cost of fully immersive VR environments and the inconvenience of the commercial CAD systems. More importantly, AR enhances the interaction between the systems and the users by allowing the users to move around in the AR environment and manipulate the objects naturally. AR assembly systems has been implemented to address a wide range of problems throughout the assembly phase in a product's lifecycle, e.g., planning, design, ergonomics assessment, operation guidance and training, by creating an augmented environment where virtual objects (instructions, visual aids, industrial components) are combined with the real objects and environment. In such an augmented environment, users can achieve real feedback and interact with virtual contents to analyze the behavior and properties of planned products, obtaining the benefits of both physical and virtual prototyping (Nee et al., 2012).

1.2.2 Existing technologies in AOG

Traditionally, assembly operators follow the assembly instructions either as hard or softcopies that are detached from the equipment. The operators have to switch between reading the instructions (paper manuals, external computers, or websites) and performing the assembly tasks. This divergence of attention will consume much time, and cause operator fatigue, reduced productivity, increased errors and assembly time. Most of the augmented instruction research focuses on solving these issues.

AR-assisted assembly guidance systems have been developed to augment necessary virtual information onto a user's view to facilitate the assembly operation. Caudell and Mizell (1992) proposed the first implementation of a classic AR assembly guidance system by combining head position sensing and real world registration with head mounted display (HMD), such that a computer-produced diagram containing pertinent information, can be superimposed and stabilized on a specific position on a real-world object. Since then, a number of studies have been reported on AR-assisted assembly guidance. AR-assisted assembly guidance enables operators to perform tasks which require a higher level of qualification. However, although there is much effort on this topic, some of the AR assembly guidance systems seem to focus solely on providing step-based instructions for the user, and overlook the user's need of timely guidance in assembly operations. In addition, a large number of previous studies were based on proof-of-concept applications. Thus, there is a need to formally explore the benefits of AR-assisted assembly guidance system in a real industrial assembly environment.

Context-aware AR assembly guidance systems were proposed to keep track of the status of the users in real-time, recognizing manual errors and task completion status at each assembly step automatically, and displaying multi-media instructions corresponding to the recognized states (Khuong et al., 2014). Recently, there have been works to investigate the recognition and tracking of the pose of the objects in an assembly, such that the corresponding information can be retrieved from the systems (Rentzos et al., 2013; Chen et al., 2015). In manual assembly tasks, the operators may require multiple sources and forms of guidance information. Therefore, pertinent information has to be filtered, organized and executed appropriately according to user cognition. From a technical perspective, this can be realized with a context-aware system equipped with multiple sensors (context-awareness guidance). However, a prerequisite for the utilization of context information within a guidance system is the knowledge and understanding of the user cognition process, which has not been well-studied in the research on assembly guidance systems currently. To study the benefits that can be achieved from application of AR in assembly tasks in supporting the whole spectrum of cognition process, Stork and Schubo (2010) investigated human cognition, i.e., from attention allocation through action execution, in AR production environments.

1.3 Research motivations

1.3.1 Assembly motion simulation

Research on AMS has been focused on the design stage, i.e., prior to the manufacturing of the physical prototypes. CAD-based approaches and VR-based approaches have been developed to realize assembly simulation in an entire virtual environment. For these AMS tasks, the mating relations and assembly constraints between components are formulated off-site based on the data of the products; the designed product can generally be manufactured in the real world without modification.

However, the modern industry has posed new challenges for AMS. To meet the fast-changing need of the customers, enterprises nowadays need to modify and/or update existing products quite frequently, e.g., modify some of the components in an assembly for updating the product functions (Du et al., 2013; Fukushige et al., 2012). For these tasks, the presence of existing real components imposes additional constraints. AMS for existing product upgrade have the following characteristics:

1) The redesign or upgrade process of a component is generally limited by the constraints (geometric, structural, functions, etc.) from the existing real components in the product assembly;
2) The AMS task normally tends to be on a smaller scale, e.g., manipulating and assembling a number of virtual components from partial of the product to the existing real ones;
3) Information from real-virtual components interaction is important, e.g., the spatial relation of a virtual new part design with respect to an existing real component, physical constraints and manipulation obstructions from the real component, etc.

Existing approaches are not efficient in addressing these issues. Both CAD-based and VR-based approaches do not allow users to relate their assembly experience to the physical context, and thus leading to a lack of real spatial feeling. These approaches implement the AMS off-site, such that there is a lack of a proper mechanism to implement immediate on-site evaluation for improvement purposes. On-site evaluation can provide an effective way to identify and address possible deviations of the product design from implementation and this is a useful technique for AMS.

The AR-based approach to AMS is a promising alternative approach. In an AR environment, the users are allowed to manipulate and assemble the redesigned virtual components to the existing real components, so that the users can obtain a realistic and immersive assembly simulation, observe the outcome of the interaction in real-time, check for possible design errors and modify the original design in the context of their final use and in the real world scale before the component is finalized and produced, thus shortening the development cycle. In this research, an AR-assisted assembly motion simulation (ARAMS) module is proposed. The proposed module consists of a hybrid tracking method to track the pose and position of existing real components, a set of interaction tools to support the intuitive manipulation of virtual components, a geometric degree-of-freedom (*DOF*) analysis method to obtain all the possible movement directions of virtual components, and a physical method to calculate assembly forces when virtual components interact with the existing real components. By allowing the users to perform AMS on-site, the system provides a feasible solution to the AMS with existing real components/sub-assemblies.

1.3.2 Assembly operation guidance

AR has been implemented widely to improve the manual assembly efficiency because it can display virtual digital information that is blended with the real work scene in the operator's view (e.g., step-by-step instructions and 3D illustrations) in real-time during an assembly operation (Makris et al., 2013). In comparison with conventional guidance methods, such as paper-based work instructions, assembly guidance systems based on AR can reduce search time for relevant instructions (Zhu et al., 2013), and allow the user to focus on the task by rendering guidance materials close to the working area spatially to minimize attention switching (Khuong et al., 2014). However, in order to improve the usefulness and effectiveness of the state-of-the-art AR assembly guidance systems, it is imperative to integrate user cognition support to deliver the most appropriate modality and amount of information so that the user can receive and process it effortlessly and enhance skills transfer from the perception of instruction to practice (Stork and Schubo, 2010). Researchers point out that an assembly task can be divided into a series of sub-tasks, including comprehending instructions, directing attention, approaching pertinent components/tools, manipulating, fastening and other user operations (Neumann and Majoros, 1998). User cognition refers to the cognitive functions dedicated to information processing during different manual assembly sub-tasks (Stoessel et al., 2008), e.g., perception, attention, memory and action. An AR guidance system can be deemed as based on human cognition if it can collect, utilize and reason cognition information, and cater to the need of appropriate guidance modality adapted to the user cognition.

Using an AR assembly system, the users should be able to control the AR contents naturally and directly, so as to manipulate rendered contents (e.g., guidance materials) freely in the 3D AR environment (e.g., 3D translation, rotation, scaling). To resolve the limitations from traditional AR guidance instructions, e.g., when virtual instructions are not rendered properly (e.g., inappropriate scale, unsuitable position, etc.), the user should be able to manipulate the instructions freely with his/her bare-hands. In addition, as current interaction tools (e.g., mouse, keyboard, and marker-based tools) may interrupt manual assembly workflow, the user should be able to input commands through natural bare-hand gestures without interrupting the workflow.

In this research, a novel human Cognition based interactive Augmented Reality Assembly Guidance Module (CARAGM) is proposed to explore the application of AR in providing different modalities of guidance to assembly operators for various cognition phases. In addition, CARAGM distinguishes itself from previous AR assembly guidance systems by implementing on-site assembly simulation between real and virtual components, and timely AR guidance to facilitate the user's on-going operation. An intuitive enhanced-bare-hand interface (EBHI) is implemented to facilitate multi-modal interaction between the user and the rendered contents.

1.4 Research objectives, significance and scope

1.4.1 Research objectives

The primary objective of this research is to propose an integrated augmented reality assembly environment (IARAE) that facilitates the entire assembly process, spanning from the design stage to the assembly operation execution, i.e., both AMS and AOG. This research aims to develop the IARAE system that comprises: (1) an ARAMS module to allow the users (primarily assembly planners and product designers) to perform assembly motion simulation with both real and virtual components during the design stage of the assembly, and (2) an AR assembly guidance module (CARAGM) which provides appropriate modality of instructions according to the user cognition stage when the user (primarily assembly operators) performs real assembly tasks. Based on the research goals discussed above, the specific research objectives are to:

1. Implement robust hybrid tracking and registration methods in the assembly process.
2. Represent and store the assembly information based on the requirements of the assembly applications to support the reasoning and inference functions, and establish rules to assess and manage the assembly information in the database.
3. Develop a geometrical analysis method to obtain all the feasible *DOF*s of a virtual component when it contacts other components.
4. Develop a physical method to calculate assembly forces exerted on a virtual component when it is manipulated by the users.
5. Develop an AR assembly guidance system for AOG that attempts to fully utilize the potentials of the AR technology and user cognition.

1.4.2 Significance and scope

The results of the present study may have significant impact on: (1) the way assembly planners and product designers design and plan an assembly, and (2) the way assembly operators perform an assembly work and help the assembly operators to improve the assembly efficiency, especially for the novices (practical orientation). The research issues to be addressed include the user interface techniques, mathematical formulations of the *DOF* merging problems and interaction forces calculation problems, and information reasoning and inference.

This thesis primarily focuses on AR tools for a typical industrial manual assembly on a workbench, e.g., automobile alternator, engine, etc. Therefore, the automatic assembly process (e.g., the robot-assisted assembly) is not considered in this thesis. For large-scale assembly, e.g., assembly planning of an aircraft wing, AR is less applicable due to the difficulty in tracking and visualizing much larger elements. Large-scale assembly is thus not within the scope of this research. A hybrid tracking method is adopted in this research. However, development of new tracking algorithms to improve the tracking accuracy is not the focus of the present research and hence will not be explored.

1.5 Organization of thesis

As shown in Figure 1-2, the rest of the thesis is organized as follows.

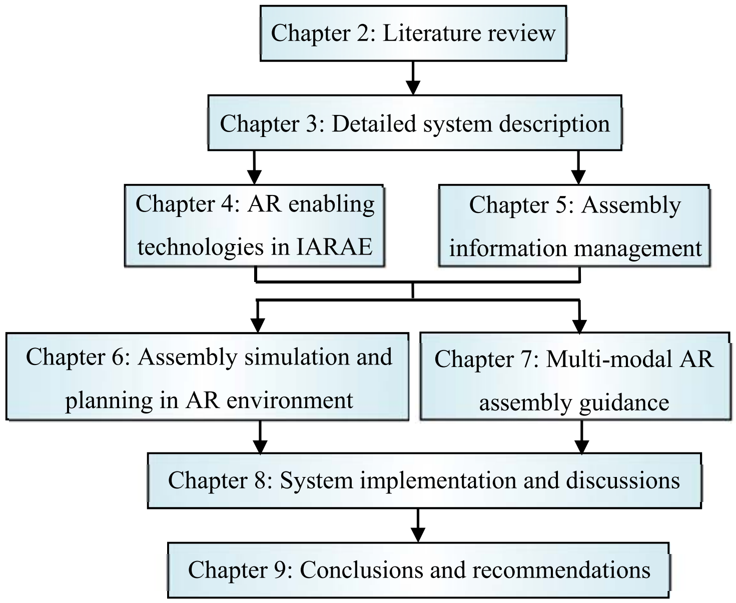


Figure 1-2 Thesis organization

The remaining part of this thesis is organized as follows. Chapter 2 presents a literature review of the status of the AR technologies applied in mechanical assembly and several research domains relevant to this thesis. A review of the current issues of the AR technologies is made, followed by a discussion of the advantages and disadvantages of the application of AR to facilitate AMS and AOG.

Chapter 3 describes the overall architecture of the system that has been studied and developed in this research.

Chapter 4 presents the kernel AR functions implemented in this research. A modified hybrid real component tracking method is proposed to reduce the tracking noise caused by the inaccurate measurements and extraction of the features during the implementation of the original tracking algorithm

(Pressigout and Marchand, 2006), a mature hybrid tracker but has limitations for industrial components tracking. In addition, an occlusion handling strategy during assembly operation is proposed. A set of experiments has been performed to evaluate the usefulness and effectiveness of the proposed method qualitatively and quantitatively. Based on the hybrid tracking method, a methodology is proposed for the incorporation of real components into the AR assembly environment.

Chapter 5 presents two ontology-based assembly information models used in IARAE for managing the assembly data for ARAMS and CARAGM, respectively. The reasoning and inference rules for pertinent information instances are described.

Chapter 6 presents an AR-based AMS module in IARAE. Two interaction tools in ARAMS are described. A novel DOF merging algorithm is proposed, and a method to calculate assembly forces based on this method during AR assembly is presented.

Chapter 7 presents a novel human Cognition based interactive Augmented Reality Assembly Guidance Module (CARAGM) to investigate how AR can provide various modalities of guidance to assembly operators for different phases of the user cognition process during assembly tasks. An intuitive enhanced-bare-hand interface (EBHI) is integrated to facilitate multi-modal interaction between the user and the rendered contents.

Chapter 8 describes the system configuration of IARAE. A set of system evaluation tests is presented to show the implementation of the methodologies proposed in Chapter 6 and Chapter 7.

Finally, Chapter 9 summarizes this thesis and gives the conclusions, contributions and recommendations for future research.

2. Literature Review

This chapter presents the background knowledge of several domains relevant to this research. Previous works related to this research can be classified into two broad areas, namely, AR technologies and AR assembly systems. An overview and a summary of the current research in these areas are presented.

2.1 Augmented reality

Augmented Reality (AR) is a set of innovative and effective human computer interaction (HCI) techniques. AR enriches the way users experience the real world by embedding virtual objects to coexist with real objects in the real world (Zhou et al., 2008). In the past two decades, AR has progressed from marker-based to marker-less, and more recently mobile context-aware methods that can bring AR into mobile and assembly workshop contexts.

2.1.1 Tracking and registration

2.1.1.1 Tracking

One of the crucial tasks in AR assembly is to develop a real-time tracking system suited for industrial scenarios, which characteristics (e.g., poorly textured objects with many smooth surfaces, large lighting variation, objects of very small sizes, etc.) challenge most of the techniques available (Engelke et al., 2013). The trends of the implementation of tracking methods in AR assembly systems are shown in Figure 2-1. As shown in Figure 2-1, marker-based tracking is the most widely used and popular tracking approach in AR assembly even until now. Many researchers implemented the marker-based tracking approach in AR assembly systems due to its accuracy, flexibility as well as ease of use (Reiners et al., 1998; Boulanger, 2004; Salonen et al., 2007). Wang et al. (2010) used a cardboard with a marker to create a virtual panel. Wang et al. (2005) explored tracking from non-square visual markers with a color-based marker to track the tool models so that the operators can manipulate the scanned, articulated real objects naturally. The use of markers is very common in AR assembly because it increases the robustness and improves the computation efficiency due to the stable and fast detection of markers in the entire image sequence. However, marker-based tracking approaches suffer from marker occlusion which may cause incorrect registration in the field of view (Zauner et al., 2003). In addition, many industrial components are too small to attach markers.

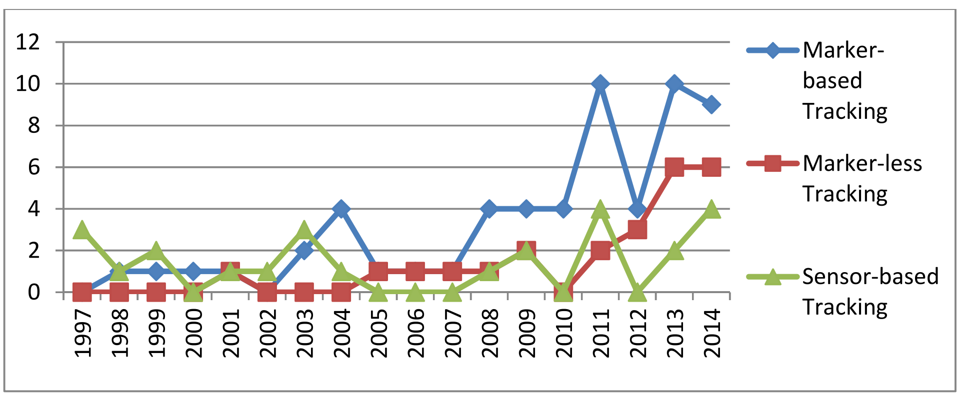


Figure 2-1 Trends for tracking approach implementation in AR assembly

Sensor-based tracking is another reliable tracking approach that has been implemented widely in AR assembly systems even before marker-based tracking is implemented (Figure 2-2). The tracking principle is based on different types of sensors, e.g., magnetic, acoustic, inertial, optical and/or mechanical sensors. Vision-based tracking relies on computer vision techniques. Generally, sensor-based trackers used in AR applications need to provide high accuracy, low latency and jitter, and provide robust operations under a wide range of environmental variations (Ong et al., 2008). Each type of tracker has its own advantages and disadvantages, e.g., optical sensors have high accuracy, flexibility and low latency, but are expensive, heavy and require extensive calibration.

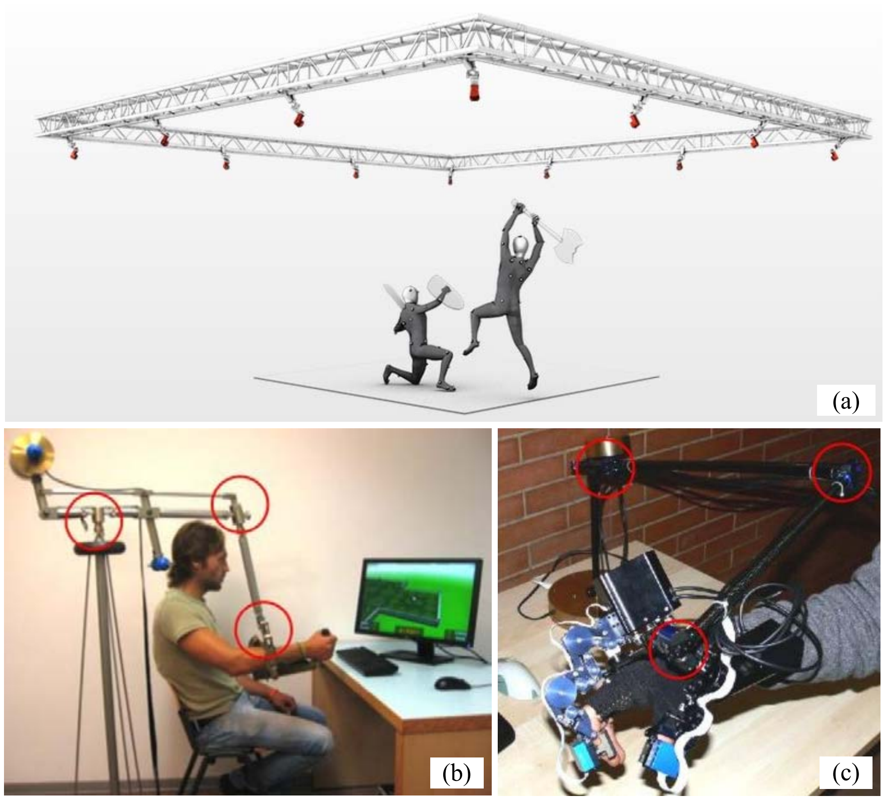


Figure 2-2 Sensor based tracking: (a) OptiTrack (http://www.optitrack.com/); (b-c) mechanical tracking systems (Fontana et al., 2013)

Marker-less tracking (Figure 2-3) is deemed to be a desirable successor of marker-based tracking recently. Simultaneous localization and mapping (SLAM) is an established technique to build up a map within an unprepared environment while at the same time keeping track of its current location based on the extracted scene features (Tan et al., 2013). This approach can provide robust tracking of the AR assembly systems even when the original fiducials are not visible. However, since SLAM systems cannot take into consideration changes of 3D structures corresponding to dynamic objects, the target working scene must be kept stationary, otherwise the recovered 3D models will become obsolete rapidly, and the system has to start from scratch for each frame of the captured video. A range of other scene feature-based tracking techniques have been reported (Yuan et al., 2008; Andersen et al., 2009; Alvarez et al., 2011). A binary descriptor is proposed (Yang and Cheng, 2012) to improve natural feature tracking by employing a more complete description compared with BRIEF (Calonder et al., 2010) and a multiple gridding strategy to capture the structures at different spatial granularities. Petit et al. (2013) proposed a tracking strategy by integrating classical geometrical and color edge-based features in the pose estimation phase. In these systems, the trade-offs between the tracking accuracy and computation cost need to be considered carefully. Recently, the popularity of graphics processor unit (GPU)-based computation acceleration is gaining attention. Hence, future work should investigate the integration of this technique in order that the systems can handle complex tracking scenes with faster speed.

Figure 2-3 Marker-less tracking: (a) Monocular SLAM (Tan et al., 2013); (b) Hybrid marker-less tracking (Alvarez et al., 2011); (c) Model based tracking (Comport et al., 2006)

2.1.1.2 Registration

The primary objective for tracking in AR assembly is to facilitate registration of virtual components and/or assembly instructions with the correct pose in the augmented space. There are two critical issues to be considered, namely, accuracy and latency.

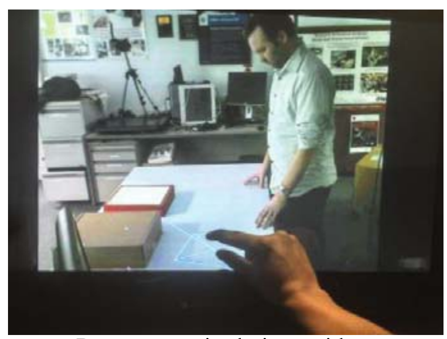
The issue of accuracy refers to the error arising from the inaccuracy present in the sensory devices, misalignments between sensors, and/or inaccurate tracking results (Dong and Kamat, 2010). To reduce the errors, Zheng et al. (2012) presented a closed-loop registration approach by implementing the desired synthetic imagery (real and virtual) directly as the goal. Yang et al. (2013) proposed a method to obtain extrinsic calibration of a generically configured RGB (red, green, and blue color model) and depth camera rig with partially known metric information of an observed scene in a single shot fashion. Implementation of advanced tracking methods, special strategies for registration and effective calibration approaches is the primary approach to eliminate the accuracy issue at the current stage.

The latency issue refers to the alignment errors of the virtual objects caused by the difference in time between the moment an observer moves and the time when the image corresponds to the new position of the observer is displayed (Nee et al., 2012). This issue can become serious as head rotations and/or user's operations become very fast. To solve this problem, Waegel and Brooks (2013) implemented a low-latency inertial measurement unit (IMU) to remedy the slow frame rate of depth cameras and proposed new 3D reconstruction algorithms to localize the camera position and build a map of the environment simultaneously, so as to provide stable and drift-free registration of the virtual objects.

2.1.2 Collaborative AR interface

Since an assembly operation has relations with many other processes in manufacturing (e.g., product design, factory layout planning, machining, joining, etc.), it is imperative to investigate how AR can play a pivotal role where assembly designers, planners as well as operators can participate together to enhance communication between them (Szalavári et al., 1998; Billinghurst et al., 1998). Liverani et al. (2004) proposed the Personal Active Assistant (PAA) that is linked to a designer workstation wirelessly to augment information from the views of workers and designers on their HMD. Boulanger (2004) presented a collaborative AR tele-training system to support the remote users by sharing the view of the local users. Shen et al. (2008) and Ong and Shen (2009) proposed a remote collaboration system, where distributed users can view the same product model from different perspectives. Collaborative AR has brought a wide range of benefits to assembly tasks, namely, flexible collaboration, knowledge retention, increased problem context understanding and awareness, and integration with existing and on-going working processes (Figure 2-4). However, sometimes due to the lack of virtual co-presence, effective communication between users is difficult. Oda and Feiner (2012) designed GARDEN (Gesturing in an Augmented Reality Depth-mapped Environment) to improve the accuracy of referencing physical objects that are farther away than an arm's length in a shared un-modeled environment by using sphere casting. Ranatunga et al. (2013) presented a method that allows an expert to use multi-touch gestures to translate, rotate and annotate an object onto a video feed to facilitate remote guidance during collaboration with other users. The system introduces a level of abstraction to the remote experts by allowing them to directly specify the object movements that are required of a local worker. Another issue is that although a number of collaborative AR systems have been implemented, few of them have been validated with rigorous user studies (Zhou et al., 2008). Formal user studies need to be conducted in future collaborative AR research.

3D referencing technique
(Oda and Feiner, 2012)



Remote manipulation guidance
(Ranatunga et al., 2013)

Figure 2-4 Collaborative AR interface

2.1.3 3D workspace scene capture

A seamless blending of the real world with computer-generated contents is often seen as the key issue to improve user immersion for AR assembly systems. The fundamental of such an issue is the lack of real-time acquisition of the dynamic assembly workspace scene. This is a challenging task which requires the state-of-the-art technology and instrumentation, e.g., camera. Figure 2-5 shows the trends on the use of cameras in AR assembly systems.

From Figure 2-5, mono cameras have been implemented in most of AR assembly systems for a long time because mono cameras are generally light-weight and convenient to use; Moreover, a simple mono camera is powerful enough to handle most of the core functions in AR technology. With development of the camera hardware, some special types of camera, e.g., stereo camera, depth camera, etc., have been produced to provide better support for information capture functions. Published research shows that a growing number of researchers began to implement these special cameras in the AR assembly systems recently (Figure 2-5). Stereo camera is a camera comprising of two or more lenses with a separate image sensor or film frame for each lens to simulate human binocular vision. Therefore, stereo cameras have the ability to capture 3D images, a process known as stereo photography. Stereo cameras may be used for 3D reconstruction or for range imaging. However, the accuracy of the stereo camera is not linear. In addition, it is not possible to calculate the distance of every pixel in the image. Recently, depth sensors, such as Microsoft Kinect, has generated great interests from researchers. KinectFusion (Newcombe et al., 2011) improves depth capture by combining the Kinect with a high end Nvidia GPU to capture a dense map of the 3D scene, which can be exported to a mesh. With these scene capture technologies, dense 3D reconstruction (Jancosek and Pajdla, 2011) can be achieved, which can facilitate the interaction of virtual objects with the real assembly workspace. However, state-of-the-art dense 3D reconstruction techniques usually suffer from insufficient accuracy, resulting in visual artefacts, such as loss of detailed shapes and rough boundaries. In addition, there is a trend towards real-time reconstruction of 3D models with meaningful structural information, which is imperative for virtual object positioning and a critical requirement for the rendering of the synthetic scene for assembly tasks. To solve the above problems, Dou et al. (2013) introduced a 3D capture system that builds a complete and accurate 3D model for dynamic objects by fusing a data sequence captured using commodity depth and color cameras, and tracks the fused model and aligns it with following captures.

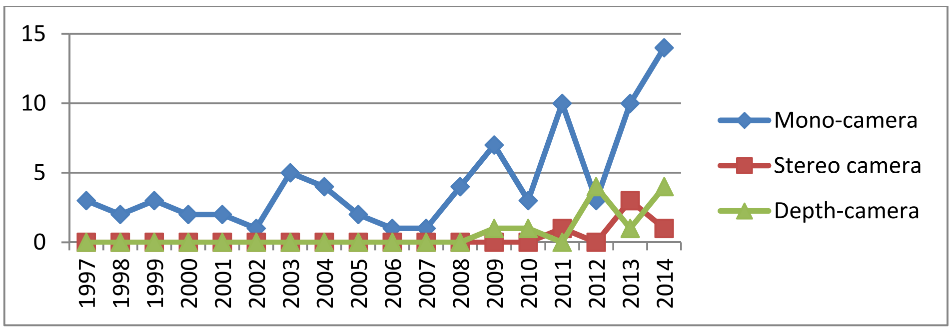


Figure 2-5 Trends for usage of cameras

2.1.4 Knowledge representation and context-aware AR assembly system

AR-based assembly systems, as an effective tool that helps the users in the assembly design, planning and operation process, requires efficient knowledge representation schemes. Therefore, knowledge representation is a critical issue in order to manage and organize the raw data available to the users. The use of ontologies can help integrate and manage valuable, unstructured information and knowledge, and provide rich conceptualization of complex domains, such as assembly (Zhong et al., 2013). Researchers have proven that product assembly ontology is useful in storing and managing assembly data, e.g., Core Product Model (CPM) (Gorti et al., 1998) and Open Assembly Model (OAM) (Rachuri et al., 2005). Ontology-based knowledge management systems have been integrated to AR operation guidance systems. Lee and Rhee (2008) built a pioneering context-aware AR system for car maintenance and assembly operations based on the ontology of workspace context. Zhu et al. (2013) implemented context ontology in an AR bi-directional authoring system as ontology is independent of programming languages and enables context reasoning using first-order logic.

While knowledge is traditionally viewed as structured information, it can also be considered as information in context, i.e., both the content and the relevant context of the information should be considered (Chandrasegaran et al., 2013). By considering the context, one of the major challenges to employ AR is to provide in-situ information which is registered to the physical world (the context), and reduce the cognitive load of particular tasks. To provide the most relevant service/information to the users (e.g., directing user attention to specific workpiece features), application and service providers should be aware of their contexts and adapt to their changing contexts automatically, i.e., context-awareness, eliminating the need to search for the information. Context-awareness generally includes two aspects, namely, the status information of people, place, time and event, and the cognitive status of the users, such as attention and comprehension. Most of the efforts of context-aware AR assembly are focused on the first aspect, such as the accuracy of tracking as well as the recognition of the working scene. Efforts are still insufficient to establish context-aware AR systems that can reflect cognitive context fully. Recently, some of the literatures which focus on cognitive context have been introduced. Hervas et al. (2014) proposed a system to generate navigation based on the user's cognitive context to supply spatial orientation and cognitive facilitation rather than based on context information which belongs to the first item.

2.1.5 AR applications in manufacturing

Due to the growing amount of efforts in AR from several reputed corporations (IBM, HP, Sony, Google, etc.) and universities, this novel technology has been applied successfully in many areas, e.g., medicine (Sielhorst et al., 2008), maintenance and repair (Feiner et al., 1993), cultural heritage (Ridel et al., 2014) and education (Bower et al., 2014). In particular, Google Glass (http://www.google.com/glass/start/), a compact and lightweight optical see-through monocular display, provides two key benefits of AR, namely, encumbrance-free and instant access to information by affixing it in the user's visual field. AR has become increasingly more popular in industry applications (Green et al., 2007; Michalos et al., 2015). In this section, a brief review of the industry applications of AR is introduced. The application of AR assembly will be described in details in the next section.

2.1.5.1 Maintenance and repair

Maintenance and repair technicians can benefit from the implementation of AR technology in two aspects, namely, the ubiquitous rendered user interfaces can reduce the effort to perceive the instructions, and the AR environment allows remote collaboration to be achieved intuitively (Hincapie et al., 2011) (Figure 2-6). Henderson and Feiner (2009) implemented a set of tests to evaluate the benefits of AR for assisting technicians in managing and performing realistic maintenance sequences. According to their user study, AR-based maintenance systems improve the performance with higher accuracy rate and shorten task completion time. Lee and Rhee (2008) developed a ubiquitous car service system using AR technology, for the scenario of a user who needs to repair his/her mal-functioning car on the road. An authorable context-aware AR maintenance System (ACARS) is proposed to enable the intuitive creation of context-relevant information from the AR developers using desktops and the authoring of AR contents from maintenance technicians on-site (Zhu et al., 2013).

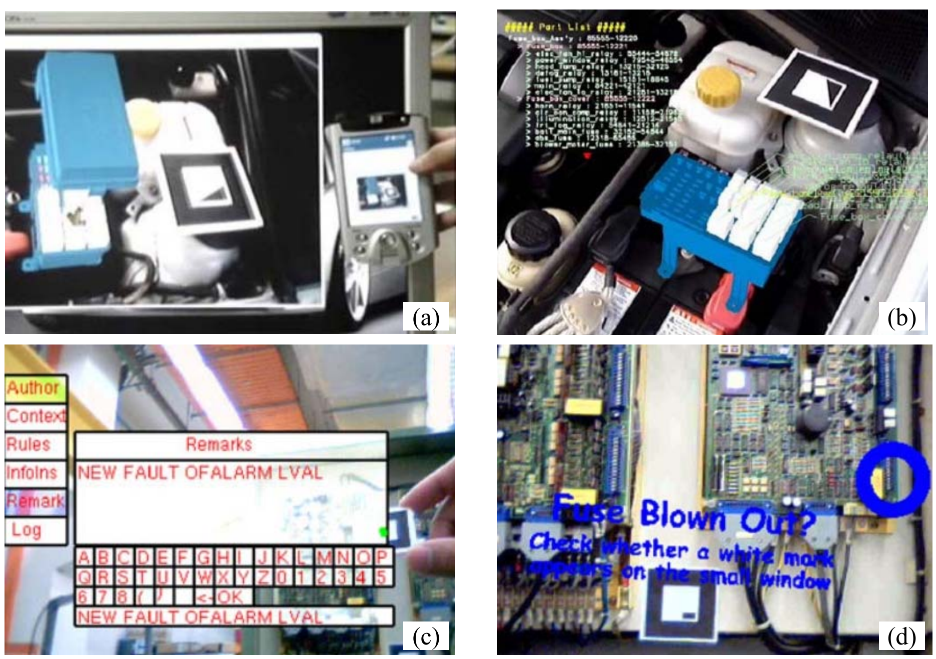


Figure 2-6 (a-b) AR based ubiquitous car service system (Lee and Rhee, 2008); (c-d) authorable context-aware AR maintenance system (Zhu et al., 2013)

2.1.5.2 Product design

A feature of AR product design systems is information visualization through augmenting virtual objects onto the real world. Ng et al. (2010) proposed an

AR computer-aided design environment (ARCADE) to support the interactive 3D modelling of everyday objects in AR environment for a layman. The users can create new designs through modifying and combining both virtual and real objects, and visualize them in a real design space.

In addition to overlay visual models for the users to determine product aesthetics, the behavior of a product can be simulated for the users to understand the functions of the products at the conceptual design stage (Ng et al., 2015; Takahashi and Kawashima, 2010). Ng et al. (2015) proposed a multi-level function-behavior-structure modeling framework to enable design reasoning and evaluation to ensure that the design is functionally and geometrically consistent. The functional behavior of a product can be simulated as a prototype in ARCADE to demonstrate the use of the product and detect potential usability issues (Figure 2-7).

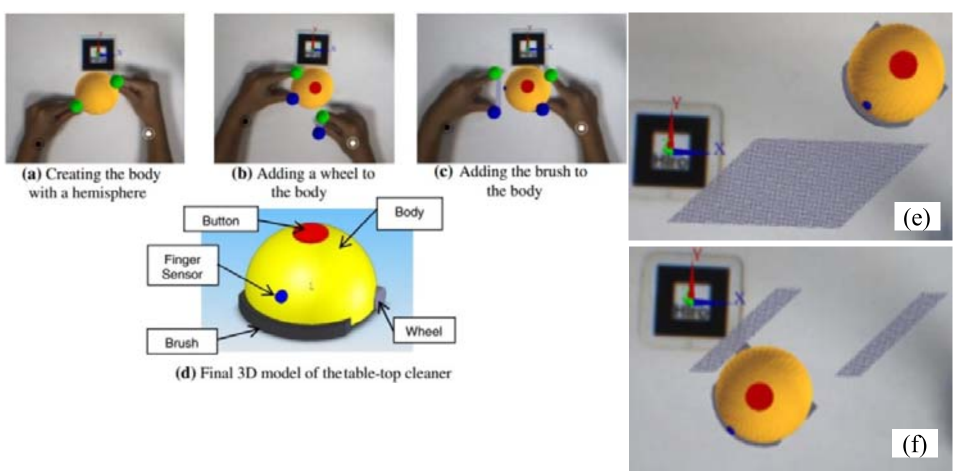


Figure 2-7 Generation of the table-top cleaner's 3D model (a-c); simulation of product functions (e-f) (Ng et al., 2015)

2.1.5.3 Other AR applications in manufacturing

As a technology that can overlay virtual information onto real scenes, AR has manifested its potential for facilitating computer-aided design and manufacturing (Figure 2-8). Over the past decade, extensive research efforts have been devoted to the applications of AR in a wide range of fields, e.g., facility layout planning (Jiang et al., 2014), robotic path planning (Fang et al., 2012), CNC machining process simulation (Zhang et al., 2010), etc. Jiang et al. (2014) proposed an AR-based hybrid facility layout planning approach. The system provides an interactive modelling method for obtaining the geometry information of the existing facilities to support real-time interactions between real and virtual contents. In addition, multiple criteria and constraints can be defined according to different task requirements of facility layout planning. Fang et al. (2012) developed the RPAR-II system for robot path planning and end-effector orientation planning using AR to enhance the human-virtual robot interaction. Using the RPAR-II system, a collision-free geometric path can be generated through human-virtual robot interaction in a real working environment for a pick-and-place task. CNC machining process simulation is another potential area for AR technology. An AR-assisted in-situ CNC machining simulation system, namely, the ARCNC system, has been developed (Zhang et al., 2010) for machining operations on a 3-axis CNC machine. This AR-assisted in-situ CNC simulation system consists of three main units, namely, a CNC machine, a display device, and the AR-assisted human-machine interfaces. Either a HMD or a monitor can be used in the in-situ system as the display device.

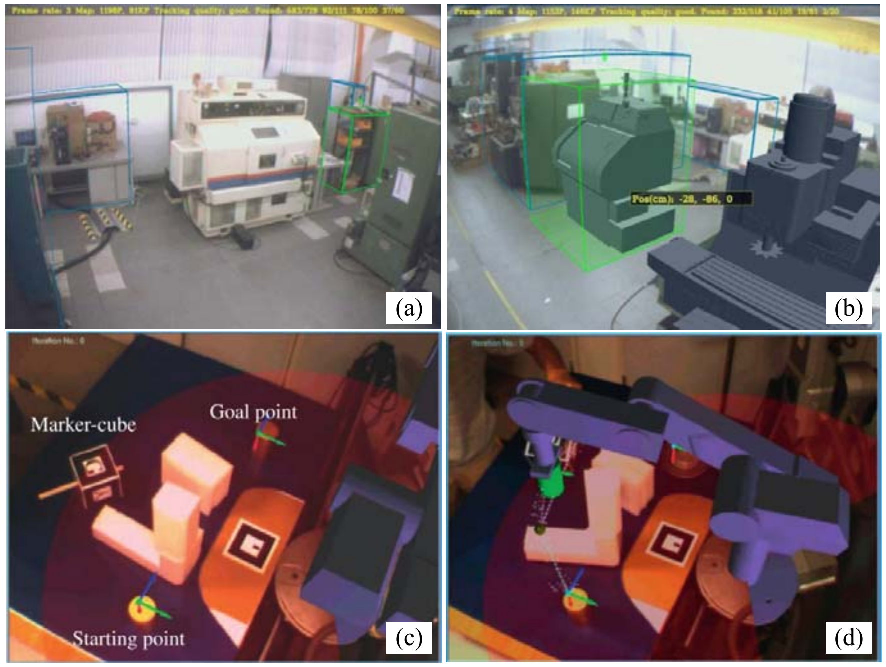


Figure 2-8 AR for facility layout planning (a-b) (Jiang et al., 2014); AR for robotic path planning (c-d) (Fang et al., 2012)

2.2 Research topics in AR assembly systems

2.2.1Typical architecture of an AR assembly system

AR technology can overcome the limitations in existing VR/CAD assembly systems as it does not need the entire real world to be modelled (Ong et al., 2008), thus reducing the high cost of fully immersive VR environments and the time consuming task in constructing the environment using commercial CAD systems. More importantly, AR enhances the interaction between the systems and the users by allowing them to manipulate the objects naturally. Therefore, AR technology has emerged as one of the most promising approaches to facilitate mechanical assembly processes. A typical AR assembly system is illustrated in Figure 2-9.

In Figure 2-9, six function modules, namely, video capture, image analysis and processing, tracking process, interaction handling, assembly information management and rendering are illustrated as the kernel modules to constitute the main loop of an AR assembly system. In addition, for each important function module, e.g., display or camera, there is a pop-up note to illustrate its characteristics, disadvantages, classifications, etc. Important pathways for data transferring on which the six kernel modules rely on are shown in color, e.g., input data pathways are in blue; while output data pathways are in orange.

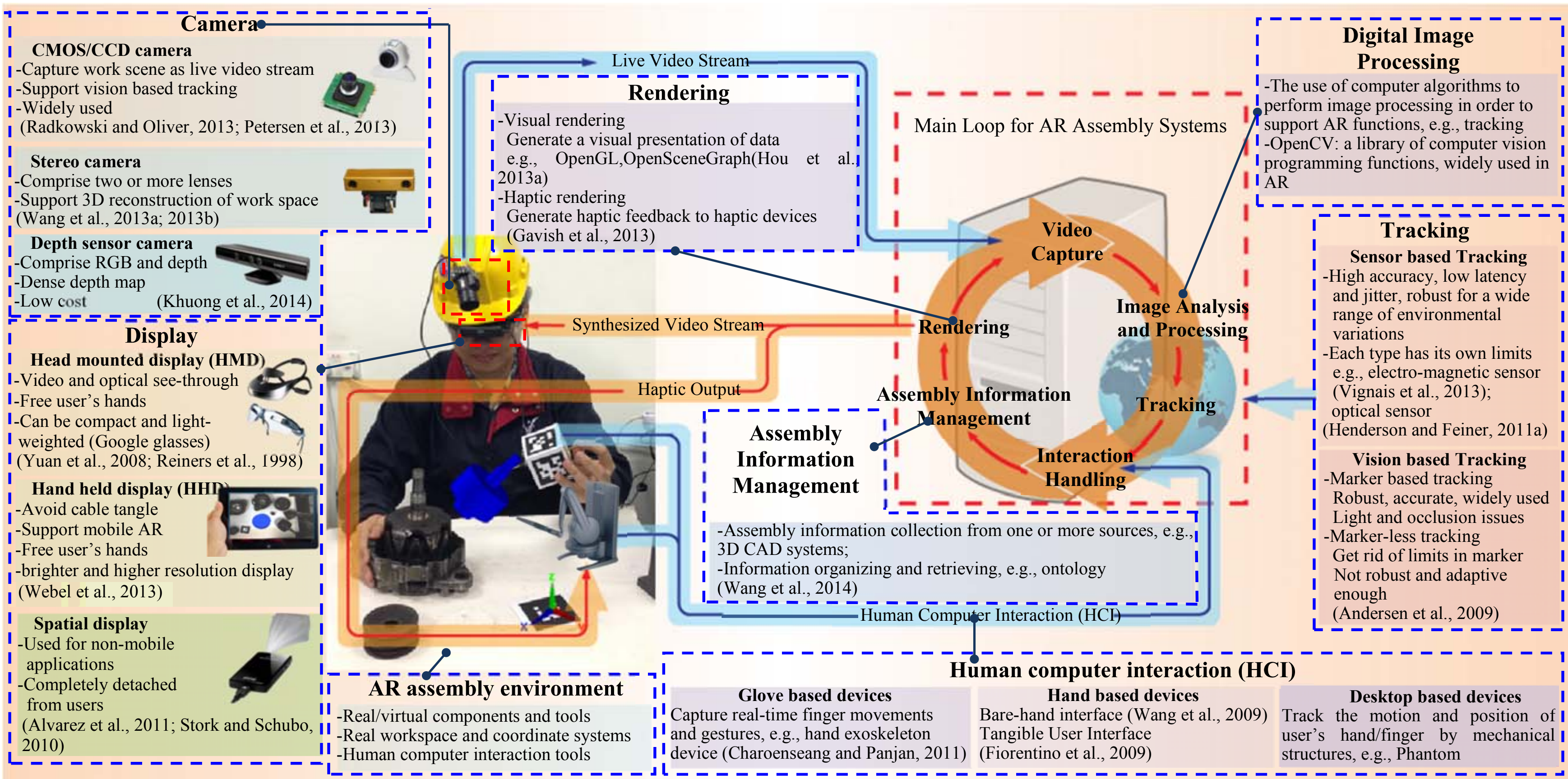


Figure 2-9 Typical AR assembly environment

2.2.1 Results of review of AR assembly research topics

During the evolution of AR assembly research, a variety of related research topics have been developed and discussed extensively. In this section, past AR assembly research has been grouped into three main categories and twelve sub-categories as shown in Table 2-1. Table 2-1 shows the number of research papers published in selected journals and conferences in each of these categories over time, and the final total percentage breakdown of the papers. Note that some papers discuss several topics and are not limited to one category.

As shown in Table 2-1, the main categories which constitute the whole AR assembly research include AR assembly guidance (120 articles, 39.47%), AR assembly training (68 articles, 22.37%), and AR assembly design, simulation and planning (116 articles, 38.16%). The category of AR assembly guidance can be divided into six sub-categories. Most of the articles that fall into this category are related to the topics of "Interactive instructions" (24 articles, 7.89%) and "Multi-media instructions" (26 articles, 8.55%). These research topics have a relatively steady number of publications per year. However, the number of papers on these topics may decrease gradually with the growing maturity of the field. Researchers also focus on context-awareness (21 articles, 6.91%), authoring (14 articles, 4.61%), effectiveness evaluation (24 articles, 7.89%), and usability evaluation (11 articles, 3.62%), which reflect more emerging research topics. These topics are under-rated because there are few publications in those topics in the past. However, these topics are attracting greater attention recently. For instance, manual AR authoring for an enterprise requires heavy investment, which can lead to redundant pathways, because manual efforts will be unnecessary if AR contents can be created automatically. Therefore, researchers are paying more attention to the topic of automatic creation of context aware AR contents for assembly operations by engineers and authoring staff as well as by the end-users (three articles in 2012, four articles in 2013, three articles since 2014). Another example is the evaluation methods for AR assembly; after almost two decades of research and development work, a framework to assess AR assembly systems is still unclear. The benefits achieved by the introduction of AR are still elusive without benchmarking with current procedures and objectives for an assembly task. Therefore, a growing number of researchers have begun to focus on the relevant topics on evaluation work, i.e., effectiveness evaluation, and usability evaluation.

The category of AR assembly training can be divided into three sub-categories. Most of the articles that fall into this category are related to the topics of "Assembly training for procedural tasks" (30 articles, 9.87%) and "Feedback for user's action" (29 articles, 9.54%). 2.96% (9 articles) concerns "Design guidelines", i.e., the development of guidelines that can form the fundamentals of an effective AR assembly training system. This topic has the potential to attract increasing attention from researchers because the design guidelines can be adapted and customized for a wide range of AR assembly training systems.

The category of AR assembly design, simulation and planning can be divided into three sub-categories, namely, "HCI" (55 articles, 18.09% in total; tool-based: 38 articles, 12.5%; glove-based: 5 articles, 1.64%; hand-based: 12 articles, 3.95%), “Assembly design and planning” (33 articles, 10.9%) and Assembly simulation (28 articles, 9.21%). “HCI” is one of the most popular research topics and the papers related to “HCI” accounts almost one-fifth of all the research works in AR assembly. This is reasonable because HCI is one of the fundamental enabling technologies in making AR assembly more useful, functional and reliable, and continues to be a popular research topic with many pertinent areas for research, e.g., bare-hand interface. All the three sub-categories of “AR assembly design, simulation and planning” are the areas where AR technology can demonstrate the greatest utility and highest potential for positive impact in assembly tasks.

Table 2-2 summarizes the major worldwide research effort using AR in mechanical assembly. The characteristics and disadvantages of the most representative systems in AR assembly, and the applications in modern assembly technology can be roughly categorized into three sections based on the life-cycle of product development, i.e., design and planning, operation guidance and training. Each section contains a brief overview of the key features and major applications with references to seminal publications and more comprehensive and specialized reviews provided for more in-depth reading. The discussion is interspersed with more detailed descriptions of selected recent studies, which demonstrate the current state-of-the-art and future trends which continue to find new and exciting applications across the assembly and other manufacturing technologies (Figure 2-10).

Table 2-1 Papers distribution over time in each category

Year	~00	01	02	03	04	05	06	07	08	09	10	11	12	13	14~	Σ	%
AR Assembly Guidance																	
Interactive instructions	3	0	0	1	1	1	0	1	2	2	1	5	1	2	4	24	7.89
Multi-media instructions	7	2	1	3	2	1	0	1	2	3	1	0	0	2	1	26	8.55
Context-awareness	1	1	1	1	1	1	0	0	1	0	1	3	3	4	3	21	6.91
Authoring	1	0	1	1	2	0	0	0	0	0	2	0	3	2	2	14	4.61
Effectiveness evaluation	2	0	0	2	1	1	0	0	4	1	1	5	0	5	2	24	7.89
Usability evaluation	1	0	1	0	1	1	0	0	1	2	1	1	0	1	1	11	3.62
AR Assembly Training																	
Procedural tasks	3	0	1	2	2	1	0	0	2	4	2	4	2	3	4	30	9.87
Design guidelines	0	0	0	0	0	0	0	0	0	0	2	6	0	1	0	9	2.96
Feedback	0	1	0	0	0	1	0	1	1	2	2	7	3	8	3	29	9.54
AR Assembly Design, Simulation & Planning																	
HCI (tool based)	4	0	0	2	2	1	1	2	4	6	3	4	5	3	1	38	12.5
HCI (glove based)	0	0	0	0	0	1	0	0	0	1	0	1	0	0	2	5	1.64
HCI (hand based)	0	0	0	0	0	0	0	1	0	1	1	3	1	3	2	12	3.95
Assembly simulation	0	0	0	0	0	2	1	1	3	5	3	7	1	4	1	28	9.21
Assembly design and planning	1	0	0	2	1	2	1	1	3	5	4	4	3	3	3	33	10.9
Total	23	4	5	14	13	13	3	8	23	32	24	50	22	41	29	304	100

Table 2-2 Major AR Assembly Research

Groups/Projects	Institutes	Area of work	Key Features	Limitations
Boeing (Caudell and Mizell, 1992), (Curtis et al., 1998), (Sims, 1994), (Mizell, 2001)	Boeing	Aircraft Design and Manufacture; Wire assembly of Aircrafts	*The first AR assembly system*; *HMD*: combined with head position sensing and a real world registration method; *Augmented Contents*: enable assembly operators to directly access digital CAD data when working	1. Ergonomic problems 2. The authoring process is sophisticated and expensive 3. Limited field of view 4. Time lag issues
Sharma's Group (Raghavan et al., 1999), (Molineros and Sharma, 2001)	The Pennsylvania State University	Assembly design and evaluation; Assembly sequence planning	*AR Assembly Planning*: Obtain the optimum assembly sequence aided by AR *Assembly Information Management*: a liaison graph facilitates the planner to consider various sequencing alternatives; *Multi-Marker-based Tracking*: provide the states of multiple tracked components simultaneously; *Assembly State Sensing*: get rid of fiducial markers; *Collaboration*: allow manufacturing engineer to interact with the assembly planner in AR environment	1. Detailed assembly process, i.e., human assembly operations and the geometry/motion information of the mechanical parts, is not considered; 2. Still in lab based prototype phase; 3. Application range of the proposed object recognition approach is limited.
STARMATE (2000 - 2003) (Schwald et al., 2001) (Schwald and Laval, 2003)	THALES, TECNATOM, CS SI, ZGDV, DUNE, EADS	Maintenance, assembly & disassembly, training	*Tracking Sensor*: electromagnetic/infra-red systems are implemented to support stable and accurate 3D tracking in real-time *HCI*: Speech and Point Input Device; *Mobility*: Mobile system.	1. The ergonomic issues of implementing HMD; 2. Electromagnetic system can suffer from magnetic disturbances in a workshop.

Table 2-2 Major AR Assembly Research (continued)

Groups/Projects	Institutes	Area of work	Key Features	Limitations
Columbia Computer Graphics & User Interfaces Lab (Feiner et al., 1993), (Henderson and Feiner, 2009, 2011a, 2011b)	Columbia University	Maintenance, assembly and construction	*Assembly Information Management*: an intelligent intent based illustration system to dynamically generate graphics *AR Assembly Guidance*: evaluate AR in psychomotor phase of a procedural task; *Domain Specific Study*: routine assembly operations to actual equipment in a field setting (professional military mechanics).	1. Not adaptive for other applications; 2. Rely on hardware, not portable.
NUS AR group (Pang et al., 2006), (Ong et al., 2007), (Yuan et al., 2008), (Wang et al., 2009), (Ong and Wang, 2011), (Zhang et al., 2011), (Ng et al., 2013), (Wang et al., 2013a; 2013b), (Wang et al., 2014)	National University of Singapore	Manufacturing	*HCI*: Bare-hand interface; virtual interactive panel & pen; RFID based interaction *AR Assembly Simulation & Planning*: constraint based, components contact handling, assembly feature design; *Assembly Information Management*: assembly tree data structure, ontology based assembly information structure; *Collaboration*: integrated design and assembly *Assembly State Sensing*: RFID based activity detection; *Tracking*: hybrid tracking and occlusion handling	1. A trade-off between bare-hand interface and haptic feedback need to be considered; 2. Feature design functions are still primitive in the prototype; 3. CAD models and information are required.

Table 2-2 Major AR Assembly Research (continued)

Groups/Projects	Institutes	Area of work	Key Features	Limitations
COGNITO(2010 -) (Gorecky et al., 2011), (Schaumloffel et al., 2011), (Damen et al., 2012), (Vignais et al., 2013), (Petersen and Stricker, 2012), (Petersen et al., 2013), (Mura et al., 2013)	DFKI, University of Bristol, University of Leeds, Centre National de la Recherche Scientifiques (CNRS) et al.	Assembly, training	*Context-sensitive authoring*: automatic instructions creation by segmenting a task video into segments on-site *Workflow monitoring*: activity recognition using sensor networks; ergonomics analysis in real-time; feedback on quality/correctness of task execution. *Recognition and Tracking*: in-hand tools and components; piecewise homographic transform strategy; relevance plane transform (RPT)	1. Cannot provide real-time feedback on the quality of task execution; 2. Only static postures were considered in ergonomics analysis; 3. Inertial sensors can suffer from magnetic disturbances.
SKILLS (2006 -) (Webel et al., 2011a), (Webel et al., 2011b), (Gavish et al., 2011), (Webel et al., 2013), (Gavish et al., 2013)	Aalborg University CEIT CEA LIST DLR KUKA Roboter GmbH et al.	Assembly, maintenance, training	*AR Assembly Training*: criteria and recommendations; sensorimotor skills as well as cognitive skills are considered; *Inter-discipline*: fusion research of cognitive science, psychology and computer science *Augmented Contents*: adaptive visual aids; *HCI*: vibrotactile bracelets;	1. Only simple haptic feedback is provided; 2. Not sure what is the optimal information visualization for different devices (e.g., HMD, tablets).

Table 2-2 Major AR Assembly Research (continued)

Groups/Projects	Institutes	Area of work	Key Features	Limitations
Augmented Reality and 3D Tracking Group (Salonen et al., 2007; 2009), (Salonen and Saaski, 2008), (Saaski et al., 2008)	VTT Technical Research Center of Finland	Assembly	*Authoring*: develop a content creation process for AR assembly instructions *Assembly Information Management*: Integrate CAD systems *Industrial Implementation*: AR assembly implementation in industrial settings	1. AR is only used to visualize information; 2. The interaction between the user and the scene is limited; 3. Authoring process is complicated and time consuming.
Billinghurst's group (Hakkarainen et al., 2008), (Lee et al., 2011), (Westerfield et al., 2013; 2015)	Human Interface Technology Laboratory New Zealand	Assembly	*HCI*: cubical user interface with distributed magnets for force feedback; mobile phone based interface for AR assembly *Adaptive guidance* combined with AR graphics	1. Limited assembly operations, e.g., screw driving and block assembly; 2. Marker based tracking limited accuracy, poor resistance to occlusion.
Center Of Excellence For Computational Mechanics (Fiorentino et al., 2009; 2010; 2012; 2013; 2014)	Politecnico di Bari	Assembly design and planning	*HCI*: tangible digital master *Data Management*: user can access/navigate/annotate the CAD model; define structural stress/constraint; manage layers and explore simulation results in a collaborative workspace *Authoring*: embed web engine to support dynamic labelling	1. Limited commands are supported in the tangible digital master; 2. Marker based tracking may be not robust and flexible enough for manufacturing environment.

Table 2-2 Major AR Assembly Research (continued)

Groups/Projects	Institutes	Area of work	Key Features	Limitations
Virtual, Augmented and Mixed Reality Group (Hou and Wang, 2011; 2013), (Hou et al., 2013a; 2013b)	Curtin University	AR assembly system evaluation	*Comparison Study (with traditional guidance)*: gender; cognitive workload; learning curve; stimulation of motivation. *Experimental Framework* for evaluating cognitive workload of using AR guidance in assembly tasks;	1. Experiments limited in laboratory based applications, e.g., LEGO assembly 2. The set of subjects (trainees) can be larger and more diverse.

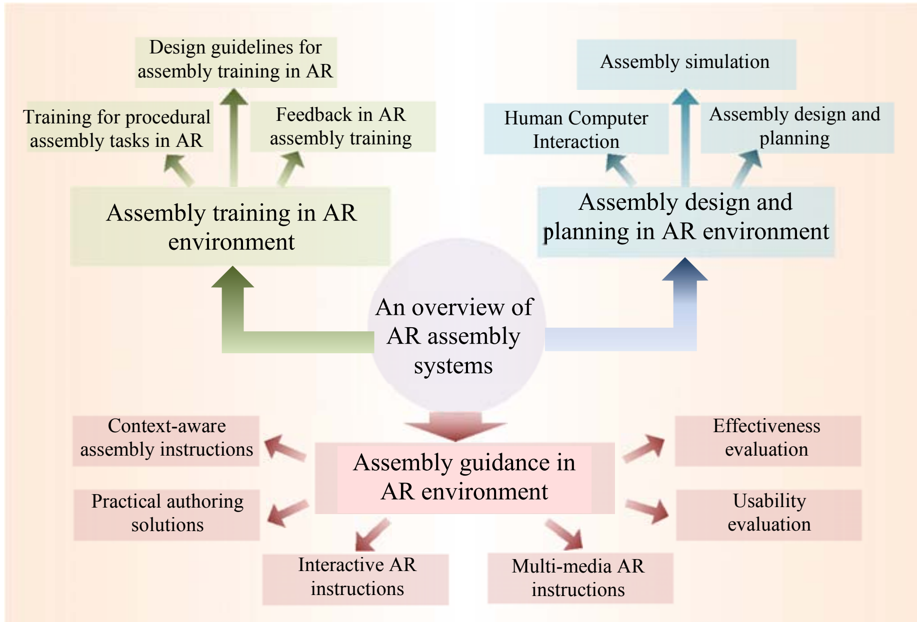


Figure 2-10 Major applications of AR technology in assembly tasks

2.2.2 AR assembly guidance

The relations between the research topics pertinent to AR assembly guidance are shown in Figure 2-11. The details of these research topics will be described in this section.

2.2.2.1 AR Multi-media and Interactive Instructions

Researchers (Caudell and Mizell, 1992; Sims 1994; Mizell 2001) have proposed the first implementation of a classic AR assembly system by combining head position sensing and real world registration with the HMD, such that a computer-generated diagram, containing pertinent information, can be superimposed and stabilized on a specific position on a real-world object. Since then, many research works on AR assembly guidance have been reported (Feiner et al., 1993; Webster et al., 1996; Curtis et al., 1998; Schwald et al., 2001; Syberfeldt, et al., 2015). Molineros and Sharma (2001) proposed an effective information presentation scheme using assembly graphs to control augmented instructions.

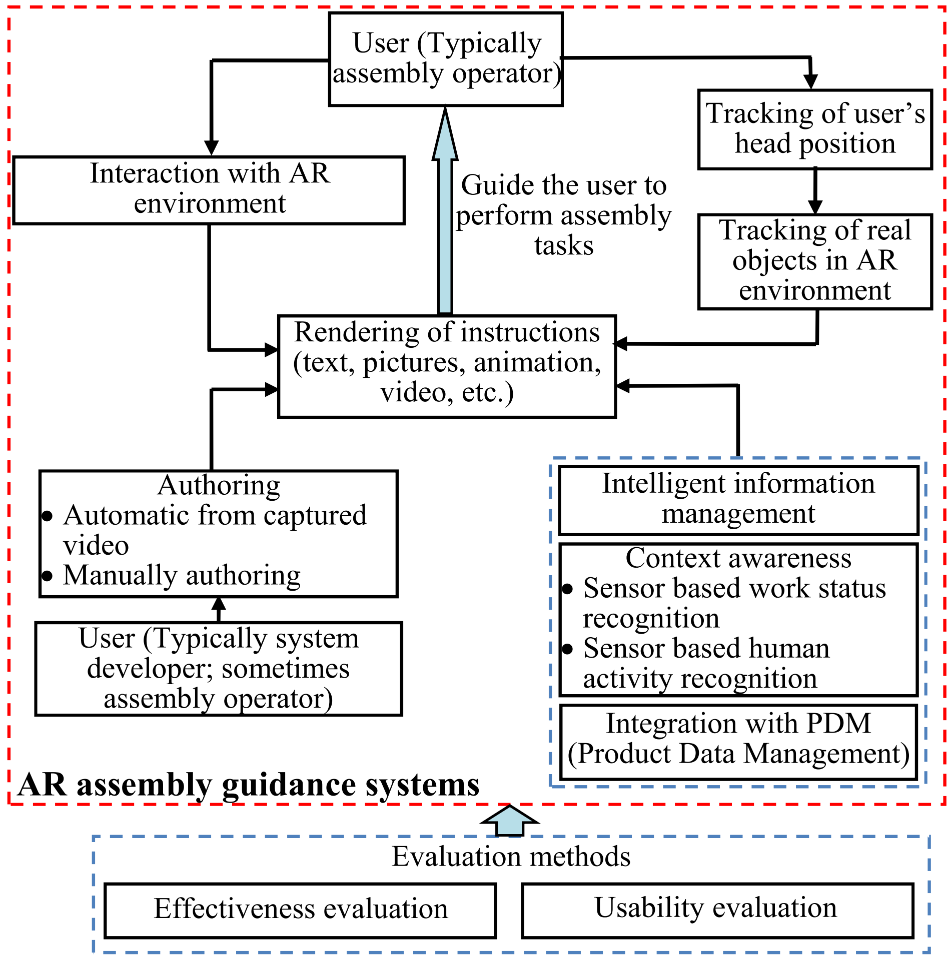


Figure 2-11 Topics related to AR assembly guidance

A few AR assembly systems have been applied in the industrial context (Schwald and Laval, 2003; Regenbrecht et al., 2005; Dul et al., 2012). Salonen et al. (2007; 2009), Salonen and Saaski (2008), and Saaski et al. (2008) proposed a series of AR assembly systems that focus on the implementation of an AR assembly system in a real setting in factory by integrating design for assembly software tools (CAD/PDM/PLM). Tumkor et al. (2013) assessed the potential of the implementation of AR in engineering educational tool for assembly. Recently, Makris et al. (2013) proposed a system which integrates AR technologies with the use of CAD data to provide visual instructions of assembly tasks (Figure 2-12b). Sanna et al. (2015) proposed a mobile AR guidance system which is aimed to support novice assembly operator to perform assembly tasks.

AR can provide intuitive interaction experience to the users by seamlessly combining the real world with the various computer-generated contents and therefore, many researchers focus on the development of interactive AR guidance systems for assembly processes (Kollatsch et al., 2014; Yuan et al., 2008; Pentenrieder et al., 2007). Sukan et al. (2014) presented an interactive system called ParaFrustum to support users to view a target object from appropriate viewpoints in context, such that the viewpoints can avoid occlusions (Figure 2-12a). Posada et al. (2015) described how visual computing methods in AR could contribute to assembly process guidance under the new industrial standard. Zhang et al. (2011) proposed a method to implement the RFID (Radio Frequency IDentification) technology in the application of assembly guidance in an augmented reality environment, aiming at providing just-in-time information rendering and intuitive information navigation for the assembly operator. Henderson and Feiner (2011a) presented the first AR system to aid users in the psychomotor phase of procedural tasks (Neumann and Majoros, 1998). The system provides dynamic and prescriptive instructions in response to the user's on-going activities. In order to enhance man-machine communication with more efficient and intuitive information presentation, Andersen et al. (2009) proposed a proof-of-concept system based on stable pose estimation by matching captured image edges with synthesized edges from CAD models for a pump assembling process.

In summary, previous works have shown the potential of AR assembly guidance systems providing multi-media and interactive instructions to improve the performance of the users. However, limitations exist in current AR systems when assisting users with complex assembly processes and the issues include time-consuming authoring procedures, integration with enterprise data, intuitive user interface, etc. Future work should examine the appropriateness of AR guidance for more complex, multi-step assembly tasks. In addition, although interactive AR assembly guidance has improved the traditional step-by-step guidance systems by providing pertinent information according to the user's requirement, the interaction scheme may disturb or interrupt the user's on-going assembly task. Therefore, it is imperative to work on detecting and recognizing the users' actions in order to provide an industrial robust hands free interaction.

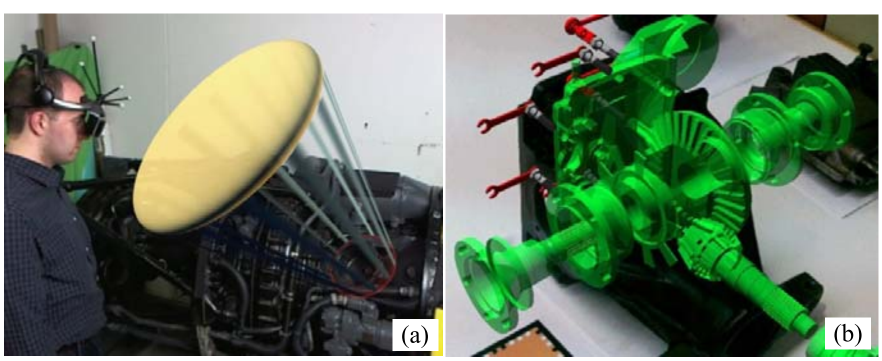


Figure 2-12 ParaFrustum (a) (Sukan et al., 2014); AR assembly guidance with data from CAD models (b) (Makris et al., 2013)

2.2.2.2 Context-Awareness and Authoring

Aiming at improving labor efficiency and accuracy, a context-aware AR assembly system keeps track of the status of users in real-time, automatically recognizing manual errors and completion at each assembly step and displaying multi-media instructions corresponding to the recognized states (Khuong et al., 2014). The ARVIKA project (Friedrich, 2002) provides a context-sensitive system to enhance the real field of vision of a skilled worker, technician or development engineer with timely pertinent information. Rentzos et al. (2013) proposed a context-aware AR assembly system, which integrates the existing information and knowledge available in CAD/PDM systems based on the product and process semantics, for real-time support of the human operator. Zhu et al. (2014) proposed a wearable AR mentoring system to support assembly and maintenance tasks in industry by integrating a virtual personal assistant (VPA) to provide natural spoken language based interaction, recognition of users' status (e.g., skill level, position, etc.), and position-aware feedback to the user (Figure 2-13c). Recently, there are studies on the recognition and tracking of the pose of the objects in an assembly such that corresponding information can be retrieved from the system. For instance, Radkowski and Oliver (2013) proposed a recognition method based on SIFT (scale-invariant feature transform) (Lowe, 1999) features to distinguish multiple circuit boards and to identify the related feature map in real time during the circuit assembly tasks (Figure 2-13d). In order to implement context-aware AR systems, 3D models of workspace scenes are often required, whether for registration of the camera pose and virtual objects, handling of occlusion, or authoring of pertinent information. However, there seems to be a lack of discussion on the topic of in-situ 3D working scene modelling in some of the proposed context-aware AR systems.

Researchers have investigated the impact of context-aware based AR on the performance of human operators as well as reducing their fatigue during assembly tasks by providing real-time user ergonomic feedback. Chen et al. (2015) proposed an adaptive guiding scene display method in order to display the synthesized guiding scene on suitable regions from an optimal viewpoint (Figure 2-13a). Damen et al. (2012) proposed a real-time AR guidance system to facilitate the sensing of activities and actions within the immediate spatial vicinity of the user. Vignais et al. (2013) proposed a system for the real-time assessment of manual assembly tasks by combining sensor network and AR technology to provide real-time ergonomic feedback during the actual work execution (Figure 2-13b).

The above systems have been demonstrated to be useful based on the user study. However, in order to be more robust, the systems need to be task-adaptive, i.e., suited for a wide range of different tasks, when they are implemented in the complex industrial tasks, because it is time-consuming to build *ad hoc* systems for tasks with different scenes and different task contents. Moreover, the implementation issues of sensors should be considered. For example, the magnetic field sensed by the sensors may be affected to yield stable and accurate pose results due to the presence of metal objects in an assembly.

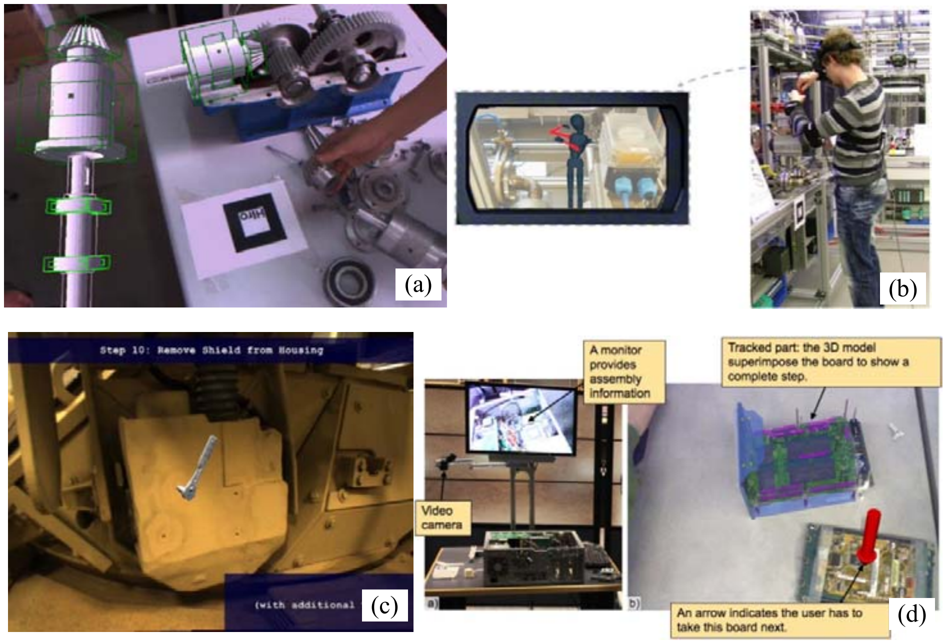


Figure 2-13 (a) Context adaptive AR guidance (Chen et al., 2015); (b) real time ergonomic feedback (Vignais et al., 2013); (c) AR mentoring system (Zhu et al., 2014); (d) on-site AR assembly guidance (Radkowski and Oliver, 2013)

Practical authoring solution in AR systems is another popular research topic which has been sought after by the researchers, who have attempted to support complex assembly tasks with AR-integrated systems to minimize costs for specialized content generation (Haringer and Regenbrecht, 2002; Zauner et al, 2003; Servan et al., 2012). Petersen and Stricker (2012), and Mura et al. (2013) reported proof-of-concept systems to create interactive AR manual automatically (for assembly, maintenance, etc.) by segmenting video sequences and live-streams of manual workflows into the comprising single tasks. Petersen et al. (2013) extended these approaches to extract the required information from a moving camera which can be attached to a user's head, providing *ad hoc*, in-situ documentation of workflows during execution (Figure 2-14c-d). Bhattacharva and Winer (2015) presented a method to generate AR work instructions in real time. Mohr et al. (2015) proposed an AR authoring system to transfer typical graphical elements in printed documentation (e.g., arrows indicating motions, structural diagrams for assembly relations, etc.) to AR guidance automatically (Figure 2-14a-b).

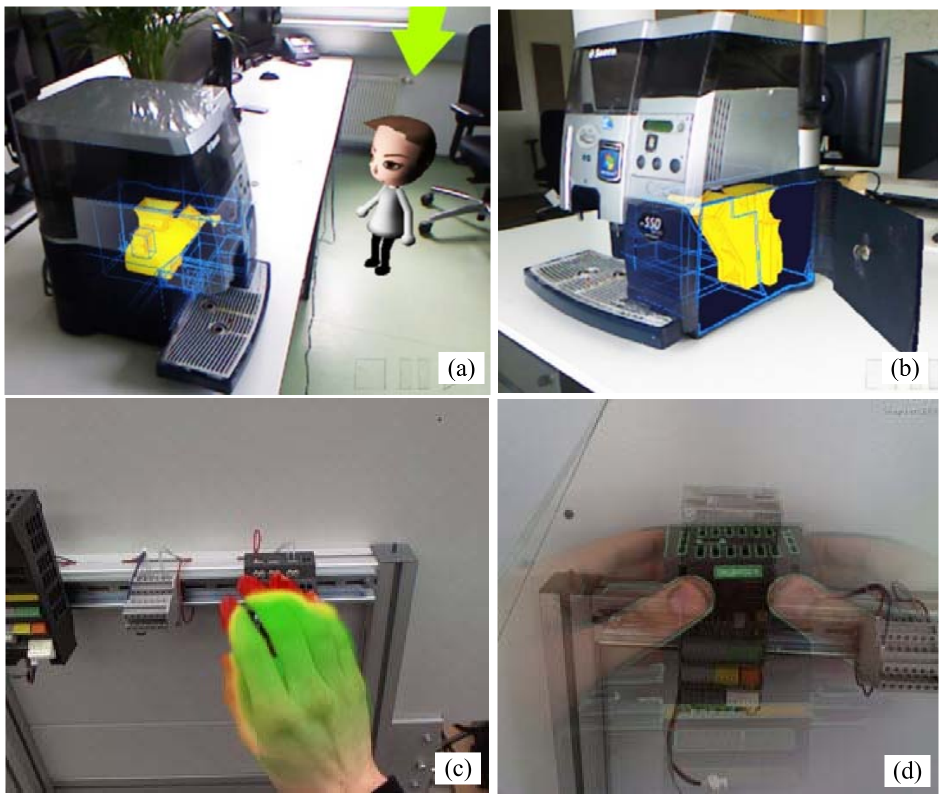


Figure 2-14 (a-b) user navigation to the extracted point of view (Mohr et al., 2015); (c-d) AR authoring by extracting information from a moving camera (Petersen et al., 2013)

AR assembly authoring systems have been enabled to cope with manual assembly operations efficiently. However, the use of AR authoring in complex industrial areas is still imperative and needs further development so that the AR authoring systems can become smart enough to understand a user's intent and generate timely context-aware guidance during assembly operations without manual input.

2.2.2.3 Evaluation of AR assembly guidance

The evaluation studies of AR applications can be roughly classified into two types, namely, effectiveness evaluation and usability evaluation (Hou and Wang, 2013). Effectiveness evaluation concerns evaluating the capability of an AR system to produce a desired result for a certain task or activity, e.g., improvement of productivity, assembly performance time, number of errors, etc. Odenthal et al. (2014) proposed a comparative study of the performance of a human operator in the event of an assembly error using head-mounted and table-mounted Augmented Vision System (AVS). Hou et al. (2013b) reported an empirical analysis in the use of AR technology for guiding workers in the field of construction assembly and evaluated the effectiveness of AR-based animation in facilitating piping assembly. The results in these works indicated a positive effect of facilitation when using the AR system in assembly tasks. Besides that, several research studies have been published that present comparative work on video see-through and optical see-through AR displays with traditional assembly instruction manual or computer-aided instruction to demonstrate the usefulness and intuitiveness of AR conditions (Baird and Barfield, 1999; Tang et al., 2003; Wiedenmaier et al., 2003; Odenthal et al., 2011). Several studies were published on comparing AR assembly systems with other types of assembly facilitation systems, e.g., VR systems, user manual based systems and audio-visual tools based systems (Boud et al., 1999; Rios et al., 2011; Suarez-Warden et al., 2011). Recently, Gavish et al. (2013) reported their empirical evaluation of efficiency and effectiveness of AR and VR systems within the scope of the SKILLS Integrated Project for industrial maintenance and assembly (IMA) tasks training to demonstrate the usefulness of the AR platform. Radkowski et al. (2015) presented an analysis of two factors that may affect the effectiveness of AR assembly training systems, namely, the complexity of the visual features, and the complexity of the product.

Usability evaluation involves investigating the ease of use and learnability of the AR assembly systems based on needs analysis, user interviews and expert evaluations. In order to test the usability of AR technology in assembly tasks, Henderson and Feiner (2009; 2011b) presented a within-subject controlled user study for a comparison of three setups for assembly and maintenance operations of a military vehicle under field conditions. Gattullo et al. (2015) proposed a set of experiments to test variables affecting text legibility and focus on deriving criterion to facilitate designers of AR interface. Recently, researchers have begun to focus the usability evaluation on the cognitive load for users (Hou and Wang, 2011; Hou et al., 2013a). The cognitive activities concern those involved in the reasoning and volitional processes that go on between perception and actual actions (Hou and Wang, 2013). Stork and Schubo (2010) investigated human cognition in AR production environments to study the benefits achieved from AR in assembly tasks. Hou et al. (2013a) proposed a set of initial experiments to assess the discrepancies between the traditional guidance and AR to evaluate the efficiency of learning or training for people involved in the assembly of complex systems.

For both effectiveness and usability evaluation, there is a large diversity among these studies with respect to the various interaction methods, virtual instructions rendering, and the level of complexity of the product. Thus, different factors that influence the effectiveness and usability of an AR assembly system are still not clear. Previous research works indicate that the use of AR for a specific *ad hoc* assembly task is beneficial. However, few works focus on the evaluation of these systems for a variety of assembly tasks varying in different factors. Therefore, the general evaluation framework and method for AR systems suited for a wide range of assembly tasks should be investigated to reflect the characteristics and effectiveness of AR systems (e.g., portability, visual intuitive, cognitive load, etc.). In addition, since emerging AR systems and services introduce a new level of complexity with respect to usability evaluation, researchers tend to become more interested in evaluating novel AR interfaces, especially how these interfaces can improve human resource capabilities and the attendant human factors.

2.2.3 AR assembly training

Training activities for technicians in the acquisition of new assembly skills play an important role in the industry. AR has been shown effective to support assembly training in some particular industrial context due to its time-efficiency, high effectiveness and the assurance for technicians to achieve an immediate capacity to accomplish the task (Reiners et al., 1998; Boulanger, 2004; Horejsi, 2015). The relations between the research topics pertinent to AR assembly training are shown in Figure 2-15.

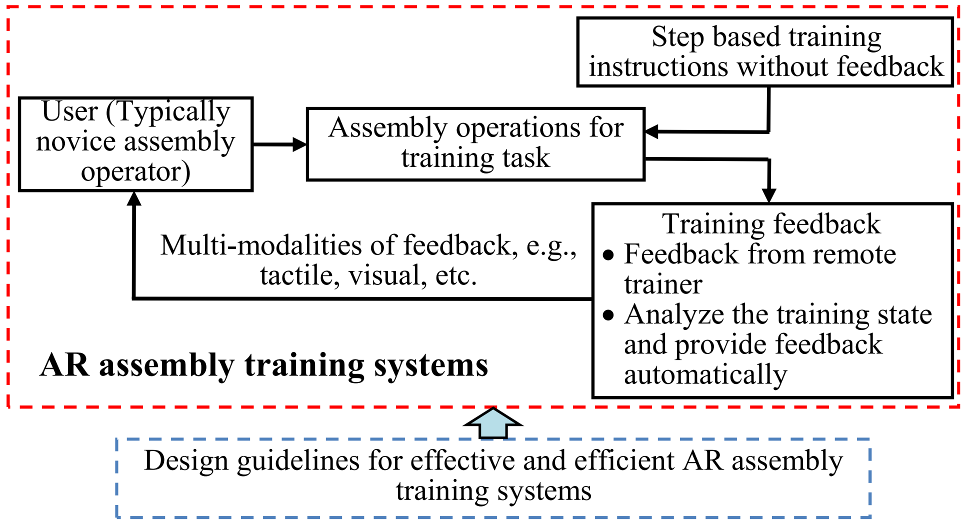


Figure 2-15 Topics related to AR assembly training

Research in this area has largely involved procedural tasks where a user follows visual or other multi-modal cues to perform a series of steps, with the focus on maximizing the user's efficiency while using the AR system (Simon et al., 2014; Peniche et al., 2012). Fiorentino et al. (2014) proposed an AR assembly training system based on large screen projection technology for the rendering of AR instructions. Liu et al. (2015) proposed an AR based system for the assembly of narrow cabin products to promote the efficiency of assembly training and guidance by creating an information-enhanced AR assembly environment. The European project STAR (Service and Training through Augmented Reality) (Raczynski and Gussmann, 2004) was developed for industrial training. It was reported that in this project, the test subjects could complete the assembly task significantly faster with fewer errors due to the employment of spatially-registered AR. While there has been much research into the use of AR to aid assembly training, most systems guide the users through a fixed series of steps and provide minimal feedback when the users make a mistake, which is not conducive to learning. In order to improve this issue, Gorecky et al (2011) proposed two novel techniques for cognitive aid and training in the European project COGNITO, namely, the active recognition using sensor networks and workflow recognition. The system can analyze and record assembly workflows automatically by observing experienced technicians in building up a system-internal understanding of assembly processes. Matsas and Vosniakos (2015) proposed an interactive and immersive simulation environment to facilitate training of simple manufacturing tasks with information feedback, e.g., safety issues, situational information.

Ability to provide feedback is an important factor in the training process which has received much attention (Pathomaree and Charoenseang, 2005; Kreft et al., 2009; Charoenseang and Panjan, 2011). Re and Bordegoni (2014) presented a monitoring system for training, such that supervisors can check the assembly/maintenance activity from a remote display and provide feedback to the users whenever necessary. Kruger and Nguyen (2015) proposed an approach to compute the positions of each part of worker's body with captured input depth images, and analyze the ergonomic scores (Figure 2-16b). Webel et al. (2013) investigated the implementation of tactile feedback and location-dependent AR information (adaptive visual aids) during the AR training process to verify the usefulness of the multimodal AR training system. Westerfield et al. (2013; 2015) integrated the Intelligent Tutoring Systems (ITSs) with AR interfaces to provide customized instruction to each trainee (Figure 2-16a). Researchers have focused on design guidelines for the design of AR assembly training systems. Chimienti et al. (2010) suggested a general procedure for unskilled operators to follow correct implementation of AR assembly training. Besides, an interdisciplinary study of AR-based assembly training using cognitive science and psychology has been reported by Webel et al. (2011a, 2011b) and Gavish et al. (2011).

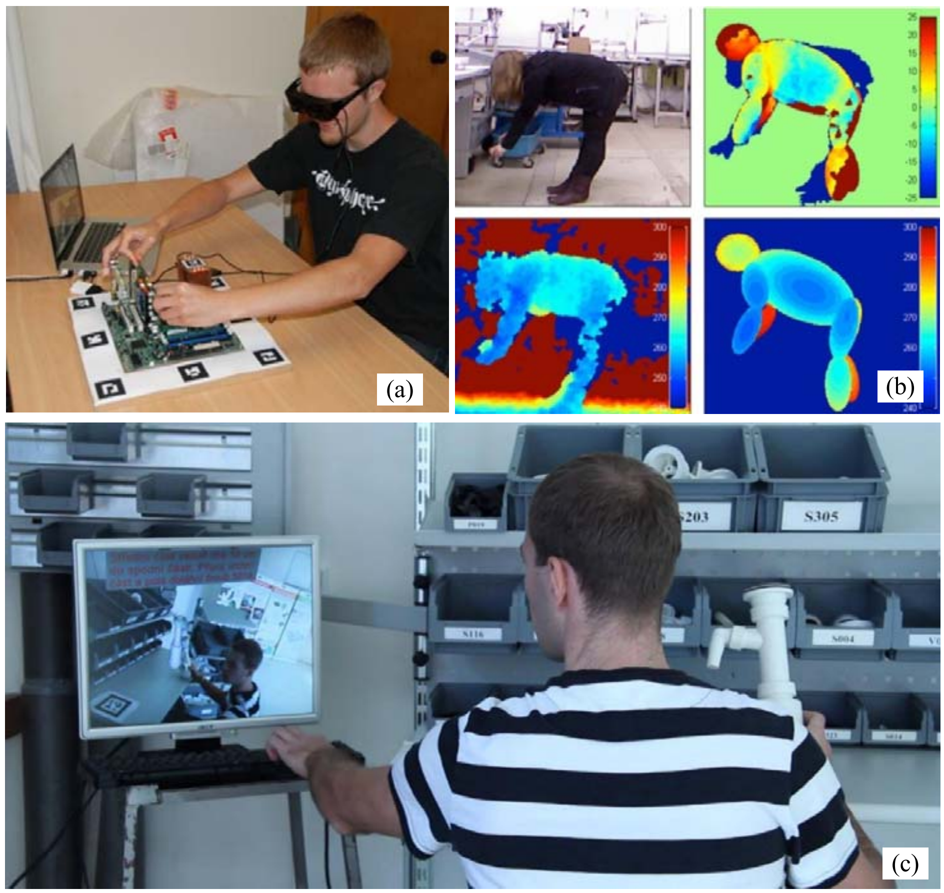


Figure 2-16 (a) AR training of motherboard assembly (Westerfield et al., 2015); (b) ergonomic analysis of trainees in assembly operation (Kruger and Nguyen, 2015); (c) AR assembly training (Horejsi, 2015)

A major challenge in the industry for AR assembly training is the ability to handle complexity in terms of number of components, safety, assembly difficulties, and rapid updating of assembly skills, though the procedures of assembly skills training are relatively static and predictable. In particular, assembly methods are adapted to various products, and they are dependent on the mating and connection relations between components. Therefore, in future, the adaptability to various methods and difficulty levels of assembly operations would be expected to be integrated with the AR assembly training system to enhance a user's comprehension. The compatibility and optimization of such integration should be investigated, such that the new AR assembly training systems can be developed in tandem with current trends of agile product development and manufacturing.

2.2.4 AR assembly process simulation and planning

Among the topics in AR assembly simulation and planning, objects manipulation has been widely studied (Billinghurst et al., 2008; Wu and Wang, 2011; Leu et al., 2013). Marcincin et al. (2011) implemented a set of open source tools to track the position and orientation of the assembly operation working base with a special gyroscopic head to measure the base's rotation, and a pantograph mechanism to measure the tilting motions. Based on the position data obtained, the authors utilized open source software to manage the visualization and simulation of the virtual objects in the assembly process, reacting flexibly to the occurrence of events and situations. The authors also developed a system which allows users to view important information about the exact position and orientation of a single assembly element during AR assembly (Marcincin et al., 2014). Woll et al. (2011) proposed an AR assembly simulation system to aid the assembly of a car generator, that allows the user to experience the spatial relationship between the components, thus enhancing the transition from assembly instructions into practical skills.

Researchers have worked on the improvement of the 3D spatial feeling in AR assembly simulation by employing geometric relations between objects. However, many of the current AR assembly simulation systems seem to be limited to the interaction between virtual objects and have ignored an important issue of incorporating real objects into the AR environment to provide the core benefits of AR, which are haptic feedback, natural interaction and better manipulation intuition. Wang et al. (2005) proposed a pipeline to incorporate real objects, e.g., tools, parts, etc., in the AR assembly workspace, such that a user can interact with several real objects among virtual objects. Nevertheless, the proposed system is a proof-of-concept prototype with several limitations, e.g., limitations of colored marker tracking, limited tracked volume, etc. Wang et al. (2010) proposed a prototype to realize the interaction between real and virtual objects. However, its scope of application in the industry is limited, as it assumes that the position and orientation of the real object as well as the pose of the camera are fixed during AR assembly.

Much effort has been reported to achieve natural and intuitive HCI in AR assembly. Velaz et al. (2014) conducted a set of experiments to compare the influence of the interaction approaches (including mouse, haptic device, marker-less hands 2D/3D motion capture system) on the virtual object manipulation of assembly tasks. Theis et al. (2015), Valentini (2009) and Wei and Chen (2010) reported interactive virtual assembly systems based on the use of a sensor-based glove. Lee et al. (2011) presented a two-handed tangible AR interface, which is composed of two tangible cubes tracked by a marker-based tracker, to provide two types of interactions based on familiar metaphors from real object assembly. These HCI methods can be accurate and intuitive, but they have high cost and require cumbersome devices. Recently, hand-based HCI has become a much pursued research topic in AR assembly simulation (He et al., 2010; Boonbrahm and Kaewrat, 2014). Arroyave-Tobon et al. (2015) proposed a hand gesture-based interaction tool named AIR-MODELLING to facilitate the designer to create virtual models of products in an AR environment (Figure 2-17a). Radkowski and Stritzke (2012) reported a method based on Kinect to observe both hands of an assembly operator, such that the system can support the operator to select, manipulate and assemble 3D models of mechanical systems. Ong and Wang (2011) and Wang et al. (2009) presented intuitive and easy-to-use interaction approaches in an AR assembly environment based on bare-hand interaction. Wang et al. (2013a) proposed a methodology to integrate 3D bare-hand interaction with an interactive manual assembly design system for the users to manipulate the virtual components in a natural and effective manner. However, since the majority of current hand-based approaches require users to undertake specific simple actions to achieve the interaction with the AR environment, these approaches lack intuitiveness. Furthermore, in the case of hand gesture-based HCI interfaces, only a few limited types of gestures have been used and the gestures are designed by researchers for optimal recognition rather than for naturalness, meaning that the mappings between gestures and commands of the computer are often arbitrary and unintuitive (Piumsomboon et al., 2013).

AR assembly systems can be created to enhance the assembly design and planning process (Raghavan et al., 1999; Liverani et al., 2004). Pan et al. (2014) proposed an automatic assembly/disassembly simulation method for accurate path planning of virtual assembly. Some works have been reported that combined manual assembly guidance with assembly planning to improve the whole assembly planning and operation process (Reinhart and Patron, 2003; Wiedenmaier et al., 2003; Zhang et al., 2010). Ong et al. (2007) and Pang et al. (2006) presented an AR-based methodology to integrate assembly Product Design and Planning (PDP) activities with Workspace Design and Planning (WDP). Aided by the WDP information feedback in real time, the designers and engineers could make better decisions for assembly design. Fiorentino et al. (2009, 2010, 2012, 2013) presented a series of work to describe assembly design review workspace by acquiring gesture commands based on a combination of video and depth cameras. Recently, as a new trend for AR assembly research, Wang et al. (2013b) and Ng et al. (2013) presented an AR system that integrates design and assembly planning to support ergonomics and assembly evaluation during early product development stage.

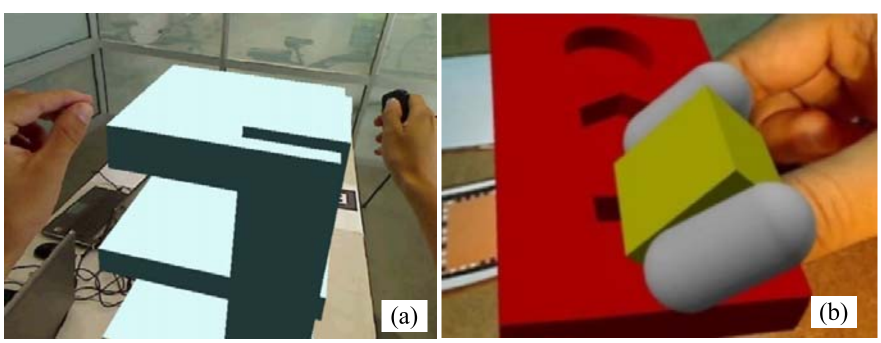


Figure 2-17 (a) AIR-MODELLING (Arroyave-Tobon et al., 2015); (b) hand based interaction tool in object manipulation (Boonbrahm and Kaewrat, 2014)

The implementation of assembly design and planning in the AR environment is promising and a growing number of researchers have studied this area. However, some limitations still exist in the state-of-the-art systems in this area, e.g., accuracy issue, intuitiveness and dependency on CAD software. Focusing on these issues, one solution is to construct an integrated AR assembly platform which can model the interaction between mating components accurately in an assembly. In addition, it is important to implement an information management method that can extract information from a CAD system, and store and reason the assembly relations independently with enhanced inference functions.

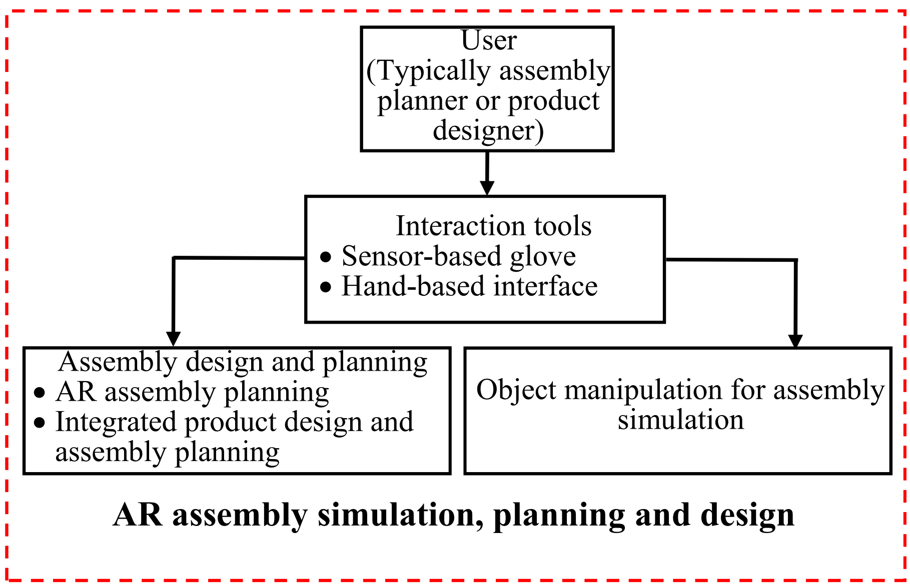


Figure 2-18 Topics related to AR assembly simulation, planning and design

3. Detailed System Description

3.1 Introduction

The objective of this research is to develop an integrated AR-assisted assembly environment (IARAE) that integrates assembly motion simulation (AMS) and assembly operation guidance (AOG) to support both product developers (e.g., product designer, assembly planner) and assembly operators. In this chapter, the detailed architecture of the IARAE system is presented.

3.2 System architecture

The system has six functional modules, which are AR-based Task Environment (ARTE), AR Kernel Functions (ARKF), AR Tracking and Registration (ARTR), Assembly Information Management (AIM), AR Assembly Motion Simulation (ARAMS), and human cognition-based interactive augmented reality assembly guidance module (CARAGM). Four modules (ARTE, ARKF, ARTR, AIM) serve as common functional modules, which are shared by the other two main functional modules, namely, ARAMS and CARAGM. The architecture of IARAE is depicted in Figure 3-1. In IARAE, the components manipulated by the user (real and/or virtual) are referred to as reference components, and the components to which the reference components are assembled onto are referred to as target components.

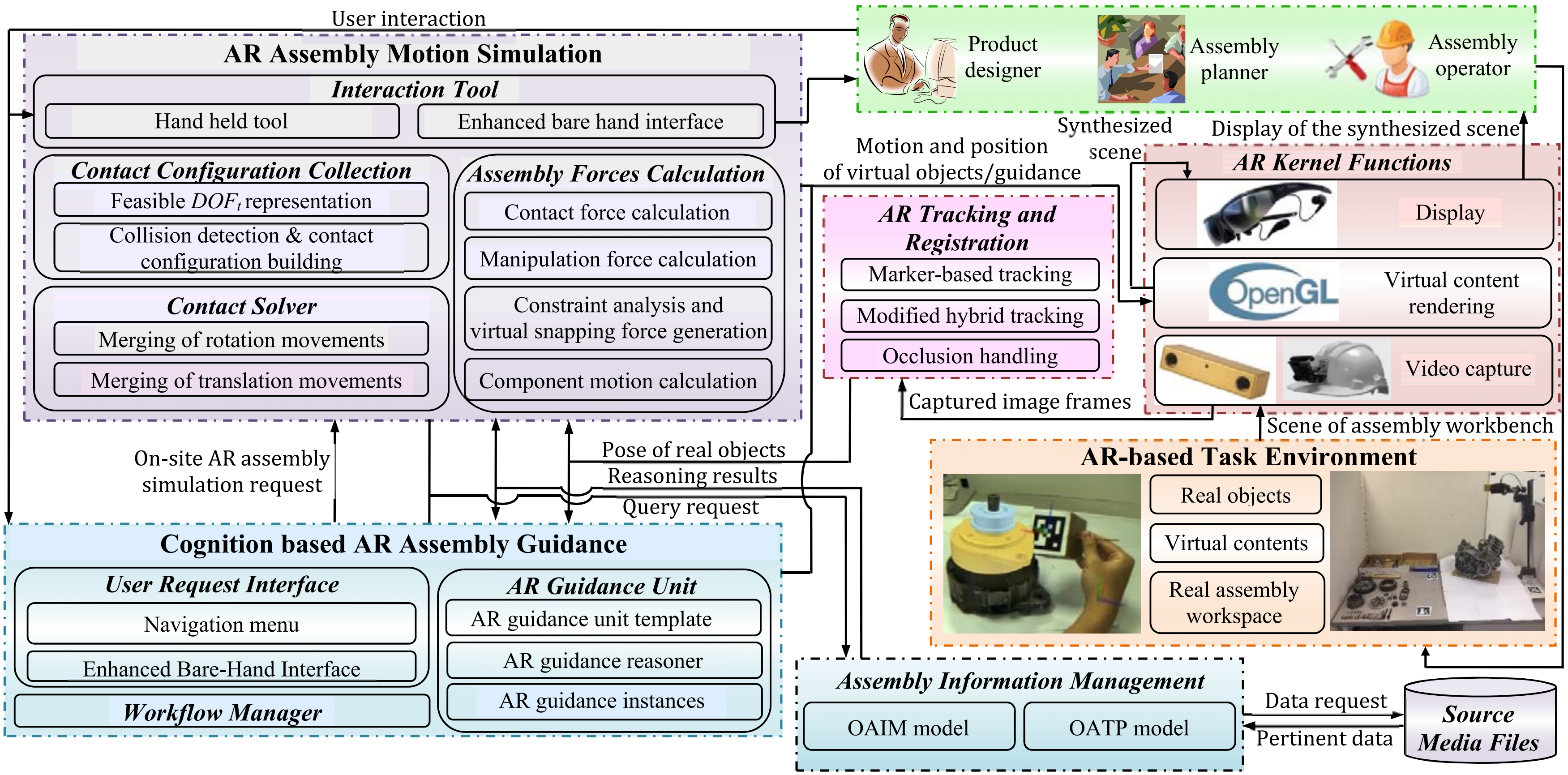


Figure 3-1 The architecture of IARAE

1. The ARTE is a real industrial assembly workbench for the users. In ARTE, computer-generated graphics are superimposed onto the real workbench for interaction with real components, interaction tools and the surroundings in order to enhance the user's perception when simulating, assessing and/or performing an assembly task. The ARKF module captures the scene of the assembly workbench from ARTE and transmits continuous image frames to ARTR. The ARTR module transmits assembly status (pose/position of real components/tools/workbench) to the ARAMS module and CARAGM. These two modules transmit the motion and position of virtual components/guidance to the ARKF module to support the registration, rendering and display of augmented contents in ARTE. The details of the implementation of ARTE, ARKF and ARTR are discussed in Chapter 4.

2. The AIM module stores all the assembly information extracted from CAD models based on ontology. Two novel ontology-based models are proposed in this research, namely, Ontology-based Assembly Information Model (OAIM) and Ontology for Assembly Tasks Procedure (OATP). The information can be accessed and modified during AR-based assembly simulation and AR assembly guidance respectively. The SMF (Source Media Files module) stores the source media file data which is necessary for the AR assembly motion simulation and AR guidance retrieval in the CARAGM. The details of the implementation of AIM are discussed in Chapter 5.

3. In the ARAMS module, users, primarily assembly planners and/or product designers, can manipulate both real and virtual components to interact with other components to verify the design. By implementing collision detection to detect the contact, both physics-based and geometry-based methods are integrated to model the virtual component behavior. A novel real time motion simulation method, namely, component contact handling (CCH), comprising contact configuration collection and contact solver, is proposed to model the contact process. The method is based on the information stored in AIM so that the behavior of components during assembly can be simulated accurately from a geometric perspective. A method to calculate the resultant forces exerted on virtual components from contacts with real components and manipulation from the user's hands (forces and torques applied, etc.) during an assembly process, and constraint analysis and component virtual snapping force generation are proposed to support AMS from a physical perspective. In addition, two interaction tools are provided to enable users to manipulate virtual components intuitively. The details of the implementation of ARAMS are discussed in Chapter 6.

4. The CARAGM manages the workflow of the AR assembly process and determines when, where, what and how to augment the virtual guidance in the ARTE to facilitate the user, and how to handle a user's request for guidance. The guidance is transmitted to ARKF so that they can be rendered to support assembly operations in real-time. An enhanced-bare-hand interface (EBHI) is proposed to support both hand gesture commands input and intuitive 3D manipulation of virtual contents in the AR

environment. The details of the implementation of CARAGM are discussed in Chapter 7.

4. AR Enabling Technologies in IARAE

4.1 Introduction

In this chapter, the AR enabling technologies, which are shared by both ARAMS and CARAGM in IARAE, are introduced. Section 4.2 presents the ARTE and ARKF modules, including the representation of real and virtual objects in ARTE, and AR kernel functions, such as capture, rendering, display, etc. The ARTR module is described in section 4.3.

4.2 AR-based task environment and AR kernel functions module

In ARTE, there are two types of components, namely, real and virtual components. For real components, a dual model representation technique is proposed in this research, namely, the tracking model (VRML file) and the geometrical model (STL file). Both models are transparent to the user during the assembly simulation process. The tracking model of a real part is dimensionally reduced to deliver high computational efficiency and accuracy; it consists of only geometric features (lines, cycles, cubes or cylinders) used in hybrid tracking (section 4.3.3). For instance, as shown in Figure 4-1a, the tracking model comprises the following geometric features, namely, two cylinders, four cycles, and a set of lines. The geometrical model (Figure 4-1b) retains its full 3D form, which is triangle-based polygonal approximation, i.e., STL model, of the original CAD model, and is used for collision detection, occlusion handling, and CCH (Chapter 6).

In contrast to a real component, a virtual component only needs the geometrical model which will be rendered using OpenGL. The assembly scene of ARTE is displayed to the users via the ARKF module, which consists of three core functions of AR technology, namely, video capture, rendering and display. ARKF captures the real assembly scene using a camera, receives tracking results of the poses of real components from ARTR module in real time during AR-based assembly simulation, and synthesizes and renders the augmented contents in ARTE to the users.

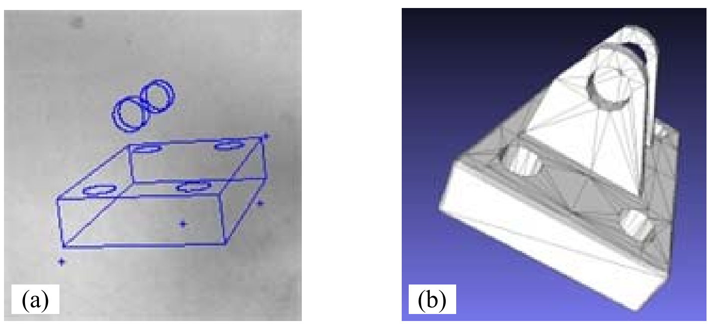


Figure 4-1 (a) Tracking model and (b) Geometrical model of a real component

4.3 ARTR module

4.3.1 Coordinate systems

As shown in Figure 4-2, for the component tracking and registration stage, the views of Bumblebee and Chameleon cameras are related by the World Coordinate System determined using the planar marker. There are seven coordinate systems (two Hand Coordinate Systems are included) in the AR environment, namely:

- World coordinate system (WCS) which is determined by the marker;
- Target component coordinate system (TCCS) which is attached to the target component;
- Reference component coordinate system (RCCS) which is attached to the reference component;

- Bumblebee coordinate system (BCS) which is attached to the bumblebee camera;
- Chameleon coordinate system (CCS) which is attached to the chameleon camera;
- Left and right hand coordinate systems (LHCS and RHCS) which are elaborated in the bare-hand interface (Ong and Wang, 2011).

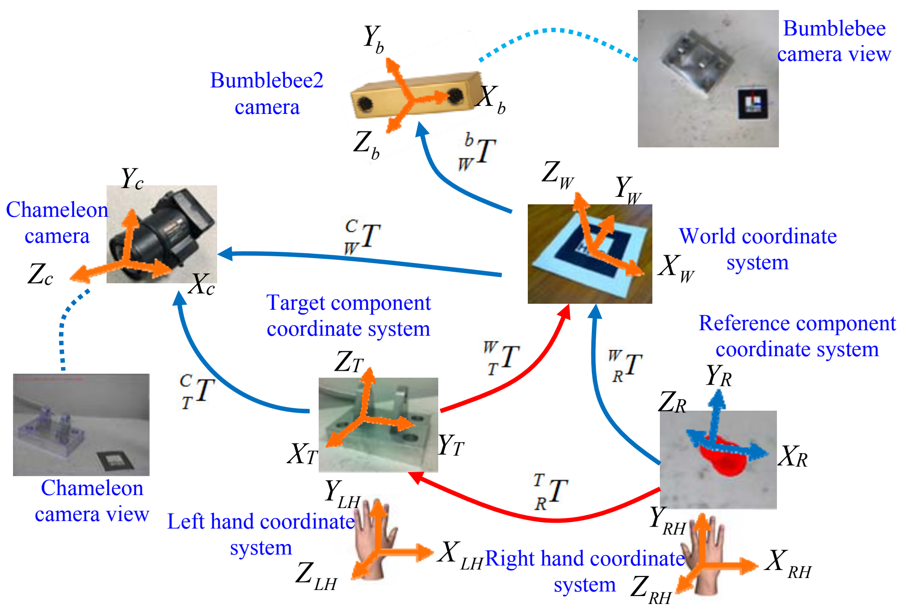


Figure 4-2 Assembly component registration and tracking system

During an AR assembly process, the bumblebee camera is maintained in a fixed position and orientation and provides the top view of the assembly workspace. The chameleon camera is mounted on a helmet to provide a front view of the workspace. As the position and orientation of the real component is changing, the transformations between the real component and two cameras are time-varying. Its accurate registration is thus guaranteed by performing hybrid tracking in every frame of the video grabbed using the chameleon camera, and the transformation between the real component and the bumblebee camera is then calculated. The necessary registration procedures are as follows:

1. Using hybrid tracking, the transformation between the real component and the chameleon camera ${}_{T}^{C}T$ can be obtained using Equation (4-1).
2. The transformation between the WCS and chameleon camera, and WCS and bumblebee camera can be achieved with ARToolKitPlus (${}_{W}^{C}T$ and ${}_{W}^{b}T$) respectively using Equations (4-2) and (4-3).
3. The pose of the real component with respect to the WCS can be calculated, and the transformation ${}_{T}^{W}T$ can be expressed using Equation (4-4).
4. The transformation between the bumblebee camera and the real component ${}_{T}^{b}T$can be obtained using Equation (4-5). With this transformation matrix, the model of the real component can have an accurate registration in the bumblebee camera's view.

$$ {}_{T}^{C}T = [{}_{T}^{C}R|{}_{T}^{C}t] \tag{4-1}$$

$$ {}_{W}^{C}T = [{}_{W}^{C}R|{}_{W}^{C}t] \tag{4-2}$$

$$ {}_{W}^{b}T = [{}_{W}^{b}R|{}_{W}^{b}t] \tag{4-3}$$

$$ {}_{T}^{W}T = {}_{T}^{C}T \cdot {}_{C}^{W}T = {}_{T}^{C}T \cdot ({}_{W}^{C}T)^{-1} \tag{4-4}$$

$$ {}_{T}^{b}T = {}_{T}^{W}T \cdot {}_{W}^{b}T = {}_{T}^{C}T \cdot ({}_{W}^{C}T)^{-1} \cdot {}_{W}^{b}T \tag{4-5}$$

4.3.2 Marker based tracking

In this research, the popular marker-based tracking open-source library ARToolkitplus (http://studierstube.icg.tugraz.at/handheld_ar/artoolkitplus.php) is implemented to determine ${}_{W}^{C}T$ (Equation (4-2)) and ${}_{W}^{b}T$ (Equation (4-3)). The ARToolkitplus is a well-known AR platform that provides a fundamental tracking scheme for developing AR-based applications. It is a computer vision (CV) based method and tracking is based on the identification of one or more planar square markers. Each marker has a unique pattern that is asymmetric in at least one direction to avoid ambiguity in identifying the marker coordinate system, as shown in Figure 4-3 where the x and y axes fall in the marker's plane, and the z-axis is perpendicular to the plane. The axes of the marker coordinate system observe the right-hand rule. Tracking of the markers involves the following image processing steps: (1) segmentation of the entire image and identification of the marker vertices, and (2) template matching of the pattern to determine the orientation of the marker.

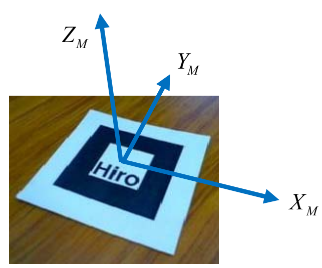


Figure 4-3 Marker Geometry and the Marker Coordinate System in ARToolkitplus

The ARToolKitPlus algorithm is based on a pinhole camera model,

$$\rho \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = A\left[R \mid T\right] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{4-6}$$

where *x*, *y* are the 2D image coordinates corresponding to the 3D coordinates *X*, *Y*, *Z*; ρ is an arbitrary factor; *A* represents the matrix of camera intrinsic parameters; and the matrix $\left[R \mid T\right]$ of extrinsic parameters consists of a rotation matrix, R and translation matrix, T that relates the marker coordinate system (WCS) to the CCS and BCS.

4.3.3 Marker-less hybrid tracking

4.3.3.1 Modified hybrid tracking algorithm

Marker-less tracking is important in the real-time AR assembly context, as the pose and position of the real components need to be obtained from the tracking results in order to support the CCH (Chapter 6.2.2) in real-time. Although marker-based tracking has been widely used and proven to be stable and reliable, it is not suitable for the tracking of real objects in ARTE because attaching physical markers to real objects will affect the efficiency and ease of the user's assembly operation. A mature hybrid marker-less tracker was proposed to track textured objects with visible edges (Pressigout and Marchand, 2006). The hybrid tracking method combines 3D model based tracking (MBT) tracker (Comport et al., 2006) with a classic vision-based tracking approach Kanade-Lucas-Tomasi (KLT) tracker (Lucas and Kanade, 1981) to improve the original algorithm's accuracy and effectiveness. However, due to the special conditions for industrial components tracking, e.g., lack of texture, smooth surface, etc., a variation from the original hybrid tracking method is imperative in this research. In the modified hybrid tracking algorithm, specific feature points (key features) are initialized manually instead of extracted from the image automatically. In addition, the modified approach implements an optimization problem with an initial condition provided by MBT, and refines the results with KLT tracking. The framework of the modified hybrid tracking algorithm is shown in Figure 4-4.

The modified hybrid tracking algorithm is described next. First, a set of key features on a real engineering component as well as the initial pose of the component are initialized by the user. The key features are a set of points on the surface of the component, and in order to ensure the registration accuracy of assembly features position, key features are selected from sites which are meaningful for assembly process, e.g., the center of projection area of a round hole or corner-like features on the contour profile (Figure 4-5). Key features are initialized by selecting their positions in the captured 2D image with their 3D locations measured in the local coordinate system of the component and stored in files as initial input to the tracking system. During real-time interaction, the MBT tracker provides an initial guess of the pose of the part (with respect to the camera), which is used to back-project the 3D key features onto the current camera image to obtain its 2D coordinates in each tracking loop. Given the 2D-3D correspondences of the key features, the position and orientation of the real engineering part can be refined using image space error minimization. The optimization problem is defined in Equation (4-7).

$$\min_{(\tilde{R},\tilde{t})} \frac{1}{N} \sum_{i=1}^{N} \left\| x_i' - P(\tilde{R} X_i + \tilde{t}) \right\|^2 \tag{4-7}$$

$(\tilde{R}, \tilde{t})$ in Equation (4-7) comprises the optimum rigid transformation between the real part and the camera coordinate system *cMo* given in Equation (4-8).

$$\tilde{R} \qquad \tilde{t}$$

$$cMo = \begin{pmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{4-8}$$

In Equation (4-7), X_i represents the pre-input 3D key features in the local coordinates of the component being tracked; x_i' represents the observed 2D tracking features coordinates in the image; N is the total number of key features and P represents the back-projection function of the camera. With the MBT tracker providing a good initial guess of the pose of the real part, the Quasi-Newton solver (Press et al., 1992) can be used to solve the optimization problem with competitive performance.

4.3.3.2 Occlusion Handling

Occlusions are unavoidable and can affect the results significantly during real component tracking. Occlusion means that during the AR assembly process, some key features of the real component are obstructed (by hands, or other real components); consequently, the tracking accuracy and robustness is affected. An algorithm for occlusion detection and handling is proposed to enhance tracking stability and robustness. So far there is no complete solution for occlusion detection during object tracking because there are no fixed patterns for occlusion. Traditional methods utilize the similarity of the color histogram and the size of targets to calculate the distance between targets when dealing with occlusion detection. However, this is not a stable method. Occlusion detection is an important task since detection failure would result in significant tracking precision loss and more seriously, the infiltration of mis-detected features caused by occlusions into the observed 2D features set may lead to tracking failure. Hence, a method is introduced to address occlusion detection to obtain higher accuracy.

In the proposed algorithm (Figure 4-4), occlusion handling is divided into three steps, namely, occlusion detection, occluded key features removal and lost key features recovery. For occlusion detection, the color histogram and key feature drift detection are implemented. During initialization, the system can obtain the template model of the key features automatically according to the user's input. The Bhattacharyya coefficient (Bhattacharyya, 1943) is adopted to compare the RGB color histogram between the current estimated candidate and the template model. Similar to the method proposed by Comaniciu et. al. (2000), the distance between the model histogram ch_M and the candidate histogram ch is defined as Equation (4-9).

$$d[ch, ch_M] = \sqrt{1 - \rho[ch, ch_M]} \qquad (4\text{-}9)$$

ρ is the Bhattacharyya coefficient and the occlusion detection rule of a color part is defined as Equation (4-10). In the proposed system, d_{thres} is set to 50.

$$occlusion = \begin{cases} true & d[ch, ch_M] > d_{thres} \\ false & otherwise \end{cases} \qquad (4\text{-}10)$$

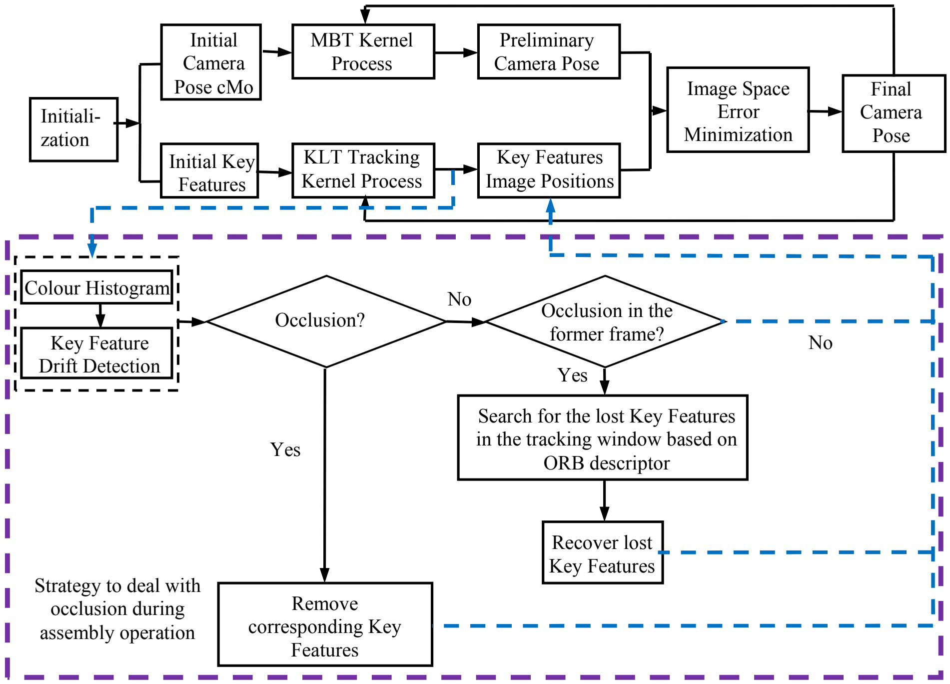


Figure 4-4 Framework of the full hybrid tracking algorithm

In order to determine whether a drift has occurred, the tracking window is regarded as a moving camera and it is tracked based on the last tracking result. If the velocity of feature points is larger than the pre-defined values (v_{xthres} and/or v_{ythres}), it means that a significant drift may happen. The average vertical velocity and average horizontal velocity can be calculated according to the result of the tracker. Hence, the drift detection assumptions are defined as in Equation (4-11).

$$occlusion = \begin{cases} true & \Delta\overline{v}_x > v_{xthres} \bigcup \Delta\overline{v}_y > v_{ythres} \\ false & otherwise \end{cases} \tag{4-11}$$

$\Delta\overline{v}_x$ and $\Delta\overline{v}_y$ are the average horizontal velocity and the average vertical velocity among the tracked points. In the implementation, the threshold for horizontal velocity v_{xthres} and vertical velocity v_{ythres} are both set to 10 pixels.

When an occlusion is detected, the information that belongs to the obstructed key features of the real object will be removed from the system memory so that the pose of the object will not be calculated from these features. If the obstruction that has been detected based on Equation (4-10) is removed from the view, the lost key features will be recovered based on the ORiented BRIEF (ORB) descriptor (Rublee et. al. 2011). In the initialization process, all the ORB descriptors of the key features are calculated and stored in the system memory and when the obstruction is removed, the system will search in the tracking window to find matching points for the lost key features using the ORB descriptor. The reason for choosing the ORB descriptor in this research is that it is rotation invariant, resistant to noise and has good real-time performance.

4.3.3.3 Implementation and Experiment

The hybrid tracking algorithms for real engineering components presented in the previous section have been implemented on a desktop (3.2 GHz Intel Core i5-650 with 4GB SDRAM Memory). ViSP (http://www.irisa.fr/lagadic/visp/visp.html) is used to implement the MBT tracking and OpenCV (http://opencv.org/) is used to implement the ORB descriptor. The goal of the proposed method is to provide a tracker that is accurate and robust enough to provide the necessary pose and position information in the AR environment to enable the interaction between virtual and real components.

4.3.3.3.1 Qualitative evaluation

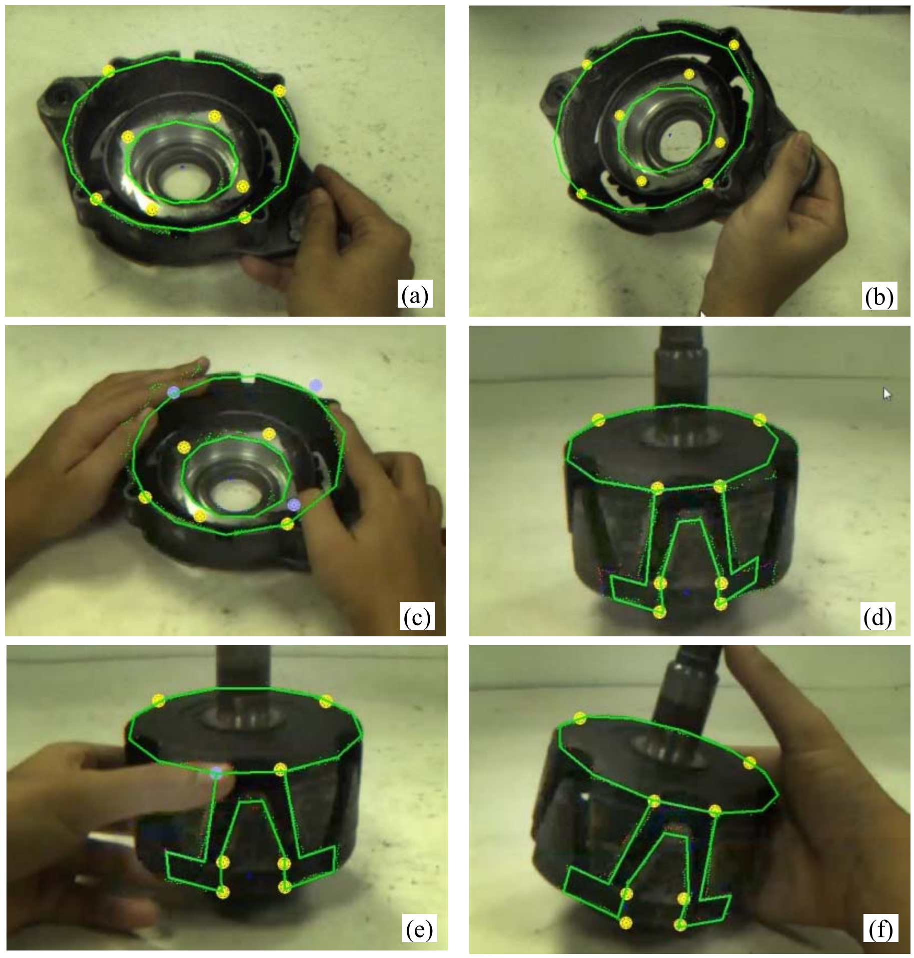


Figure 4-5 Tracking of real components in AR assembly

The objective of the qualitative evaluation is to show the observations of the implementation of the hybrid tracking method to track different components during an assembly process. The criteria for evaluation are that the alignment of the virtual contents (e.g., components, key features, etc.) to the real components should be accurate and the jittering effect should be small. The evaluation comprises the following steps, namely, qualitative data collection (capture of image, video, etc.), observation, and undesired outcomes identification (e.g., misalignment, jittering, tracking failure, etc.). The results are shown in Figures 4-5 and 4-6. Figure 4-5 shows the implementation of the hybrid tracking algorithm to track different industrial components (front cover (a-c) and rotor (d-f) of an alternator) during an assembly process. Forward projection of the tracking model appears as green lines and the key features appear as yellow points. The method is robust for multiple temporary and partial occlusions (occluded key features can be detected, and appear as blue points) caused by the user's hands and self-occlusions of the object itself during tracking (Figures 4-5c, e).

In Figure 4-6, virtual components are added into the AR environment based on the pose of the real component obtained from the proposed hybrid tracking method. In Figure 4-6a, the virtual bearing is augmented with the real front cover and in Figure 4-6b, the virtual bearing and pulley are added with the rotor. Figure 4-6c shows the alternator back cover subassembly. With the pose from the tracking of the real component and the geometric models provided, the virtual components can be manipulated to interact with the real ones. As shown in Figures 4-5 and 4-6, the virtual contents remain stable and visually accurate registration with the real components, and this is an important pre-requisite for the interaction between virtual and real objects.

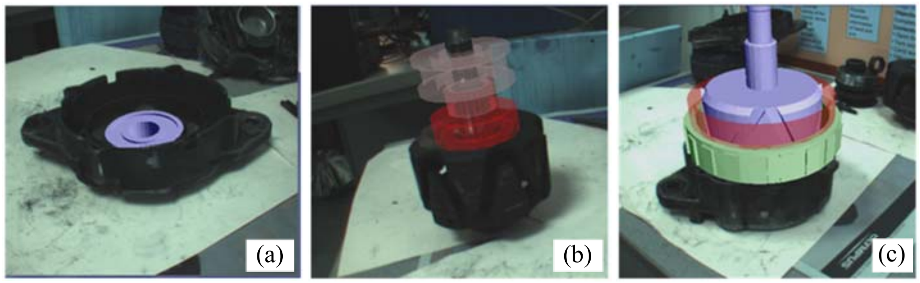


Figure 4-6 Augmentation of virtual components

4.3.3.3.2 Quantitative evaluation

In this section, the numerical results that measure and quantify the tracking accuracy will be provided. The object for evaluation of tracking accuracy is the front cover (shown in Figure 4-5(a)). The key features are shown in the figure with yellow points and the tracking model is shown with green lines. The errors illustrated in Figure 4-7 are computed with the expression 4-7, by substituting the estimated *cMo* in this expression. In the assembly process, the camera is mounted onto the operator's head. Error is calculated according to Equation (4-7). Figure 4-7 shows the errors before and after visual correction in relation to the number of visible key features during a typical user interaction (assemble engineering parts). The manipulation of the real object (front cover) can be divided into four phases, namely, partial occlusion, translation, rotation and 3D movements (translation and rotation together). It can be seen that the proposed method is robust against key feature occlusions, resulting, on average, in an accuracy of 3.4281 pixels, while the average accuracy of model-based tracking is 17.4135 pixels.

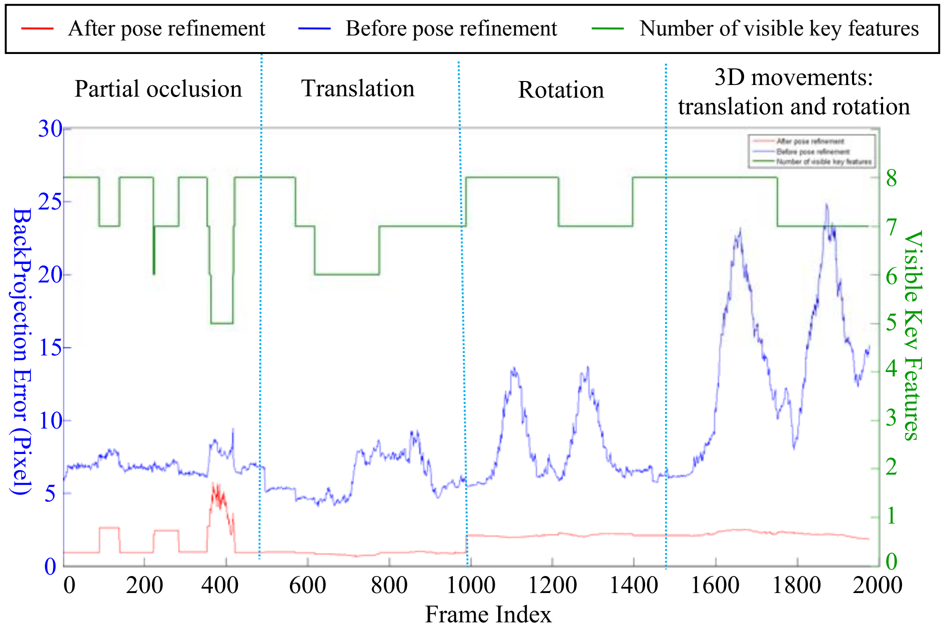


Figure 4-7 Back projection error of the key-features

5. Assembly Information Management

5.1 Introduction

Assembly information management is essential in an AR-aided assembly system. Ontology has been widely used for assembly information modeling as it is independent of programming languages, enabling reasoning using first order logic, etc. (Zhong et al., 2013). In addition, ontology has been applied in industrial context modeling and context-aware knowledge inference for AR maintenance process operations (Zhu et al., 2013; 2014). However, existing assembly ontology is not specific for ARAMS and/or ARAOG. In IARAE, two ontology based assembly information models are described, namely, OAIM and OATP. Section 5.2 presents OAIM, which is used to capture the contact and mating information for assembly simulation, and support the reasoning of component movements from the assembly relationships among the components. Section 5.3 presents OATP, which is used in the assembly guidance information reasoning during an assembly task.

5.2 OAIM

5.2.1 Overview of OAIM

OAIM is used to classify data associated with the components so that ARAMS can recognize their functionality, and reason the required information when queried by the ARAMS module. As shown in Figure 5-1, there are four types of concepts in OAIM, namely, class, subclass, property and sub-property, and they are represented using different shapes. Each class can have a few subclasses, and the relationships between the instances of classes/subclasses are represented as properties. Both the class and subclass can have properties.

OAIM has four classes, namely, *Assembly*, *Component*, *AssemblyFeatureSurface* and *MGDE*.

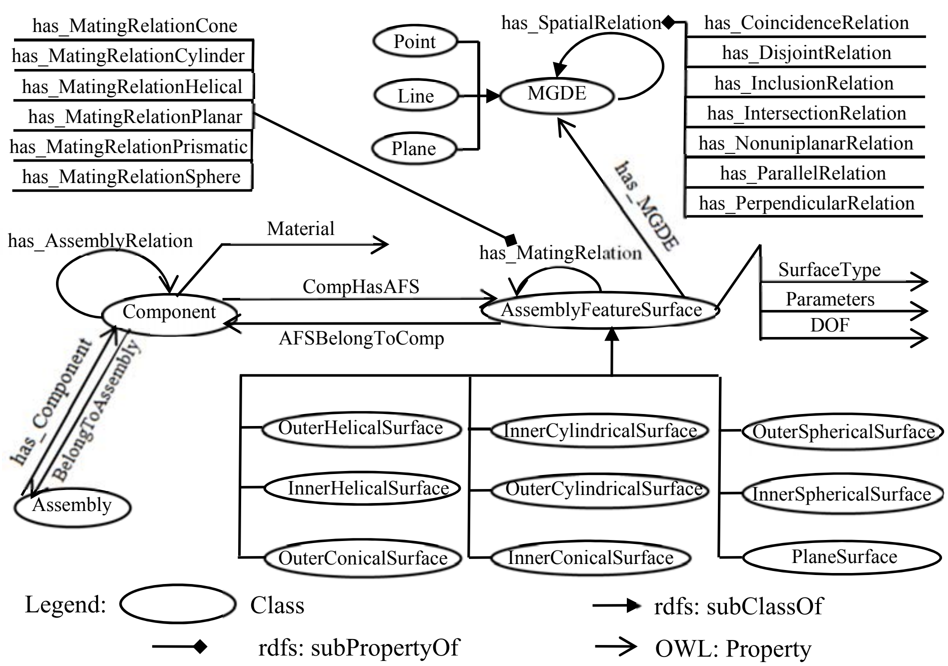
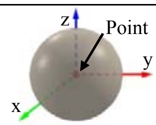
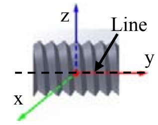
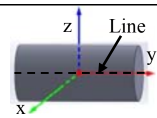
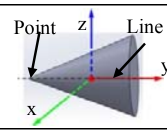
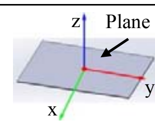


Figure 5-1 The OAIM architecture

Assembly represents the entire product, and it is a finite set of components that have assembly relations with each other. *Component* represents a part/component which constitutes the product, and it has certain properties, such as material, weight, etc. The material indicates what the component is made of, e.g., alloy, cast iron, etc. The primary function of *Component* is to store information of all information instances which represent the properties of a component, hierarchical assembly relations to *Assembly* (*has_Component* and *BelongToAssembly*) and constraint relations between components (*has_AssemblyRelation*).

AssemblyFeatureSurface (*AFS*) represents the mating surfaces in an assembly, such as plane, cylindrical surface, etc. Each component of an assembly can be regarded as a closed geometry that consists of a number of instances of *AFS*s.

Table 5-1 Various types of AFSs

*AFS*s	*MGDE*s	*AFS*s	*MGDE*s
Inner (outer) spherical surface		Inner (outer) helical surface	
Inner (outer) cylindrical surface		Inner (outer) conical surface	
Plane surface			

In OAIM, a general surface representation (Zhong et al., 2013) is adopted and modified to comprise nine types of common feature surfaces (Table 5-1), which form the nine subclasses of *AFS* (Figure 5-1). *AFS* implements the property of *has_MatingRelation*, which has sub-properties of *has_MatingRelationCone*, *has_MatingRelationCylinder*, etc., to represent the mating relations between two instances of *AFS*. *AFS* has properties of parameters and DOF. The parameters for *AFS* are used to describe the geometric characteristics, e.g., origin, local coordinates, radius, main axis, etc. The *DOF* is used to represent the mobility of *AFS*, e.g., rotation-positive-x, translation-negative-y, etc. *MGDE* (minimum geometric datum element) (Zhang et al., 2011) represents the smallest geometric element to locate *AFS* and it has three subclasses, namely, *point*, *line* and *plane*. *MGDE* has the property of *has_SpatialRelation* (with sub-properties of *has_CoincidenceRelation*, *has_DisjointRelation*, etc.) to represent the spatial relations between the *MGDE*s from a pair of *AFS*s.

5.2.2 Rules definition for the reasoning of mating relations

The reasoning of mating relations can be modeled using semantic web rule language (SWRL) (http://www.w3.org/Submission/SWRL/) rules. A SWRL rule consists of a body (a set of conditions) and a head (a set of actions, i.e., mating relations to be reasoned when all the conditions are satisfied). Variables referring to the instances of the concepts defined in the ontology (class, subclass, property, and subproperty) can be included in the rules. For example, the mating relations between a pair of *AFS*s can be inferred from the spatial relations between *MGDE*s from these *AFS*s (Rule 5-1).

InnerCylindricalSurface(?a)∧OuterCylindricalSurface(?b)∧
Line(?p)∧Line(?q)∧has_MGDE(?a,?p)∧has_MGDE(?b,?q)∧
hasRadius(?a,?s)∧hasRadius(?b,?t)∧equal(?s,?t) (Rule 5-1)
∧has_CoincidenceRelation(?p,?q)->
has_MatingRelationCylinder(?a,?b)

In the representation in Rule 5-1, the variable *a/b* refers to an inner/outer cylindrical surface, variables *p* and *q* refer to two lines (axes of the cylindrical surfaces), and variables *s* and *t* refer to the radius values of the two cylindrical surfaces. Each condition and action in a rule is a rule atom. For example, *has_MGDE(?a,?p)* is a defined SWRL atom, which determines whether the line *p* is the *MGDE* of *a*. The mating relations are specifications of the bounding relationship between *AFS*s in order to locate the components relatively in the entire product assembly. The representation of *AFS*s and the mating relations between them for an industrial example are shown in Figure 5-2.

With the *MGDE*s and their corresponding spatial relations, the geometrical characteristics of each pair of *AFS*s can be described by an OWL class and property assertions, laying the foundation for the reasoning of the *DOF*s of the virtual component behavior when it interacts with other components. For example, if there is a pair of mating cylindrical surfaces, the rule for reasoning the resultant *DOF*s is as follows (Rule 5-2): when the conditions are satisfied, four feasible *DOF*s (positive and negative rotation directions along z axis, and positive and negative translation directions along z axis) can be inferred.

InnerCylindricalSurface(?a)∧OutercylindricalSurface(?b)∧ has_MatingRelationCylinder(?a,?b)->has_rotzp, has_rotzn, has_transzp, has_transzn (Rule 5-2)

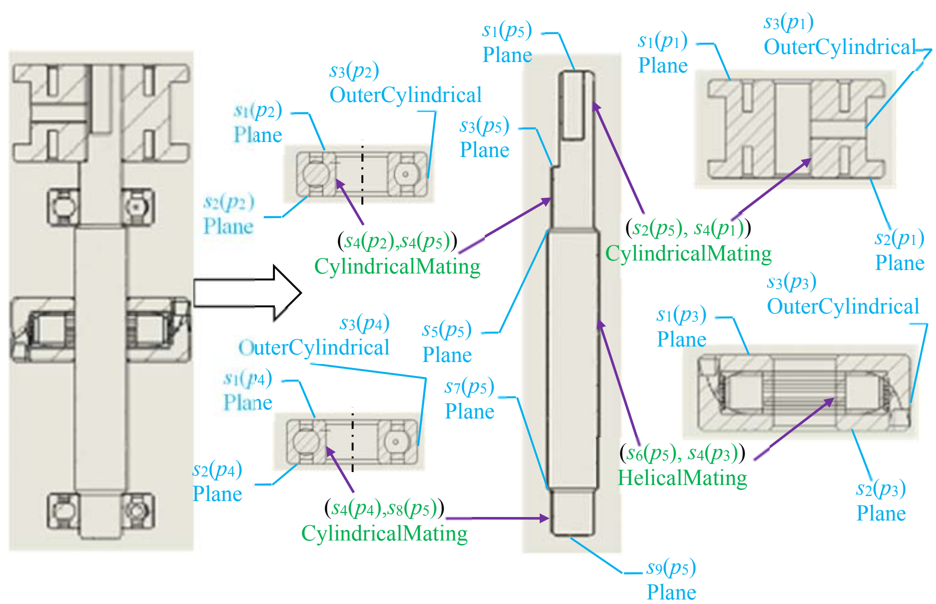


Figure 5-2 Assembly spatial relation representations between AFSs of components $\mathbf{p_1}, \mathbf{p_2}, \mathbf{p_3}, \mathbf{p_4}, \mathbf{p_5}$; $\mathbf{p_i}$ represent the i-th component; $\mathbf{s_j}(\mathbf{p_i})$ represents the j-th AFS on $\mathbf{p_i}$.

5.2.3 Information instance modeling

As all the concepts in OAIM are linked to their corresponding CAD models, the modeling of information instances involves loading the CAD file of the component into the system, and extracting its component information (e.g., materials, weight), *AFS*s, *MGDE*s, and their hierarchical relations from specific data structures of CAD models. The extraction process is automatic after the user loads the CAD file, and the extracted information is stored as information instances of the concepts in OAIM. To use OWL/SWRL to represent assembly information, the OAIM is implemented using the Protégé tool (http://protege.stanford.edu), which is a tool that provides a visual integration environment for creating, editing, and saving ontology.

5.3 OATP

OATP is proposed specifically for representing the user's activity as well as cognition information during an assembly operation. In CARAGM, OATP is proposed to store the pertinent information for an assembly process. As shown in Figure 5-3, there are two types of concepts in OATP, i.e., class and property, and they are represented using different shapes. Classes in OATP are used to illustrate three aspects of information in an assembly guidance process, i.e., cognition information (User, CognitionPhase), process information (AssemblyState, Tool, and Operation), and component configuration (Component, AssemblyFeature). These classes are illustrated in Table 5-2.

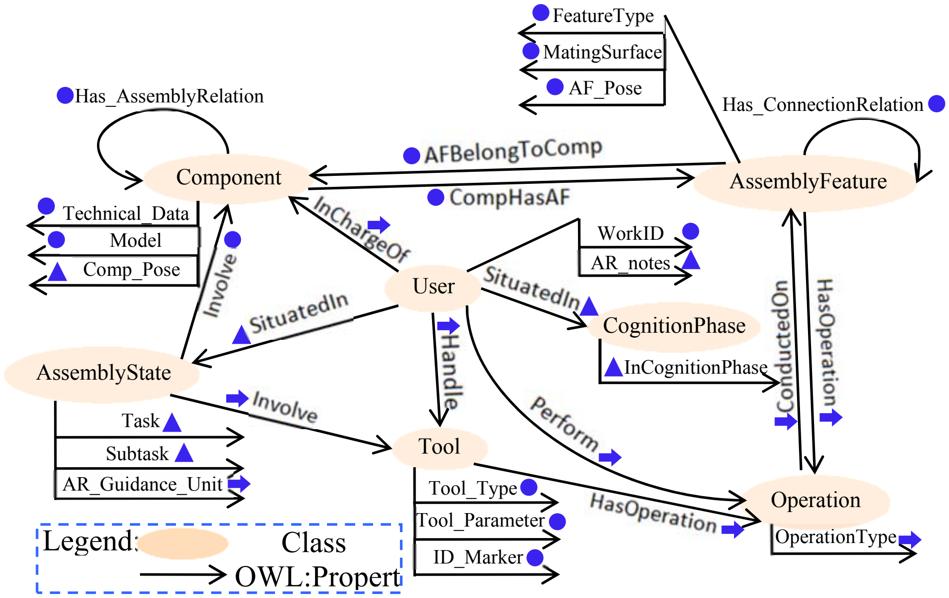


Figure 5-3 OATP

Table 5-2 Classes in OATP

Class	Property	Content and example
User	WorkID	ID for an operator
	AR_notes	Stores the events or observations during an assembly process that are input by the user through the EBHI
	The User class represents all the personnel involved in the assembly work.	
CognitionPhase	InCognitionPhase	Stores the cognition phase of the user.
	CognitionPhase represents the four cognition phases happening in sequence in each step of the assembly task, i.e., perception, attention, memory and execution.	
Tool	Tool_Type	Stores the type of a certain tool.
	Tool_Parameter	Stores the geometrical and functional parameter of a certain tool.
	ID_Marker	Stores the ID of a small size marker (typically 8mm) attached to the tool in order to facilitate the user to recognize the appropriate tool for a certain operation and assembly feature.
	Tool represents the tools used in different assembly/disassembly operation.	
Component	Technical_Data	Comprises attributes to facilitate the user to get familiar with the component, such as material, weight, structure and functionality, etc.
	Comp_Pose	Pose of the component with respect to the world coordinates in ARTE, which can be obtained from the tracking process in real time.
	Model	3D CAD model of the component.
	Component represents the components that constitute the product.	
AssemblyFeature	FeatureType	Type of typical assembly features, e.g., nut, bolt, dovetail, etc.
	MatingSurface	The set of surfaces that constitute the assembly feature, e.g., plane, cylindrical surface, cone surface, etc.
	AF_Pose	Pose of the assembly features with respect to the local coordinate system attached to the component
	AssemblyFeature represents the connection relations between components.	
AssemblyState	Task	Describe which component the user is manipulating at the current assembly state.
	Subtask	Depict the sub-tasks in a certain assembly task, e.g., approach to the component/tool, manipulation, and fastening, etc.
	AR_Guidance_Unit	The AR_Guidance_Unit represents instances of AR guidance.
	AssemblyState represents the abstraction of the user's progress in an assembly task.	
Operation	OperationType	Include translation, rotation, fastening, etc.
	Operation represents the abstraction of the various assembly works.	

Each class can be linked to other classes with the relationships between them represented by properties, and each class can have certain attributes (properties). All properties are divided into two categories, namely, static and dynamic. The static properties (marked with a round tag in Figure 5-3) describe inherent features or attributes of the instances of OATP classes, and these properties have been fixed during the product development processes, e.g., 3D model of the component, mating surfaces of two components. Static properties can be extracted from CAD file, external repositories (e.g., enterprise PDM (Product Data Management)), and results of assembly planning, etc. The dynamic properties describe the attributes which can be adapted to the changing assembly status and human cognition process. Some of the dynamic properties (marked with a triangle tag) can be collected from the user inputs and sensor readings (e.g., tracking results), while the others (marked with an arrow tag) need to be derived based on the static and dynamic properties using SWRL rules. For example, the operation information for the fastening process of two bolts after aligning the reed valve cover can be inferred from the assembly state and tool information.

Tool(?b)∧Tool_Type(?b,socket) ∧Tool_Parameter(?b,8)
∧ID_Marker(?b,socket_8)∧AssemblyState(?a)
∧Task(?a,ReedValveCover)∧Subtask(?a,Fasten)->
Operation(?c) ∧Operation_Type(?c,screwing) (Rule 5-3)

In the above reasoning rule, the variable *a* refers to the current assembly state (ReedValveCover), variable *b* refers to the tool (socketwrench) involved in *a*, and variable *c* refers to the operation (screwing) involved in *a*.

6. Assembly Simulation and Planning in AR Environment

6.1 Introduction

This chapter introduces the ARAMS module, which implements a novel method for AMS in an AR environment, allowing users to manipulate both real and virtual engineering components in an assembly intuitively to interact with other components. ARAMS provides (1) two intuitive interaction tools, which include a convenient hand held interaction tool, and an enhanced bare-hand interface (EBHI) enabling users to manipulate virtual components realistically using natural hand gestures, (2) a component contact handling (CCH) strategy to model and determine all the possible movements of virtual components when these virtual components interact with other components during assembly simulation, (3) a method to calculate the resultant forces exerted on virtual components from contacts with real components and manipulation from the user's hands (forces and torques applied, etc.) during an assembly process. Thus, ARAMS can position virtual components accurately, simulate the assembly motions realistically, assess product assembly design and identify potential assembly issues. The real virtual interaction in the ARAMS module is based on the information transmitted by the AIM module in each frame.

6.2 Methodology

The objective of the ARAMS module is to determine all the feasible *DOF*s of the reference components at any time instance throughout the entire assembly simulation, and provide realistic components motion simulation corresponding to user manipulation based on the proposed CCH strategy. Physics-based simulation approaches are integrated to enable virtual components to behave as their physical counterparts in an AR-based environment based on the calculation of assembly forces. In addition, physics-based methods have been implemented to provide accurate collision detection and physics-based behavior modelling among contacting geometric surfaces (Figure 6-2a-b). Furthermore, the system allows a user to interact with the virtual components with either a hand held interaction tool or EBHI. The overall flow chart for the assembly simulation module is shown in Figure 6-1.

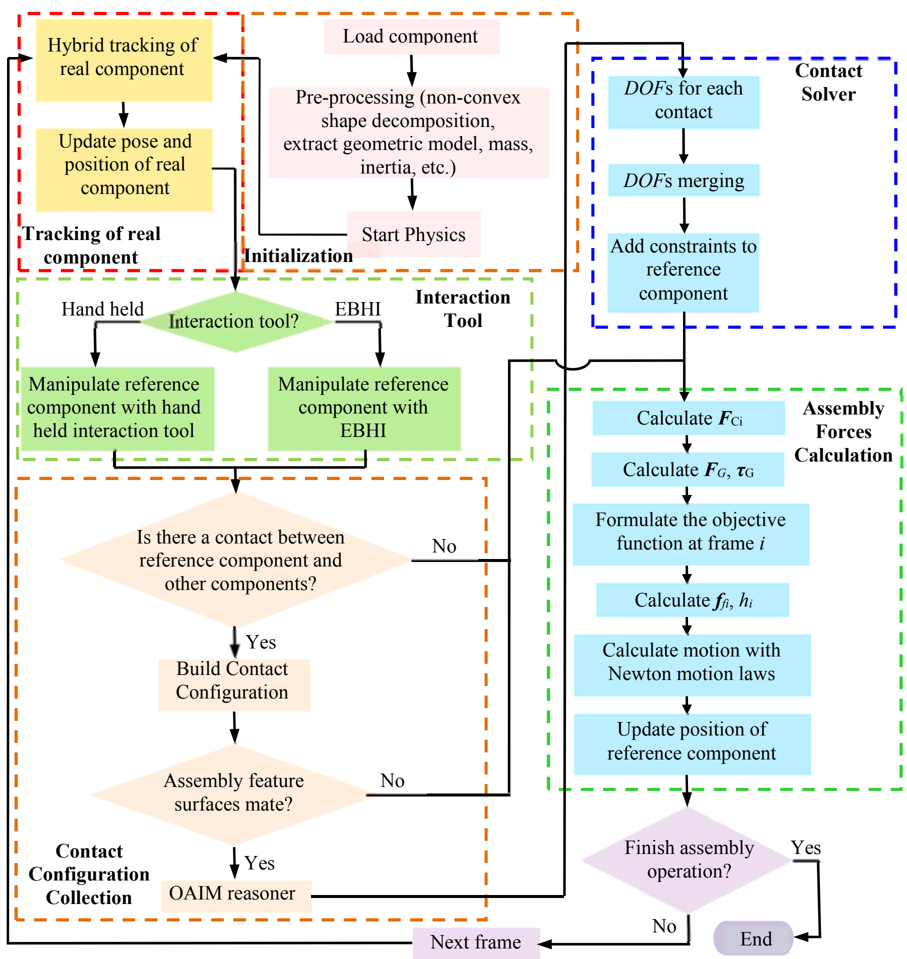
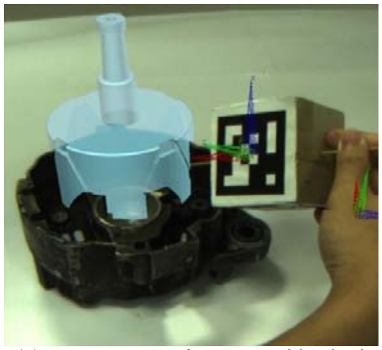


Figure 6-1 Integrated Physics-Constraints AR Assembly Simulation Environment

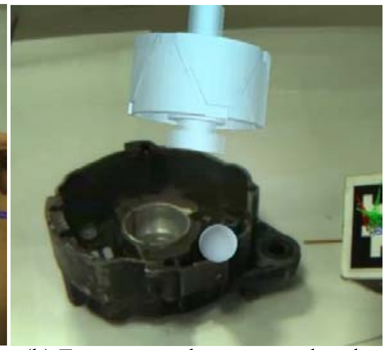
6.2.1 Interaction tools

6.2.1.1 Hand held interaction tool

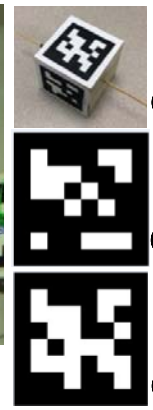
The hand held interaction tool (Figure 6-2) is implemented to enable the user to approach and move the virtual component during assembly operations. Markers are used as trackers to register the movement of the interaction tool. Two marker patterns are used. Marker one (Figure 6-2d) is used to track the movement of the interaction tool. While the pose and position are provided in real time, ray testing (Bender, et al., 2014) is implemented to select components in the augmented scene. Once the ray testing returns a virtual component, the system will regard this as a potential reference component and determine whether there is an existing reference component. If there is no reference component attached to the tool at the previous frame, the system will generate a general (6 *DOF*s) soft constraints (Bender et al., 2014) between the tip of the interaction tool and the reference component, such that the integration of the constraints from the interaction tool can be done easily and the manipulation can be stable. If there is an existing reference component, the system will update its pose and position. After the soft constraints have been confirmed, the system will simulate realistic component manipulation in the AR environment. When the user wishes to release the reference component, he can switch the visible marker to marker two (Figure 6-2e), which is used to indicate the signal to release the reference component.



(a) Inter-penetration caused by lack of physics engine



(b) Free contact between real and virtual components with physics engine



(c)

(d)

(e)

Figure 6-2 Implementation of physics engine and interaction tool

6.2.1.2 Bare hand interface

Many assembly tasks are objects manipulation with multi-*DOF*s, and 3D bare-hand interactions are effective and natural in manipulating components, tools and subassemblies (Ong and Wang, 2011) in an AR environment. In ARAMS, an EBHI is developed to support dexterous manipulation by considering the manipulation forces exerted so as to move virtual components precisely and realistically in an assembly simulation task, using both single and dual hands gestures (Figure 6-3).

To achieve interaction between a user's hands and the virtual components, a small sphere is rendered on each interaction patch for different hand gesture configurations (Figure 6-3). A collision detection method (Bender et al., 2014) is implemented to determine contact between a virtual component and the interaction patches. When a sphere collides with a virtual component, its color will change. To manipulate a virtual component when all the virtual spheres on one hand are in contact with the component, a dynamic component motion simulation is coupled to the tracked hand configuration by adopting a virtual linear and torsional spring-dampers model (Garbaya and Zaldivar-Colado, 2007) to represent the visual dynamic behavior of the components during assembly simulation. This spring-damper model can support physically realistic manipulation of virtual components and perform force feedback rendering. To illustrate the spring-damper model, effective forces and torques are introduced. Assume at frame *i*, the hand pose is represented as $(\boldsymbol{q}_i^l, \boldsymbol{q}_i^o)$; at frame *i+1*, the pose of the hand grasping a virtual component is $(\boldsymbol{q}_{i+1}^l, \boldsymbol{q}_{i+1}^o)$. $\boldsymbol{q}_i^l$ is the 3D position of the hand at frame *i*, and $\boldsymbol{q}_i^o$ is the quaternion to describe its orientation. The effective force and torque used to move a virtual component along the trajectory of the hand based on a spring-damper model can be represented as equations (6-1) and (6-2), where $\boldsymbol{v}_i^l$ and $\boldsymbol{v}_i^o$ are the linear and angular velocities of the virtual component at frame *i*. $k_{SL}(k_{SO})$ and $k_{DL}(k_{DO})$ are the coefficients of the linear (angular) spring and damper, which need to be tuned empirically to achieve stable and smooth dynamic motion of the virtual components. The effective forces and torques in Equations (6-1) and (6-2) cannot be applied to move a virtual component directly to achieve natural and intuitive manipulation, as the component movement is determined solely based on contact forces and frictional torques from the interaction patches between the fingertips and virtual components (Ciocarlie and Allen, 2009). Hence, these contact forces and torques from each interaction patch have to be computed (Section 6.2.3).

$$\boldsymbol{f}_{effect}=k_{SL}(\boldsymbol{q}_{i+1}^l - \boldsymbol{q}_i^l)-k_{DL}\boldsymbol{v}_i^l \tag{6-1}$$

$$\boldsymbol{\tau}_{effect}=k_{SO}(\boldsymbol{q}_{i+1}^o - \boldsymbol{q}_i^o)-k_{DO}\boldsymbol{v}_i^o \tag{6-2}$$

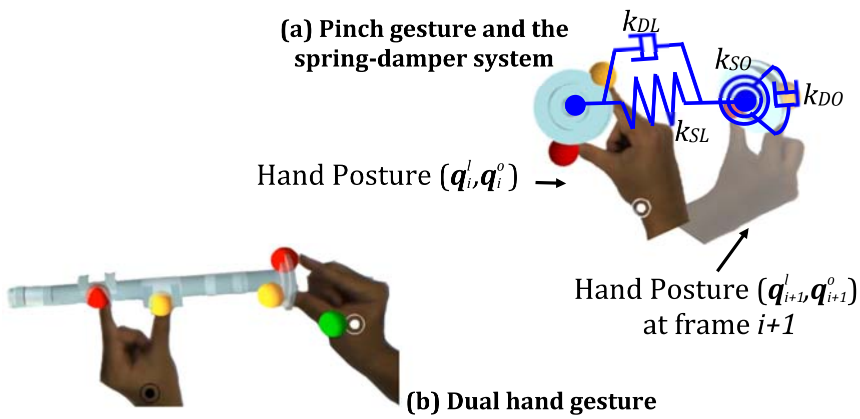


Figure 6-3 Spring-damper for virtual object simulation and intuitive gestures

6.2.2 Component contact handling

Contact occurs when the reference component collides with other components. In this research, the possible movement directions at each time instance are represented as the instantaneous *DOF*s at each captured video frame *t*, denominated as DOF_t. Although researchers have been working on the determination of DOF_t (Liu and Tan, 2007), there are some limitations as the information of the contacts and mobility of the mating pairs cannot be deduced automatically during the assembly process; instead, the information is typically input by the user. In addition, there is incomplete information about the DOF_t.

The proposed CCH strategy comprises contact information collection based on the reasoning functions in OAIM, and a contact solver, which is used to calculate the DOF_t for the reference component based on the contact information (Figure 6-1). The determination of the DOF_t starts with contact configuration collection. A contact configuration refers to the information that models the contacts, including the *AFS* type and parameters of the contacting

*AFS*s, the triggering condition of the geometric constraints, and the mobility data. The *AFS* type and parameters are the information instances stored in OAIM. Triggering conditions comprise the conditions to recognize a mating relationship between the *AFS*s, e.g., the angle between axes and the distance between two points (Ong and Wang, 2011). The mobility data of the contact represents the feasible motion directions, i.e., *DOF*s, of an *AFS* according to contacts with its mating *AFS*s. When collision happens between a pair of *AFS*s, the system will build the corresponding contact configuration. With this information, the system can identify the satisfaction of mating *AFS*s and infer the corresponding *DOF*s automatically according to the rules described in Section 5.2. Through the mapping between the assembly contact configurations and the mating relations of the *AFS*s, the system can capture and infer contact and assembly relations dynamically during AR-assisted assembly operations.

In order to represent the mobility data of mating *AFS*s, a popular approach, namely the unit sphere representation (USR) is adopted and Figure 6-4 is adapted from (Iacob et al., 2011). In USR, given a component in a 3D environment, the set of feasible translational directions, which is denoted as *TD*, can be depicted as a set of vectors that connect the origin to the points on the sphere. The *TD* for mating *AFS*s can be empty, a point on the sphere (e.g., mating *Outer/InnerCylindricalSurfaces*), and a hemi-sphere with a great cycle plane as the boundary (e.g., mating *PlaneSurfaces*, Figure 6-4c). The set of rotational directions, which is denoted as *RD*, can be depicted as a set of axes emitting from the origin of the sphere, as illustrated in Figure 6-4.

Figure 6-4b is the USR without DOF_t information; while Figure 6-4c is the USR representing the DOF_t information of P_1 in Figure 6-4a, where the upper hemi-sphere (in green color) represents the *TD* with a PlaneSurface contact, and the thick solid lines represent the *RD* (yellow and purple lines represent clockwise and anti-clockwise rotations respectively). All the feasible *DOF*s of P_1 are shown in the USR, which serves as input to the contact solver.

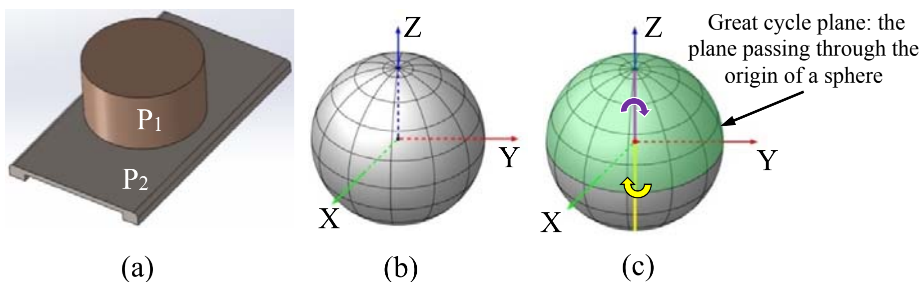


Figure 6-4 The unit sphere for the situation of two parts assembly (Iacob et al., 2011)

In assembly processes, the ARAMS module needs to deal with multi-contacts between the reference component and other components simultaneously and combine the *DOFs* from each contact to determine the resultant DOF_t of the reference component. Therefore, the contact solver is implemented to perform the *DOFs* merging process, which is illustrated in Figure 6-5, wherein two contacts happen on a reference component simultaneously.

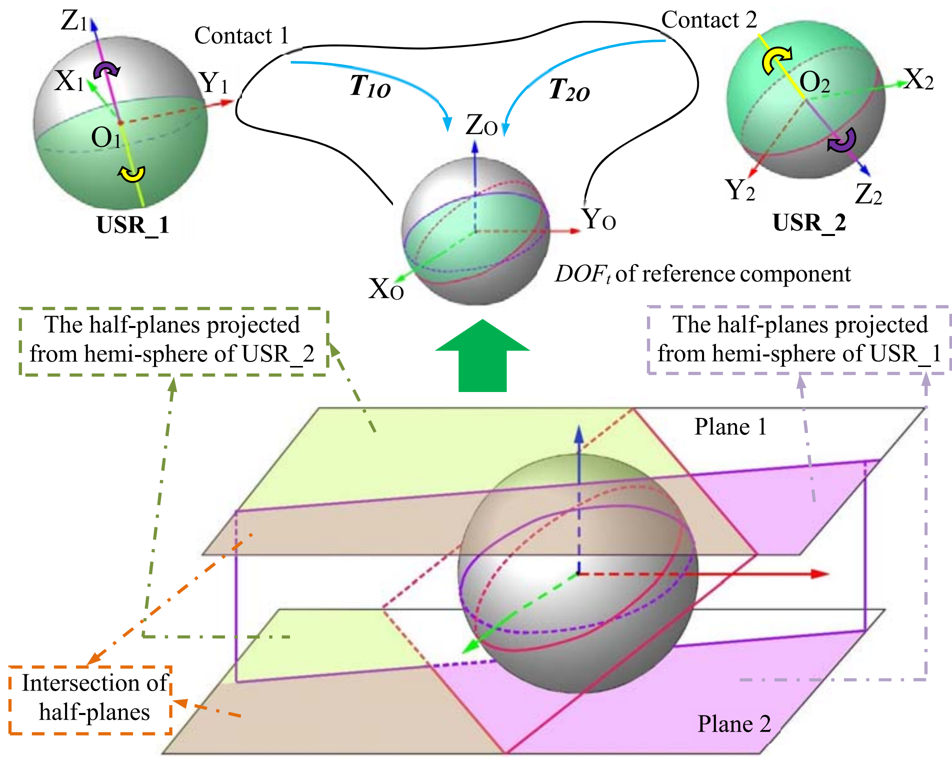


Figure 6-5 An example to illustrate DOF merging

The *DOFs* merging process illustrated in Figure 6-5 can be described as follows. Two sets of feasible motion directions (TD_1 and RD_1; TD_2 and RD_2) can be inferred from the two contact locations based on collected contact configurations. These motion directions can be illustrated with USR, namely USR_1 and USR_2. The system needs to transform these two sets of motion directions from each local coordinate system to the reference component coordinate system through the 3D transformation matrices T_{1O} and T_{2O} (Equation 6-3).

$$
\begin{aligned}
[TD_{1O}, RD_{1O}] &= [TD_{11}, RD_{11}] \times T_{1O} \\
[TD_{2O}, RD_{2O}] &= [TD_{22}, RD_{22}] \times T_{2O}
\end{aligned}
\quad (6\text{-}3)
$$

In Equation (6-3), TD_{ij} represent the set of translational directions of contact i expressed in coordinate system j. If TD_{ij} is empty, the set after the transformation TD_{iO} is still empty; if TD_{ij} is a point or hemi-sphere, TD_{iO} represents the point or hemi-sphere after the transformation in Equation (6-3). RD_{ij} represents the set of rotational directions of contact i expressed in coordinate system j. RD_{iO} represents the set of rotation axes after the transformation in Equation (6-3).

Since the contact solver can perform the transformations in Equation 6-3 based on the collected contact configurations, the feasible motion directions can be transformed into the same coordinate system (the component coordinate system) automatically. For rotational directions, the merging condition for *RD*s on the two contact locations is when their rotation directions are coaxial with the same direction and both origins of the rotation vectors are located along the common directions (Iacob et al., 2011). The algorithm for obtaining the merging *RD*s can be described in Algorithm 6-1.

To obtain the merging translational directions, an extension of the stereographic projection on two 2D planes is first defined (Figure 6-5). The process can be introduced as sub-routines: s_1 = STEREOGRAPHIC_PROJECTION(S_1) (Agoston, 2005), which projects point/hemi-sphere (S_1) onto the plane to obtain the corresponding point/half-plane (s_1). As a consequence, the 3D problem has been transformed to a 2D problem, i.e., to find the intersection of half-planes/points. The 2D intersection problem can be solved with a divide-and-conquer algorithm (Berg et al., 2008), embodied as a subroutine in the system: INTERSECTION_2D(*H*). The input for the algorithm is a set *H* of half-planes/points in the plane, and the output is the convex polygonal region (h refers to the instances of half-planes/points in set *H*):

$$C := \bigcap_{h \in H} h \tag{6-4}$$

Algorithm 6-1: INTERSECTION_ROTATION

Input: RD_{1O}, O_{1O} and RD_{2O}, O_{2O} from two contact sites on reference component

Output: RD_O, O_O

Begin
  Store all the p rotation axes in RD_{1O}, ($rd_{1O1}, rd_{1O2}, \ldots, rd_{1Op}$)
  Store all the q rotation axes in RD_{2O}, ($rd_{2O1}, rd_{2O2}, \ldots, rd_{2Oq}$)
  $RD_O = \varnothing$
    for i:=1 to p, **do**
    {
      for j:=1 to q, **do**
        {
        if ($rd_{1Oi} \cdot rd_{2Oj} = 1$ and $(O_{1O} - O_{2O}) \cdot rd_{1Oi} = \pm 1$), **then**
          {
            Add rd_{1Oi} to RD_O;
            Add O_{1O} to O_O;
          }
        endif
        }
      Endfor
    }
  Endfor
End

Next, the polygonal region that is obtained can be mapped inversely to the unit sphere, with a sub-routine P_I = INVERSE_STEREOGRAPHIC_PROJECTION(p_I) (Agoston, 2005), which projects the intersection polygon (p_I) that has been obtained on the plane back onto the unit sphere P_I, such that the merging translational *DOF*s can be achieved. As the projection establishes one-to-one and onto mapping between points/hemi-spheres on the spheres and points/polygons on the planes, the two sub-routines of stereographic projection can obtain unique output. The whole process of *DOF*s merging in the contact solver can be described in the following pseudo-code of Algorithm 6-2.

Algorithm 6-2: The Merging of DOF_t from Multiple Contacts

Input:	A set of motion directions TD_C, RD_C (c = 1,2,…,m) from *m* contact sites on the reference component
Output:	The merging DOF_t (TD_O, RD_O) in component coordinate system

```
Begin
Store all the m contacts happen on the reference component
for contact c:= 1 to m, do
{
  Transform TD_CC from local coordinate system to component coordinate system to get TD_CO;
  Transform RD_CC from local coordinate system to component coordinate system to get RD_CO;
  if c = 1 then
    TD_O := TD_CO
    RD_O := RD_CO
  endif
  if c > =2 then
    { if (TD_O or TD_CO) is ∅, then
        TD_O := ∅
      Else
      {
        (h_O)  = STEREOGRAPHIC_PROJECTION(TD_O)
        (h_CO)= STEREOGRAPHIC_PROJECTION(TD_CO)
        h_O = INTERSECTION_2D(h_O, h_CO)
        TD_O = INVERSE_STEREOGRAPHIC_PROJECTION(h_O)
      }
      Endif

      if (RD_O or RD_CO) is ∅, then
        RD_O := ∅
      Else
        (RD_O,O_O) = INTERSECTION_ROTATION(RD_O, O_O, RD_CO, O_CO)
      Endif
    }
}
Endfor
End
```

From the algorithm 6-2, the instantaneous DOF_t can be obtained, and these directions form the mobility data for the reference component. Based on this, the behavior of the reference component can be determined when the user manipulates the component with the interaction tool in the AR-based assembly environment.

The *DOF* representations and merging are illustrated in Figure 6-6. With physics-based simulation, i.e., assembly force calculation (Section 6.2.3), the proposed system can avoid omitting the detection of assembly interferences. Thus, constraints between mating *AFS*s will be satisfied immediately along with users' adjustment on the position of the component. As shown in Figure 6-6, after the user moves component c_1 interactively to a location indicated in Figure 6-6a, c_1 can be moved freely in the 3D space. As shown in the corresponding USR, the entire sphere is in green color and all the rotation axes are represented with thick solid lines, meaning that there are no constraints attached to c_1. When the user adjusts c_1 to the location as indicated in Figure 6-6b, five contacts (plane mating pairs) will be detected. The CCH will first collect the contact configurations from the contact locations, and transform the *DOF*s from each contact location to the component coordinate system of the reference component. With the contact configurations as input, the contact solver can calculate the merging result DOF_t for c_1. At this stage, the *TD* for c_1 comprises two points, i.e., the positive and negative x_O directions; the *RD* is an empty set. While c_1 is moved further to the position indicated in Figure 6-6c, another contact between c_1 and c_2 can be established and c_1 reaches its final assembly state. Figure 6-6 (d-f) shows the process of inserting reference component c_3 to the target component c_2.

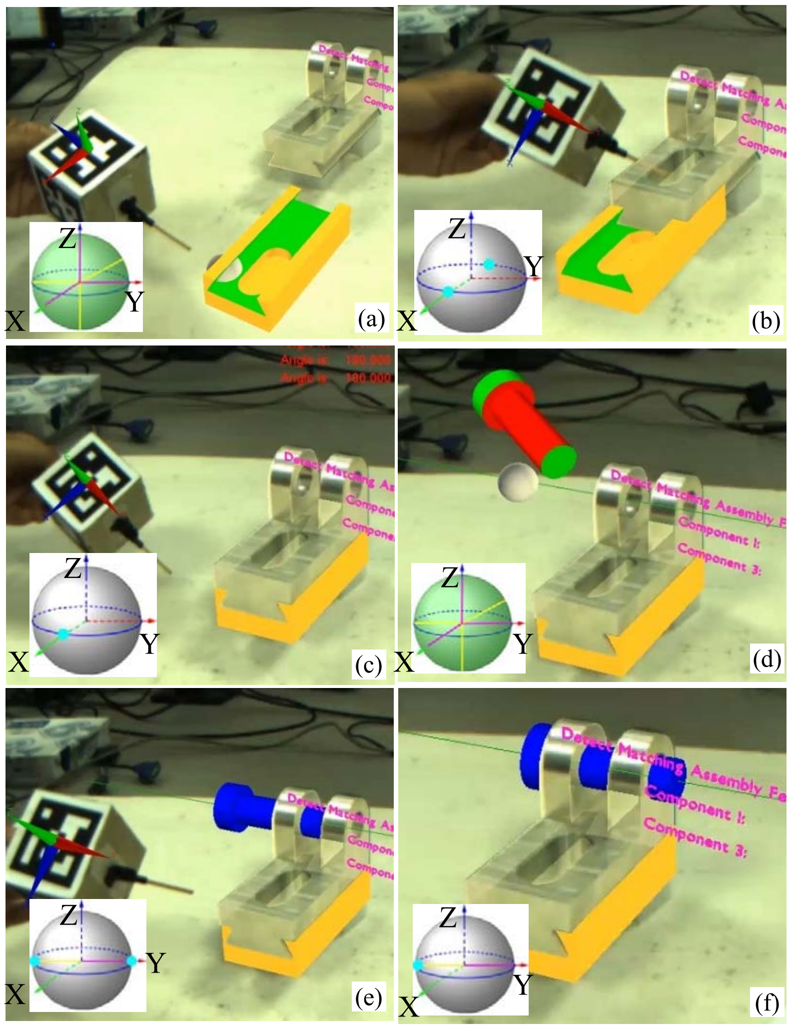


Figure 6-6 The DOF representations and merging for contact modelling

6.2.3 Assembly forces calculation

In order to obtain realistic assembly manipulation of the reference component, it is imperative to calculate assembly forces that drive the reference component to interact with other components in ARTE. As shown in Figure 6-1, the contact forces, the gravity, the virtual snapping force, and the manipulation forces exerted on the reference component are required to be calculated. To maintain the reference component in a quasi-equilibrium motion state, an optimization objective function is formulated to calculate the manipulation forces. Based on these forces, the motion of the reference component from frame *i* to *i+1* can be achieved. These forces can be rendered in the ARTE scene to provide comprehensive feedback to users to facilitate assembly evaluation and design. All the components are assumed to be perfectly rigid.

6.2.3.1 Determination of Contact forces

Contact force $\boldsymbol{F}_{ci}$ is created when collisions occur between the reference component and other real/virtual components. The force magnitude depends on the stiffness, shapes of colliding surfaces, and interpenetration of the contacting components. It can be calculated using a penalty method (Faure et al., 2008), where the contact force is generated to repel the components in order to reduce the interpenetration. $\boldsymbol{F}_{ci}$ is applied on the contact point and the direction is along the contact normal. To generate a continuous contact force in the contact process, a square function (Equation 6-5) is defined to represent the relation between the contact force and the distance between contacting components. This function increases rapidly as the distance decreases, and can be implemented easily to avoid unstable simulation issues. a_{stiff} is a positive constant related to the stiffness of the contacting components, and needs to be tuned empirically, i.e., to get the parameters through a set of practical tests to ensure stable simulation results; d_{repel} is the repelling distance, which is a positive value, enabling contact to happen when components become close rather than actually touch each other. In ARAMS, d_{repel} is set to 1mm to achieve stable assembly simulation.

$$\boldsymbol{F}_{ci} = \begin{cases} 0 & (d > d_{repel}) \\ a_{stiff} \cdot (d - d_{repel})^2 & (d \leq d_{repel}) \end{cases} \tag{6-5}$$

6.2.3.2 Constraint analysis and virtual snapping force

An assembly task in ARAMS begins with coarse motion, during which the user manipulates a virtual reference component from its initial position to the target component, but the components do not contact. The user can perform the coarse motion quickly without high accuracy, except at the end of the movement, where a transition to the mating motion (i.e., contact happens and fine pose adjustment for reference component is required) occurs. In order to facilitate the swift and smooth transition process, virtual snapping force/torque is implemented. When a reference component is manipulated around its mating position at a certain distance (translation d_L and rotation d_O) and the distance is within a pre-determined threshold (d_L<120mm, d_O<40°), ARAMS can detect the mating *AFS*s by matching parameters in contact configuration and create a virtual snapping force $\boldsymbol{F}_{VS}$ and torque $\boldsymbol{\tau}_{VS}$ to facilitate refining the position of the component accordingly, and the magnitudes of the force and torque are inversely proportional to the distance. The values of d_L and d_O are tuned empirically, i.e., the parameters are obtained through a set of practical tests to ensure stable simulation results.

$$\|\boldsymbol{F}_{VS}\| = k_{VSL}/(d_L+\varepsilon_{0L}) \tag{6-6}$$

$$\|\boldsymbol{\tau}_{VS}\| = k_{VSO}/(d_O+\varepsilon_{0O}) \tag{6-7}$$

k_{VSL}/k_{VSO} are coefficients of the virtual snapping force/torque, and ε_{0L}, ε_{0O} are positive constants to prevent zero denominator. The virtual snapping force and torque help users to achieve precise component manipulation through snapping the reference component to its target position, such that an ideal initial condition (small translation and rotation distance) can be provided for the mating motion. The virtual snapping force and torque are relatively small, and will not introduce disturbance to the assembly simulation; when the reference component contacts the target component, the coarse motion phase terminates and the virtual snapping force/torque will disappear.

6.2.3.3 Determination of manipulation forces and torques

To achieve stable manipulation of a virtual component, the forces and torques exerted on the component have to be in a quasi-equilibrium state, *viz.*, satisfying the following conditions:

Condition (a): Resultant forces from EBHI, gravity, contact forces, virtual snapping force and effective force from the virtual spring-damper model should be close to a quasi-equilibrium status (equation 6-8). $\boldsymbol{f}_{fi}$ represent contact forces from the interaction patches and $m_0\boldsymbol{g}$ represents the gravity of the reference component. $\sum\boldsymbol{F}_{ci}$, $\boldsymbol{F}_{VS}$ and $\boldsymbol{f}_{effect}$ represent the resultant force from the contact forces, virtual snapping force and effective forces, respectively.

$$\text{Resultant forces} = \sum\boldsymbol{f}_{fi}+\sum\boldsymbol{F}_{ci}+\boldsymbol{F}_{VS}+m_0\boldsymbol{g}-\boldsymbol{f}_{effect} \tag{6-8}$$

Condition (b): The resultant torque should be close to a quasi-equilibrium status (Equation 6-9), where $\boldsymbol{r}_i/\boldsymbol{s}_i$ is the vector from the center of mass of the reference component to its i-th interaction patch (with EBHI)/contact point (with components), h_i is the scale of the frictional torque from the i-th interaction patch, and $\boldsymbol{n}_i$ is the normal vector of the surface at the i-th interaction patch.

$$\text{Resultant torque} = \sum(\boldsymbol{r}_i \times \boldsymbol{f}_{fi} + h_i \cdot \boldsymbol{n}_i) + \sum(\boldsymbol{s}_i \times \boldsymbol{F}_{ci}) + \boldsymbol{\tau}_{VS} - \boldsymbol{\tau}_{effect} \quad (6\text{-}9)$$

Condition (c): Forces exerted from user's hand should be smooth over time to reduce discontinuity in component motions.

$$\text{Smoothness of hand contact forces} = \sum(\boldsymbol{f}^{t}_{fi} - \boldsymbol{f}^{t-1}_{fi})^2 \quad (6\text{-}10)$$

$$\text{Smoothness of frictional torques} = \sum(h^{t}_{i} - h^{t-1}_{i})^2 \quad (6\text{-}11)$$

Optimum manipulation forces and torques can improve the manipulation effectiveness and reduce the jittering effect during AR-based assembly simulation, and improve assembly efficiency. This problem is formulated as an optimization problem below, and solved using a convex optimization method (Boyd and Vandenberghe, 2009).

$$\text{Min} \quad \omega_1(\sum \boldsymbol{f}_{fi} + \sum \boldsymbol{F}_{ci} + \boldsymbol{F}_{VS} + m_0\boldsymbol{g} - \boldsymbol{f}_{effect})^2 + \omega_2[\sum(\boldsymbol{r}_i \times \boldsymbol{f}_{fi} + h_i \cdot \boldsymbol{n}_i) + \sum(\boldsymbol{s}_i \times \boldsymbol{F}_{ci}) + \boldsymbol{\tau}_{VS} - \boldsymbol{\tau}_{effect}]^2 + \omega_3 \sum(\boldsymbol{f}^{t}_{fi} - \boldsymbol{f}^{t-1}_{fi})^2 + \omega_4 \sum(h^{t}_{i} - h^{t-1}_{i})^2 \quad (6\text{-}12)$$

$\omega_1 \sim \omega_4$ represent the weight of each condition and $\sum\omega_i = 1$. As the state of quasi-equilibrium of the force and torque is more important than the smoothness of the hand contact forces and frictional torques, ω_1 and ω_2 should be much larger than ω_3 and ω_4. Based on this, $\omega_1 \sim \omega_4$ are set as 0.45, 0.45, 0.05, 0.05 respectively. The force/torque from the user's fingertips ($\boldsymbol{f}_{fi}$, h_i) are exerted on the manipulated reference component directly, and the feasibility of these optimization results ($\boldsymbol{f}_{fi}$, h_i) is tested to ensure the manipulation forces are within the Coulomb's friction cone (Liu, 2009), such that the assembly simulation is realistic and meaningful.

7. Multi-modal AR assembly guidance

7.1 Introduction

In this chapter, the architecture of the CARAGM module is presented to demonstrate how AR can provide different modalities of guidance to assembly operators for the various cognition phases.

7.2 User cognition model and system overview

7.2.1 User cognition model in ARAOG

In order to integrate the user cognition process to CARAGM, an appropriate user cognition model for manual assembly should be adopted through an investigation on human cognitive research (Neumann and Majoros, 1998; Zaeh et al., 2009). The integration of the model is based on the assumption that the entirety of the human cognitive process during a manual assembly task is processed in a roughly sequential order, until the execution is carried out on the assembly task. The user cognition model is adapted from (Stork and Schubo, 2010), and the model is implemented in the CARAGM as it is convenient to decompose the cognitive process into different phases, and the usefulness and effectiveness of the model has been demonstrated.

The cognitive process is divided into four phases, namely, perception, attention, memory, and execution. In the perception phase, the user begins to identify and comprehend the necessary instructions of an assembly task. Hence, in this phase, the prime guidance modalities are rendered instructions, e.g., the 3D animation of the assembly process, rendered text/image instructions, etc. In the attention phase, the user needs to identify and locate the necessary items (components, tools, etc.) on the assembly workbench for the current work step, and therefore, the AR guidance system should prompt the user to localize the items, and avoid unnecessary shifts of attention. Therefore, the modality of guidance in this phase is attention-directing augmented symbols, e.g., 3D arrows. In the memory phase, the user begins to organize the current task into a sequence of sub-tasks (manipulation, fastening, etc.) and consider how to accomplish each sub-task within a reasonable time. Hence, the user should be able to add AR notes, i.e., 3D text input by the user and rendered in the AR environment when needed, in order to encode plans of procedures, knowledge about the components and tools, etc. The memory phase exists throughout the entire cognition process, such that the user can add and retrieve the AR notes when the task is executed, thus avoiding the user from memorizing a long sequence of operations, warnings and instructions during assembly. One of the characteristics that CARAGM distinguishes from other systems is the AR guidance in the execution phase. The pose and position of the tools and components are tracked by the system to provide timely AR guidance. Users can simulate the assembly process on-site to enhance understanding. Error feedback in the haptic form can be generated if the user fails to perform the correct actions.

7.2.2 Overview of CARAGM

The CARAGM is related with the four common functional modules (ARTE, ARKF, ARTR, AIM) in IARAE (Figure 3-1 in Chapter 3). The EBHI is implemented to support both hand gesture commands input and intuitive 3D manipulation of virtual contents in the AR environment. The SMF stores the source media file data which is necessary for the AR guidance retrieval in the CARAGM module. The CARAGM manages the workflow of the AR assembly process and determines when, where, what and how to augment the virtual guidance in the ARTE to facilitate the user, and handle the user's request for guidance.

7.3 ARTE for CARAGM

Figure 7-1 shows the setup of ARTE specific for CARAGM, including physical assembly workbench, real components/tools and virtual contents. There are three registered function areas in the ARTE with the three ID markers, namely, the assembly workspace, toolbox, and components store. The function of the ARTR module is to track the real objects using the modified hybrid marker-less tracker (Chapter 4), and tracking of the function areas of ARTE using a marker-based tracking method (ARToolkitplus, http://studierstube.icg.tugraz.at/ handheld_ar/artoolkitplus.php).

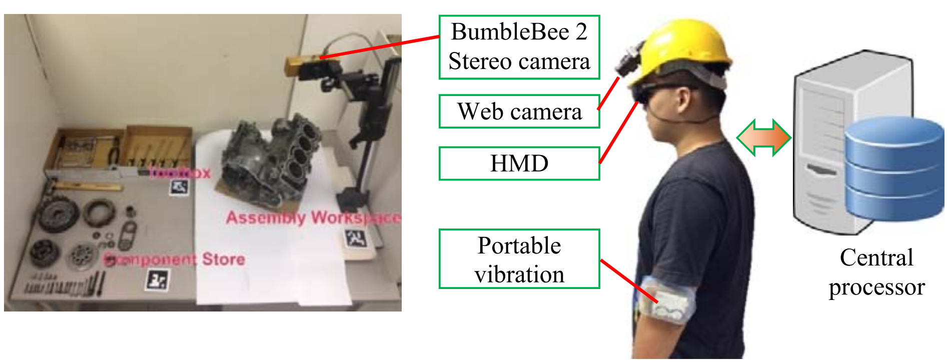


Figure 7-1 The proposed ARTE

As shown in Figure 7-1, two cameras are used in the prototype system. The first camera is a Bumblebee2 stereo camera mounted on top of the assembly workbench to provide 3D positions of the user's hands. The second camera is a common web camera mounted on the user's helmet to capture the user's view. The display is a stereo video see through HMD constructed from an 800×600 resolution color display with an average frame rate of 45 fps. The cameras and HMD are connected to a desktop (4GB SDRAM Memory, 3.2GHz Intel Core i5-650, ATI Radeon HD4550 512MB graphics card), which is used as the central processor to store, manage and process the assembly information.

7.4 CARAGM

7.4.1 Enhanced bare-hand interface

In the system developed in this research, the EBHI is adopted over the traditional interface design (mouse, keyboard, joystick, etc.) to provide the most natural way of human computer interaction (HCI) in the AR assembly environment. The original 3D bare-hand interface (BHI) (Wang et al., 2013a) has been formulated and developed using computer vision technologies. In the current system, the BHI has been enhanced to recognize two types of gestures, namely, iconic gestures (static gestures in the air) and 3D manipulation gestures.

Figure 7-2 shows a few examples of these gesture types. In order to satisfy the basic requirement of an AR interface, a point and click gesture is implemented to trigger virtual options on a virtual control panel for request for user guidance. Many of the user's requests can be realized through this gesture, and the most natural way to perform this gesture is by an outstretched index finger.

When the fingertip is in the button area continuously for 2~3 seconds, the gesture is recognized as click and the function associated with the button is activated. The interface includes other gestures to improve the control efficiency, such as shortcut commands, e.g., next step, last step, etc. An easy-to-remember set of gestures that provides a rich enough vocabulary to create useful interfaces is illustrated in Figure 7-2.

In addition to these gestures, the system supports freehand 3D gestures to manipulate (e.g., translation, rotation, scale, etc.) both virtual components and guidance material, and this is a functional extension of the EBHI described in Section 6.2.1.2. Users can assemble virtual components to real components to simulate the assembly process. The user can also manipulate the virtual guidance materials (3D text, images, etc.) in the event that these materials are not displayed properly, such as overlaying important region of the user's view, inappropriate scale, unsuitable viewpoint directions, etc. The user can move a virtual component with EBHI (Figure 7-3d-f). The user can deselect a virtual object by enlarging the distance between two fingertips such that one or two virtual spheres are not in contact with the virtual object. In addition, the user can scale guidance materials in 3D by moving his hands/fingers farther or nearer to each other, respectively (Figure 7-3b-c). In addition to these gestures, CARAGM supports other freehand gestures to facilitate assembly operations. One example is the 'open palm facing down' posture (Figure 7-2g-h), that let the user navigate to the home screen of CARAGM from any guidance modality. In addition, as the bare-hand interface provides the 2D/3D position of the fingertips and central points for both hands, users can configure other hand gestures to be suited for the specific applications.

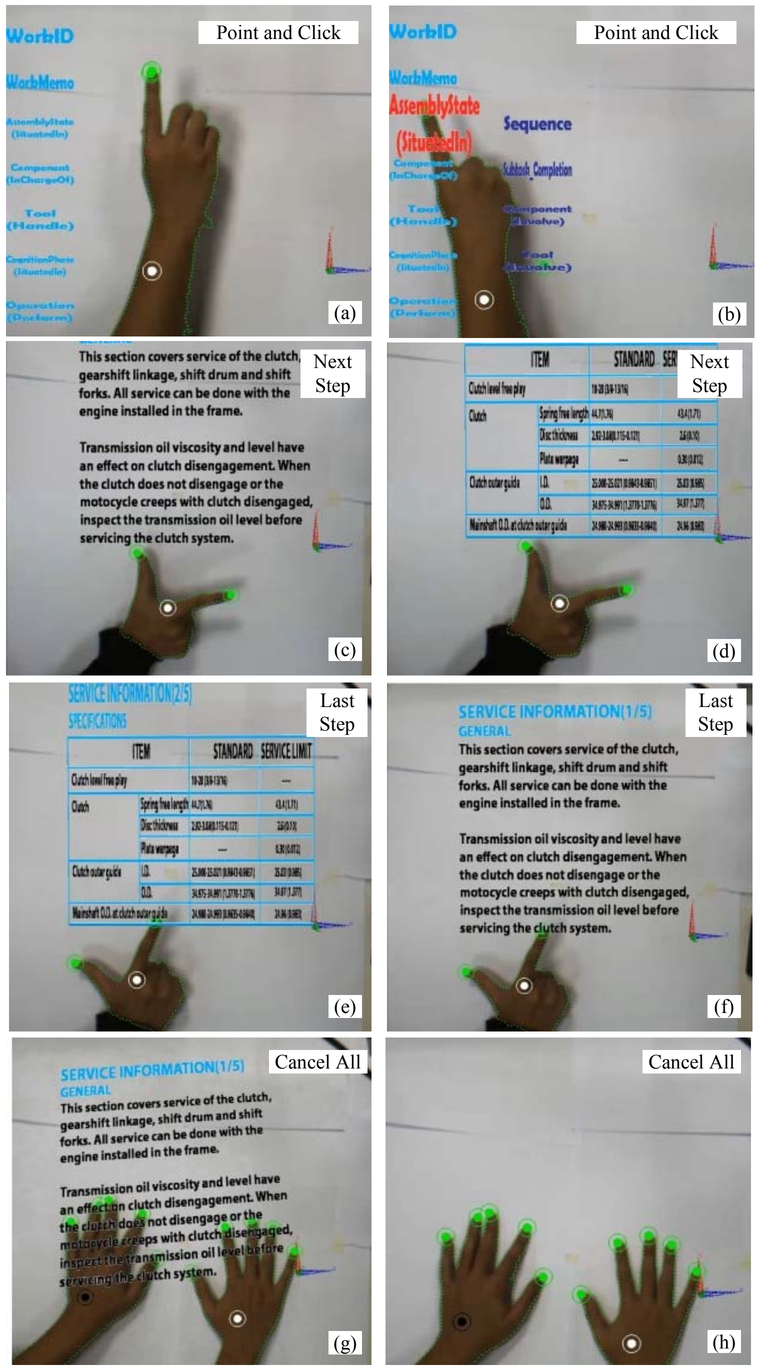


Figure 7-2 Example iconic gestures

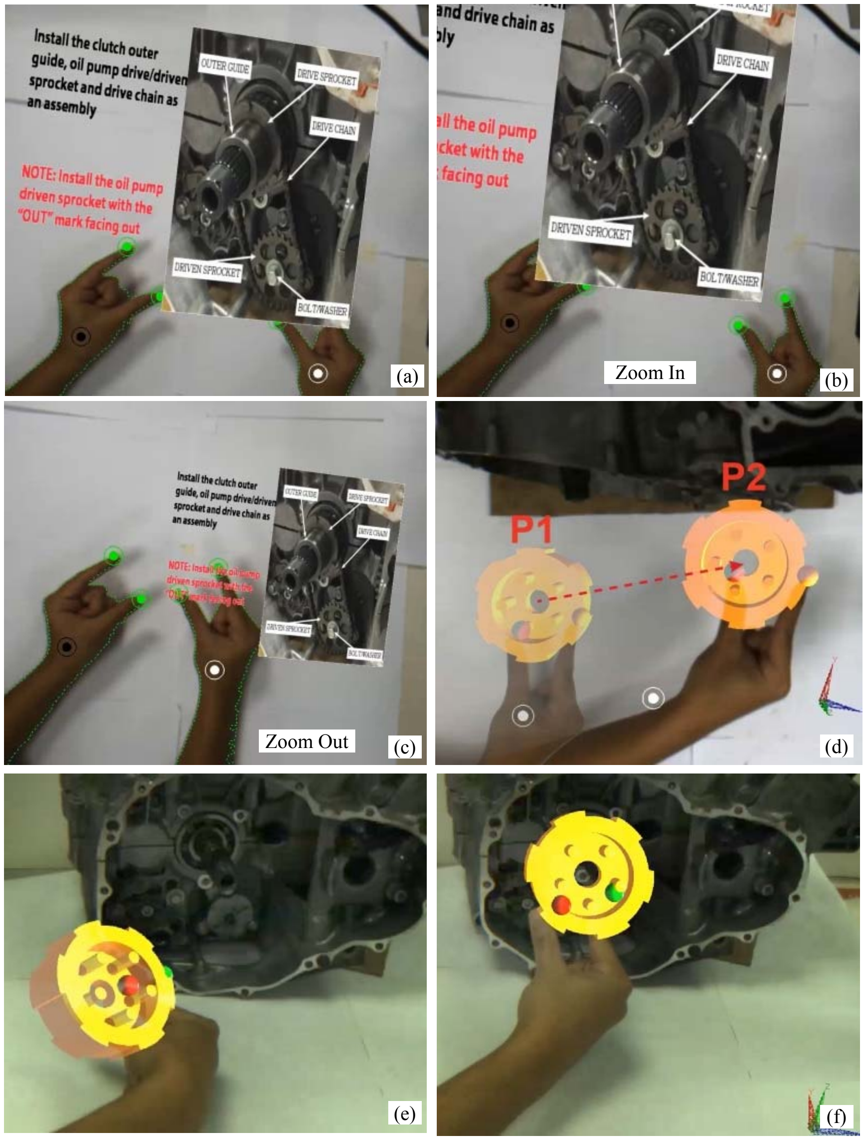


Figure 7-3 3D manipulation gestures

Haptic feedback is important to improve the quality of user performance of assembly tasks, because it can alert the users promptly when they have not performed an operation correctly, so as to make a correction. Haptic feedback can be accomplished using a portable vibration device (Figure 7-4), which can receive error signals from the system through blue-tooth and implement vibration stimuli to the user's arm. The haptic feedback set is worn around the elbow of non-dominant arm of the user in case the vibration may interfere with the user's assembly operation. The vibration feedback is useful for the AR guidance system, especially when a large amount of guidance information has to be provided for the user through vision.

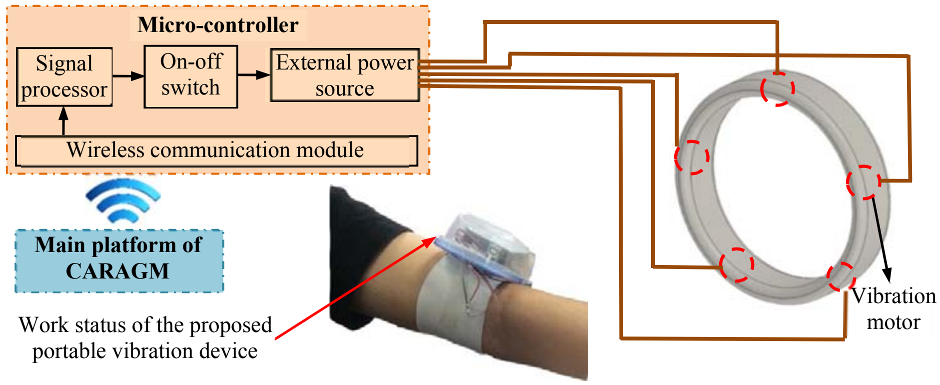


Figure 7-4 The proposed portable vibration device

7.4.2 AR guidance unit

AR assembly guidance management involves modeling of the AR assembly guidance information template, and defining the reasoning rules to provide the appropriate instance of the template based on a user's cognition need and task progress. In CARAGM, a semantic data based assembly guidance information template, which is encoded as a XML file, has been implemented. The system can represent various specific realization of the template by adapting the parameters with the data from assembly simulation during the development process (Wang et al., 2014) and engineering data from external repositories (e.g., enterprise PDM, assembly simulation results, etc.). This specific realization is an instance of AR assembly guidance. In the current system, the AR guidance for an assembly task is composed of AR assembly guidance instances, which can be categorized and stored based on their functionality, the cognition phases involved, components, tools, modalities, etc.

The assembly guidance template has five properties, namely, Content, Source Media Files, CognitionPhase, Registration and Motion, and Modality. Content has four parameters, namely, AssemblyState, Component, AssemblyFeature, and Tool. The relations between these parameters and the information they stored have been illustrated in OATP. Source media files are used to store the paths (File Path) and types (File Type) of the media files which present the guidance information, e.g., text, image, video, 3D models, etc. CognitionPhase has been defined in OATP and is used to classify various modalities of AR guidance corresponding to the different cognition phases of the user. Registration and Motion manages the position (Translation, Rotation, Scale) and motion (LinearMotion, RotaryMotion) of the rendering of the AR guidance information instance. The Modality represents the different types of AR guidance, e.g., text, animation, attention-directing augmented symbols, on-site assembly simulation, etc.

The CARAGM acquires the data of static properties and/or data of partial dynamic properties (marked with triangle tags in Figure 5-3 in Chapter 5), and transmits the data to the OATP. The data of the derived dynamic properties within OATP will be inferred by the reasoner and transmitted to the ARKF module to present the corresponding AR guidance instance. Two of the reasoning rules for the assembly task are given next.

AssemblyState(?a)∧Task(?a,ReedValveCover)∧CognitionPhase(?b)∧InCognitionPhase(?b,perception) →Subtask(?a,taskcomprehension)∧AR_Guidance(?c,ReedValveCover,perception) Rule (7-1)

AssemblyState(?a)∧Task(?a,ReedValveCover)∧CognitionPhase(?b)∧InCognitionPhase(?b,execution)→Subtask(?a,manipulation)∧Subtask(?a,alignment)∧Subtask(?a,fastening)∧AR_Guidance(?c,ReedValveCover,execution) Rule (7-2)

When there are multiple AR guidance instances available, e.g., the guidance for instruction comprehension can be text, image, animation, etc., the user can select the most appropriate one through EBHI. The information of the assembly state can be obtained through tracking the manipulated component or from user inputs, and the information for the cognition phase can be obtained from user inputs. The guidance instance to be rendered can be reasoned based on the updated assembly state and user cognition phase in real time, and the visualized information can thus be synchronized.

7.4.3 User request interface

The CARAGM module needs to handle user requests, facilitate the user to navigate through the extensive engineering information, and provide the corresponding guidance instance during the assembly process. In CARAGM, the user can send the commands by activating buttons in the virtual navigation menu to request for suitable modality of AR guidance, access to the information instances stored in OATP or create new information instances (e.g., add AR notes) to update the assembly guidance database. The virtual navigation menu is based on the screen coordinate, and it is a virtual display of computer augmented information, such as virtual buttons (Figure 7-5). Therefore, with the clicking and pointing functions of EBHI, the user can activate the virtual buttons. By storing engineering information through the use of formatted information representations, reasoning and inferring functions of ontology, the desired information and guidance instance from the repository can be retrieved. When the user obtains the data from one information instance, he can also obtain the pertinent instances of concepts having relationships or associations stored in OATP. For example, as shown in Figure 7-5a, the main navigation menu is displayed on the left side of the view plane, and each button of the menu represents a class/property which is pertinent to the User class in OATP. In Figure 7-5b, when the user activates the 'AR_Guidance_Unit' button, the system infers the most appropriate AR guidance instances (Figure 7-5c) based on the rules described previously (Section 5.3 and Section 7.4.2). The user can cancel the AR guidance contents and return to the main navigation menu by using cancel gesture with EBHI.

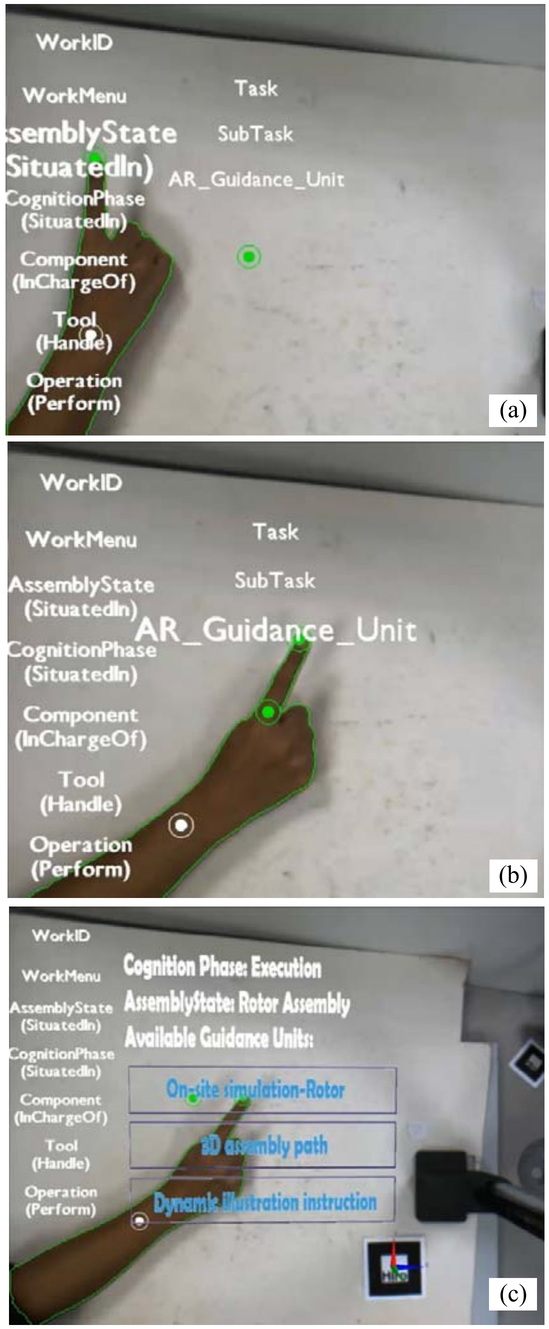


Figure 7-5 Navigation menu

7.4.4 Workflow manager

As shown in Figure 7-6, there are two modes to activate an instance of AR guidance during an assembly operation, namely, automatic mode and user request mode. In the automatic mode, the guidance instance for each user cognition phase will be activated automatically in a sequential order. If the user needs to replay an instance, the user can send the request to the system using EBHI. However, the AR guidance system will become less efficient when there is much visualization content to display, e.g., navigation menus, multi-media instructions, etc., as greater visualization content will cause more shift of the operator's attention focus. Hence, in the user request mode, the user can request for the most suitable modality of AR guidance for each cognition phase.

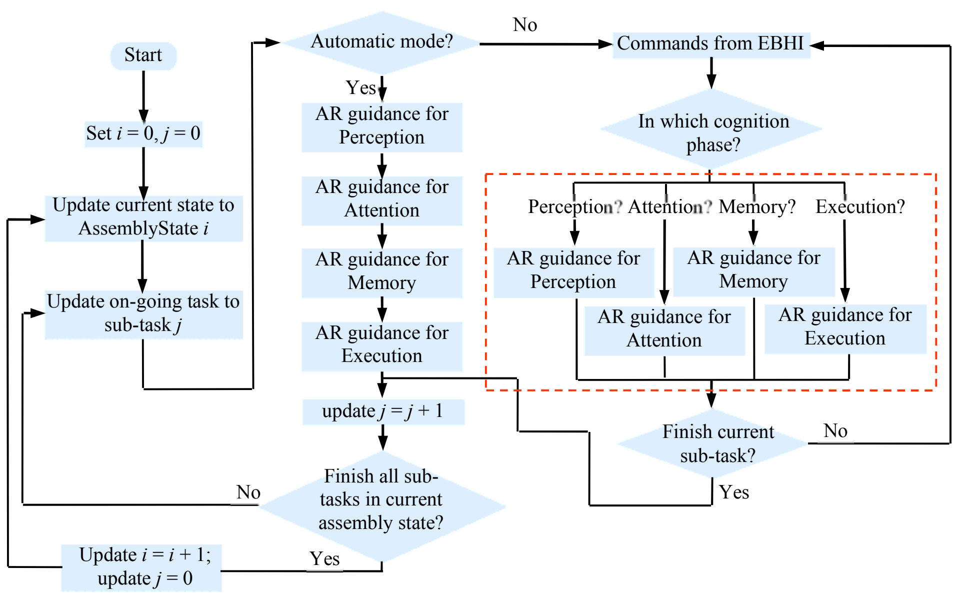


Figure 7-6 Workflow of CARAGM

For the perception phase, AR guidance instances that are related to the assembly of the component are presented by clicking the button of the corresponding component on the virtual navigation menu with EBHI (Figures 7-2 and 7-3). The modality of AR guidance in this cognition phase is similar to traditional AR assembly guidance systems (e.g., text, image and/or animation). The modality of AR guidance for the attention phase is to use 3D arrows to direct the user's attention. The positions of the toolbox/components have been pre-defined and attached with markers. When the user's view focuses on the correct toolbox, highlights are implemented to guide the user to find the tool (Figure 7-7b). The small id-markers implemented in the proposed system are attached to a certain component/tool during the assembly process. For example, the id-marker in Figures 7-7c-d is related to the wrench socket head with a 10mm diameter and it is the corresponding tool for the fastening operation of the component. When the correct tool has been identified, the pertinent technical details on the component/tool can be retrieved and rendered on the scene. The printed id-markers are pasted onto the components/tools as the CARAGM is still a laboratory-based prototype; these printed markers will be replaced by laser etched markers when the prototype is implemented in an industrial production environment. The memory phase begins when the user starts to plan the current assembly task. Although the proposed system provides various modalities of AR guidance, the assembly operators may still need to record their own understanding of how to perform the operation in notes. In such cases, the user can create the AR notes by inputting the text with EBHI and a virtual keyboard (Ong et al., 2012). These created AR notes will be rendered when the user selects it from the virtual navigation menu.

For the execution phase, it is assumed that the users have achieved a basic understanding of the assembly task during the perception and attention phases; therefore, in this phase, some abstract but intuitive symbol-based timely AR guidance is provided. The timely AR guidance can adapt its content with the user's activity and/or progress of the assembly task. Three AR guidance modalities are provided in the execution phase, namely, augmentation of virtual component that is aligned with the real component, on-site assembly simulation, and 3D dynamic assembly paths with illustrative instructions (Figures 7-7e-l). When the execution phase begins, the user needs to first initialize the pose of the target/reference component. For the first guidance modality in the execution phase, the virtual model of the reference component will be rendered with accurate 3D spatial relationship with the target component. The rendering is updated as the user moves the target component in real time (Figures 7-7e-f), such that the user can control fully the augmented guidance in a natural way. In addition, in order to enhance the transfer from perception to practice, the user can manipulate the virtual reference components to simulate the assembly process on-site through the EBHI (Figures 7-7g-h). When the user begins the execution of assembly operation, the system presents the dynamic 3D assembly path leading to the target location. In Figures 7-7j-l, during the manipulation of the reference component, a dynamic 3D arrow that is pointing from the axis of the reference component to the axis of the target component, is displayed to provide a visual hint to the user to assist him/her to locate the reference component. The size and color of the arrow are updated dynamically to reflect the magnitude of the motion required to achieve the desired alignment (e.g., large red arrows and small green arrows indicate large and small corrections respectively). The haptic feedback will be provided when the user has manipulated the reference component in a wrong direction. Dynamic illustrative instructions are provided to help the user identify the connection ports (assembly features/surfaces) on the target/reference component (Figure 7-7i). The contents of the instructions comprise the feature types, the distance and the angles to align the reference component appropriately (Figures 7-7i-l).

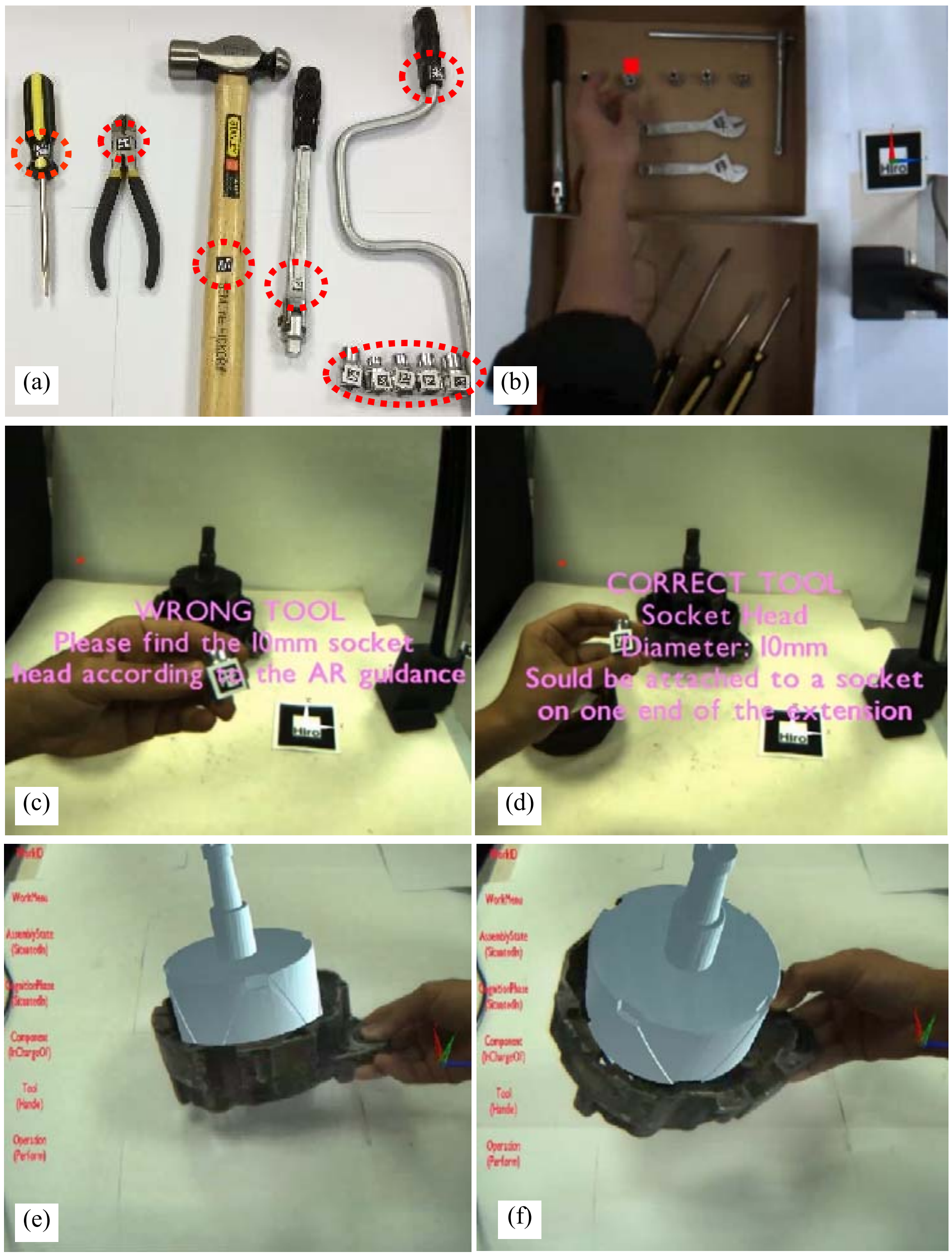


Figure 7-7 Various modalities of AR guidance in CARAGM

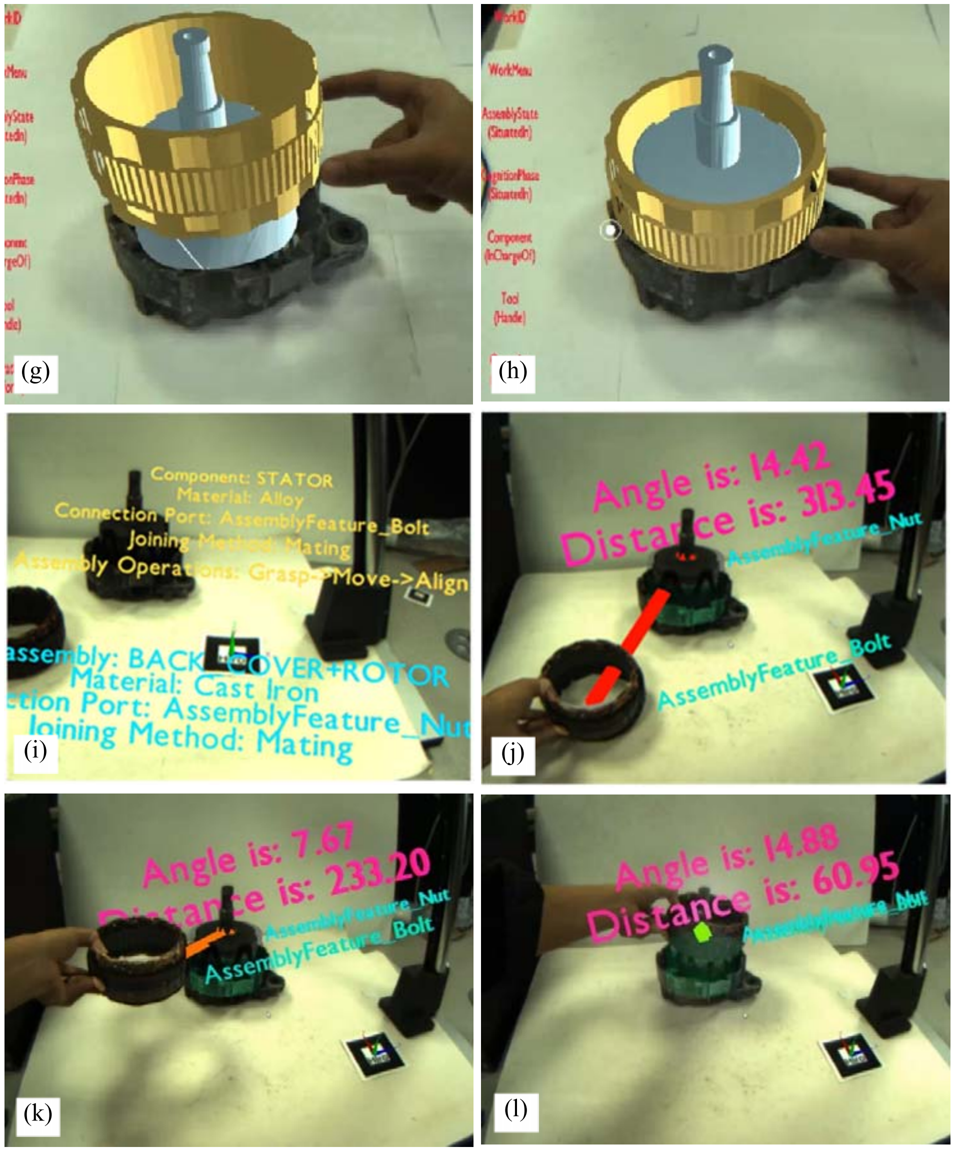


Figure 7-7 Various modalities of AR guidance in CARAGM (continued)

8. System Implementation and Discussion

In this chapter, case studies and tests are presented to demonstrate the implementation of ARAMS and CARAGM in IARAE.

8.1 Implementation of ARAMS

8.1.1 Component contact handling strategy

8.1.1.1 ARAMS configuration and implementation

A prototype system has been developed based on the methodologies presented in Sections 4 to 6. The ARKF and ARAMS modules have been implemented using Visual Studio 2010. The MBT tracker and KLT tracker have been implemented with the ViSP tracking platform (http://www.irisa.fr/lagadic/visp/visp.html). The AIM module has been developed using OWL API (http://owlapi.sourceforge.net/) and the Pellet reasoner (http://clarkparsia.com/pellet/), and AIM communicates with the other modules via socket communications. The implementation of the physics environment is based on the open-source library Bullet Physics Engine (http://bulletphysics.org). The setup of the prototype system is shown in Figure 8-1. It includes a Chameleon USB 2.0 digital camera, a desktop (4GB SDRAM Memory, 3.2GHz Intel Core i5-650, ATI Radeon HD4550 512MB graphics card) as the central processor to store, manage and process the assembly information, a HMD and a desktop display are used as rendering devices, and a hand-held interaction tool. A marker is fixed on the assembly workbench to determine the world coordinate system so that the camera can track its own pose and position with respect to the world coordinate system.

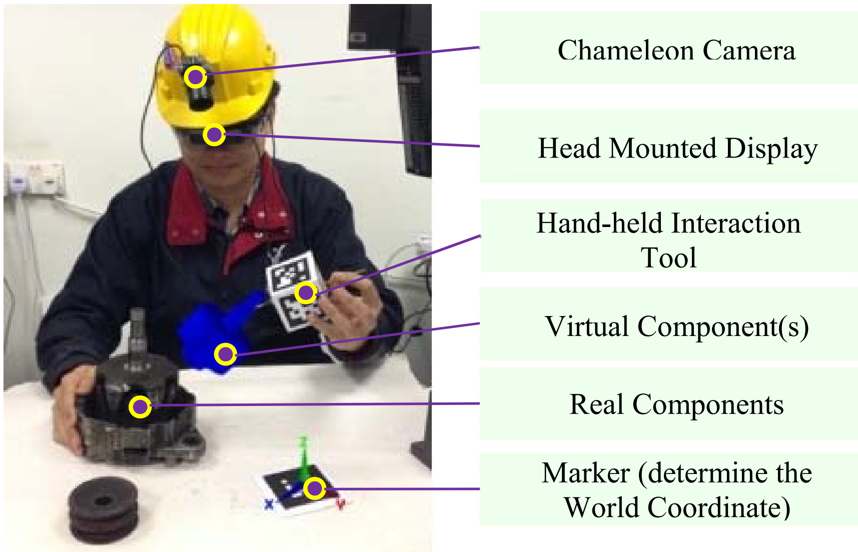


Figure 8-1 Setup of ARAMS

8.1.1.2 Case study

This section presents a case study of an automobile alternator (MITSUBISHI MEO77789). The components involved in this case are shown in Figure 8-2. Specifically, the alternator is composed of two covers (front cover and rear cover), rotor-1, rotor-2, stator, bearing, lifter bearing and pulley.

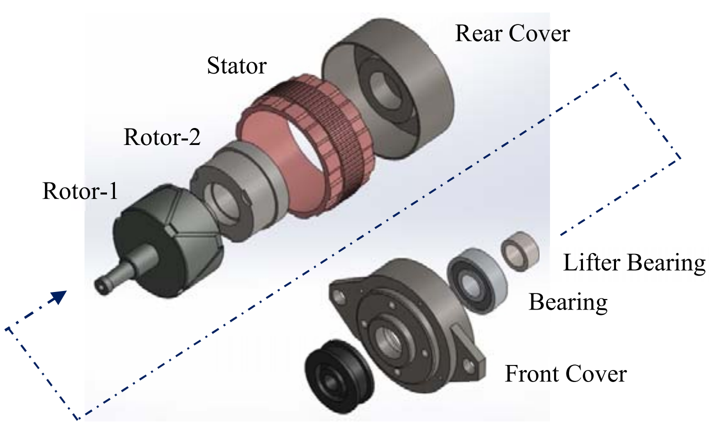


Figure 8-2 CAD models of the case study

During assembly simulation and planning, the operator is equipped with a HMD and a head-mounted camera. Figure 8-3 shows the initialization process of a representative component. During this process, the operator needs to accomplish the registration process by selecting a set of feature points sequentially (Figure 8-3a). The set of feature points is selected by the user using a mouse through clicking on the captured image. The feature points must be selected in sequence, because there is a map between the positions of the selected feature points on the image and the 3D coordinates of these feature points. After the point selection process, the pose of the real component can be obtained (Figure 8-3b) using pose estimation algorithms available in ViSP. Based on the initial pose of the component, the system can track the real component and provide the pose matrix in real time (Figure 8-3c).

The geometric shape information and design data (dimensions, materials, etc.) of the component are extracted from the CAD model and sent to the AIM module for reasoning and inference during the initialization process of the component. The system will infer the relations of *AFS*s based on reasoning rules and stored information instances. The assembly simulation and planning process is performed next.

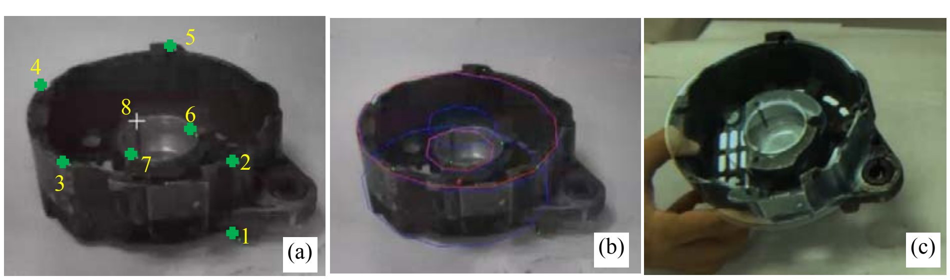


Figure 8-3 The registration process of a real component

In Figure 8-4a, the user grasps the virtual rotor-2 by manipulating the interaction tool and moves rotor-2 towards rotor-1. During the assembly operation, when the components are colliding, the system builds the contact configuration (surface types, parameters, feasible DOF, etc.) for the contact surface pairs, and detects the possible mating relations. If no mating relations are recognized, the behavior of the virtual component is simulated with physics properties (e.g., gravity, avoidance of inter-penetration, velocity, acceleration, etc.). In Figure 8-4b, two cylindrical mating relations are detected, and the position and orientation of rotor-2 in the user's hand are adjusted automatically to ensure that both cylindrical mating relations are met precisely. In this case, the feasible *DOF*s for the two mating relations are {*transz+, transz-, rotz+, rotz-*} and {*transz+, transz-, rotz+, rotz-*} with respect to the local coordinates of rotor-2 respectively, and therefore the merging DOF_t for the rotor-2 component is {*transz+, transz-, rotz+, rotz-*} according to Algorithm 6-2 in Section 6.2.2, meaning that when the two mating relations are held, the interaction tool can only manipulate the virtual component within the merging DOF_t. This assembly process is completed when the bottom planar surfaces of rotor-2 and rotor-1 are in contact and a plane mating relation between them is recognized and established (Figure 8-4c). In Figure 8-4d-f, the operator assembles the virtual sub-assembly of the rotor (rotor-1 and rotor-2) with the real rear cover and this is a case of multi-virtual component interaction with a single real component. Figures 8-4g and 8-4h show the process to assemble the virtual stator to the sub-assembly of real rear cover, and virtual rotor-1 and rotor-2. After this step, the tracking model is updated because the real stator and rotor have been assembled onto the real rear cover (Figure 8-4i). The updating method of the tracking model is to integrate the tracking features from each separate tracking model and let the operator remove occluded features in the view interactively (e.g., with a mouse). This tracking model updating process is implemented whenever a new real component has been added. Figures 8-4i-j show a cylindrical mating relation and a plane mating relation are satisfied after the front cover assembly process. The assembly process ends with the steps illustrated in Figures 8-4k-l, where the operator manipulates the pulley to interact with the pre-assembled assembly.

This case study shows that ARAMS can help the user grab the virtual components and assemble them onto real components aided by CCH. Since users cannot manipulate the components precisely, thresholds have been implemented based on the human proprioceptive position sense for mating relationship recognition (Van Beers, et al., 1998). For example, for *has_MatingRelationPlanar*, there are thresholds for two parameters. The first threshold is the distance between a point on one plane and the projected point of this point on the second plane (5mm), and the second threshold is the angle between the normals of these planes (10°). For *has_MatingRelationCylinder*, there are two parameters. The first parameter is the distance between a point on one axis and the projected point of this point on the second axis (5mm); and the second parameter is the angle between these two axes (10°). The values of these parameters are chosen empirically.

Figure 8-4 The assembly simulation and planning process

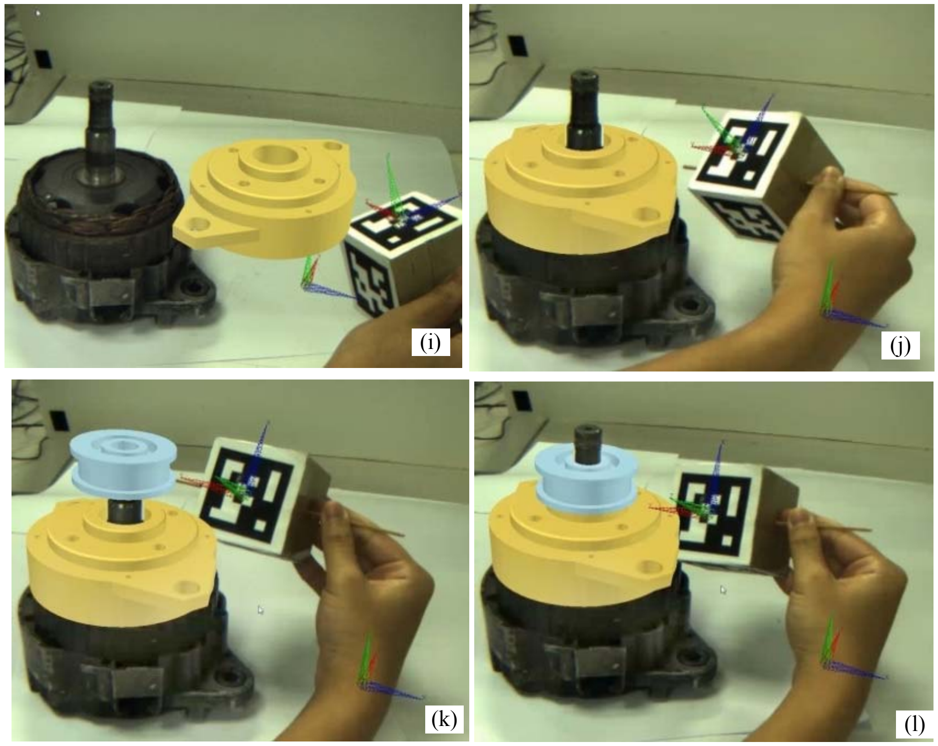


Figure 8-4 The assembly simulation and planning process (continued)

8.1.1.3 System evaluation

8.1.1.3.1 Feasibility and efficiency test of CCH strategy

The purpose of the test in this section is to evaluate the feasibility and efficiency of the proposed CCH strategy. The participants are required to perform a set of AR assembly simulation tasks with a pre-determined assembly sequence, which is described in Figure 8-4, to verify that the users can perform AR assembly using ARAMS (feasibility). The efficiency of the CCH strategy is evaluated based on the user performance. The setup of the system used by the participants is described in Section 8.1.1.

The measurements are performed after each reference component has been loaded into the AR environment; these measurements include the completion time of each task (time when loading is completed to when the reference component is assembled in the final position) and the pose and *DOF*s of the reference component when it has been aligned with the target component. Two different types of contact handling modes are tested. For the first mode, no CCH strategy is implemented (only the physics engine is implemented to handle the contact). In the second mode, the CCH strategy is implemented. Each participant repeats the whole assembly sequence (seven assembly tasks) twice in each case. Therefore, there are $2 \times 7 \times 2 = 28$ assembly tasks for each participant. Seven participants were invited to conduct the test, namely, five men and two women, and they are aged between 22 to 33 years. All the participants are familiar with AR, including two with assembly design and planning experience. Four of the participants performed AR assembly simulation in mode two (CCH is implemented) first, and the others performed the simulation in mode one (CCH is not implemented) first.

The statistical analysis is described based on the results of $28 \times 7 = 196$ measurements. Figure 8-5 shows a summary of all the performance results, i.e., the task times for each step of the assembly for all the participants in the two modes. The average time for all the participants and tasks is 31.5s with a standard deviation of 14.8s. The standard deviation is sensitive to the users' operation proficiency and task performance. In this experiments, the users have different levels of assembly experience, and therefore, their task completion time can spread widely. Mode one, where the participants are required to complete assembly tasks without the support of CCH, shows the worse results. The average task completion time is 35.5s versus 27.5s for mode two. This difference shows that the use of CCH provides a real gain in the task completion time. Without CCH, although the physics engine ensures that no inter-penetration happens when the components contact each other, there are jittering and unstable results when performing the insertion operations because no unfeasible *DOF*s are removed from the simulation. The difference in the mean value shows that there are significant differences between the two modes ($p<0.001$). As can be seen, the histograms in Figure 8-5 show that concentration measurements lower than 31.5s (total average) is 61.2% for case 2, against 41.8% for case 1. The deviations for completion time in the two modes are 17.1s for case 1 and 10.7s for case 2. The deviations reflect when the participants performed the assembly tasks in mode one, greater dispersed results of the completion time are shown, meaning that the users cannot perform stable assembly operation simulation; thus, the effectiveness and efficiency of AR assembly performance are decreased.

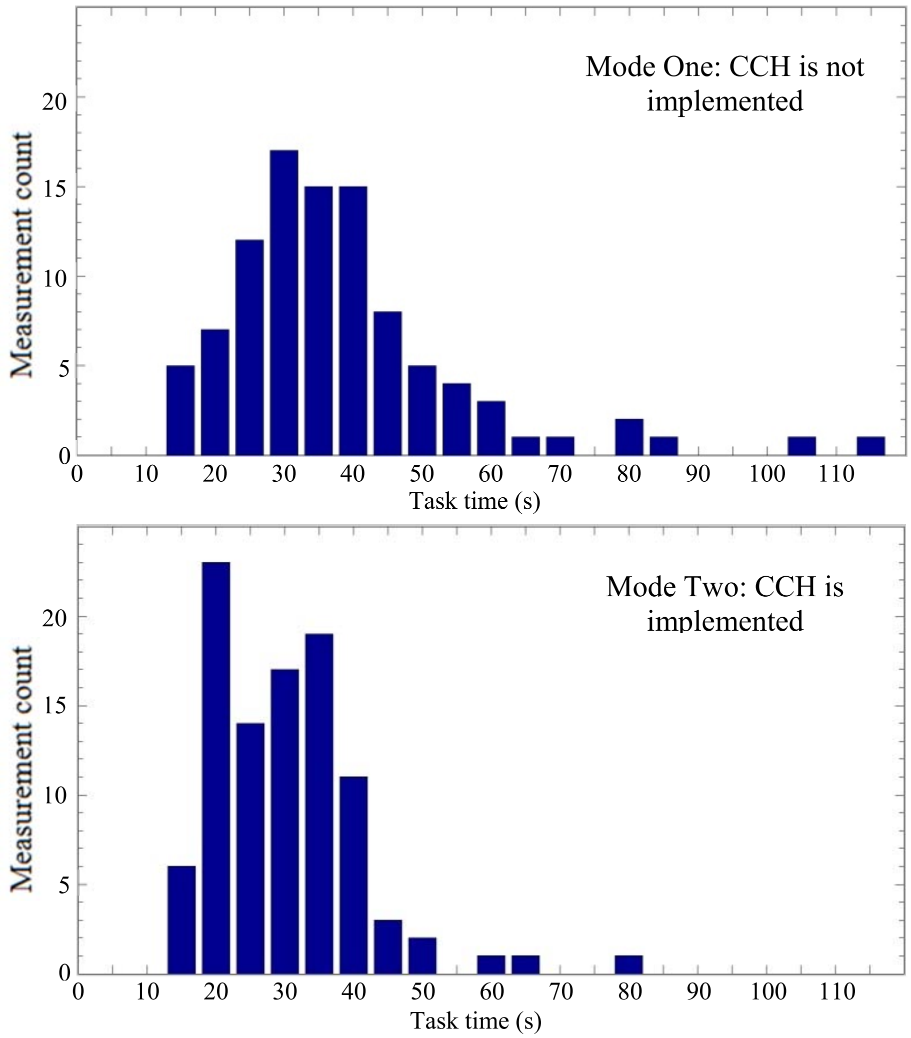


Figure 8-5 Distribution of completion time for each assembly task

According to the measurements, the poses of the geometrical models of the reference and target components are perfectly aligned and the corresponding inferred *DOF*s are correct. This means that CCH performs accurately in the AR assembly tasks. Hence, the primary source of system error comes from the misalignment between the real component and the corresponding tracking model. This misalignment is a computer vision issue (i.e., visual effects) and will not affect the performance of CCH. According to the participants from the two groups, they agreed that the implemented tracking method provides a good enough result for the proposed AR assembly simulation system. The virtual components remain stable and visually accurate registration with the real components, and very little jittering are observed (Figure 8-4). The quantitative results for the misalignment errors in the ARAMS will be provided in the next section.

8.1.1.3.2 System accuracy

The misalignment error is measured continuously when a target component is manipulated in 3D space. In this test, the assembly task of the virtual rotor to the real rear cover is selected (Figure 8-4d-f). As shown in Figure 8-6, a marker is attached to the target component, and the transformation ${}^{M}_{T}T$ which is the description of the target component frame $\{T\}$ with respect to the marker frame $\{M\}$ is measured manually. As the transformation between the reference $\{R\}$ and target $\{T\}$ components ${}^{T}_{R}T$ can be known *a priori*, the ground truth pose of the reference component {R} with respect to the camera frame {C} ${}^{C}_{R}T$ can be obtained using Equation (8-1).

$$ {}^{C}_{R}T = {}^{C}_{M}T \cdot {}^{M}_{T}T \cdot {}^{T}_{R}T \qquad (8\text{-}1) $$

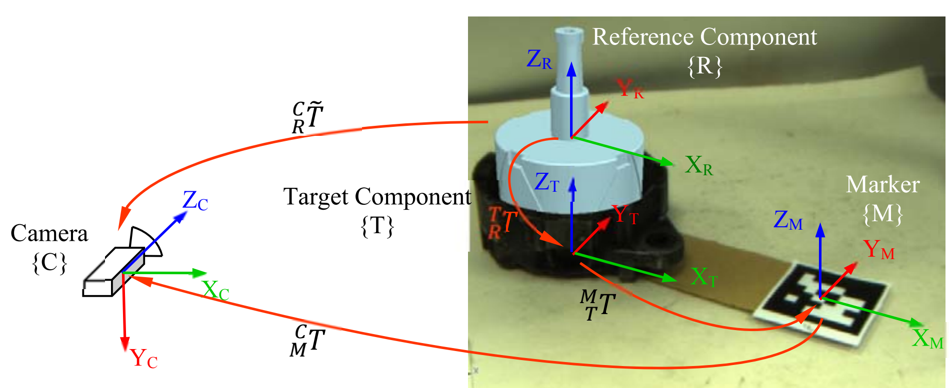


Figure 8-6 Principles for the measurements of misalignment error

${}^{C}_{M}T$ is the pose estimated using AR markers. The estimated pose of the proposed system ${}^{C}_{R}\tilde{T}$ is compared with the ground truth ${}^{C}_{R}T$ as shown in Figure 8-7. ${}^{C}_{R}\tilde{T}$ is calculated with equation (8-2).

$$ {}^{C}_{R}\tilde{T} = {}^{C}_{T}T \cdot {}^{T}_{R}T \qquad (8\text{-}2) $$

${}^{C}_{T}T$ is obtained from the implemented tracking method. The misalignment errors of the reference component are presented in Table 8-1.

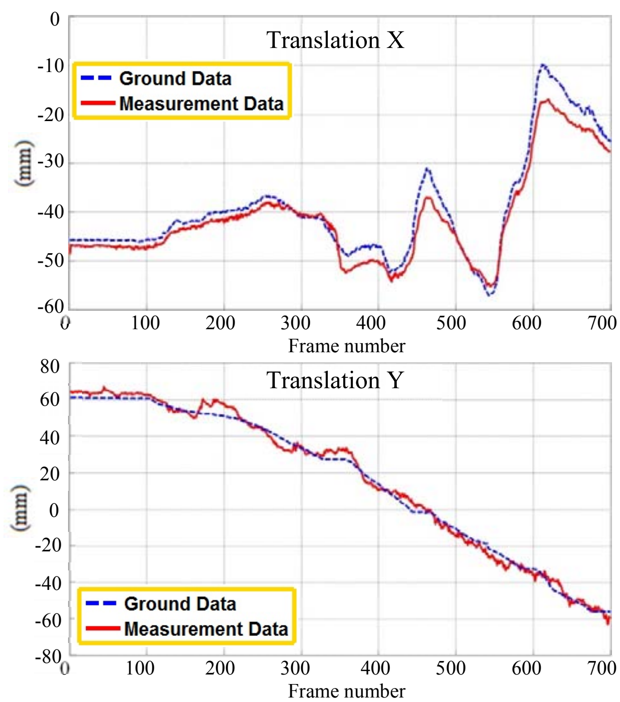


Figure 8-7 6DOF pose plots of the reference component in the accuracy test

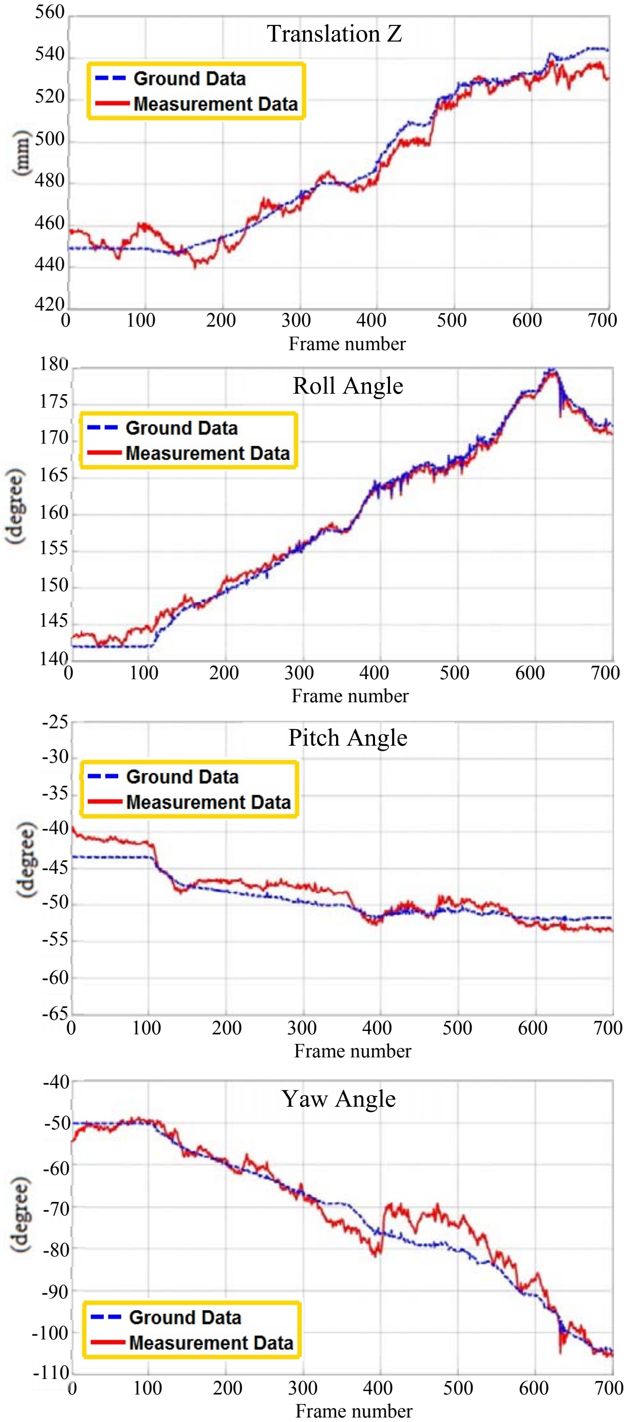


Figure 8-7 6DOF pose plots of the reference component in the accuracy test (continued)

The results in Table 8-1 show the accuracy of the proposed AR assembly system. The standard deviation is relatively large compared with the mean value, indicating the relatively wide spread out of the data, which can be a source of the jittering visual effect in an AR application. Nevertheless, the standard deviation is still small enough for the research in this thesis. Although the accuracy satisfies the current application, in future when a higher level of precision is required, it is necessary to improve the tracking method. Further improvement depends on the development of advanced marker-less tracking algorithms in the area of computer vision.

Table 8-1 Misalignment Errors

	x (mm)	y (mm)	z (mm)	roll (degree)	pitch (degree)	yaw (degree)
max	7.6847	8.4569	14.4798	2.8535	4.2018	9.7980
mean	2.2123	2.7416	4.8417	0.7595	1.2727	2.6433
std	1.9224	3.2153	5.3995	0.9379	1.2618	3.3126

8.1.1.3.3 Interactive efficiency test

In order to compare the interactive efficiency of ARAMS with respect to traditional VR-based systems, the ARAMS is extended to be implemented in a VR environment. Two traditional interaction methods, namely, keyboard-based interaction and sensor-based interaction, are implemented to replace the handheld interaction tool in ARAMS. The keyboard-based interaction allows the users to move and rotate a virtual component step-by-step while certain keys are being pressed. The sensor-based interaction uses two data-gloves for the purpose of gesture recognition. It allows the users to move and rotate a virtual component step-by-step while certain gestures are being recognized. In order to avoid the influence of the learning effect, another group of seven participants (age between 24 to 33) were invited to test the system. All the participants use computers regularly and four of them have experience in the use of AR-based systems. The user study consists of two parts, namely, a system test where the completion time for each task for these three interaction conditions were recorded, and a post-test survey that recorded their impressions of the experience. At the beginning, a training session, which took approximately 10 minutes, was conducted to allow the participants to familiarize themselves on the use of these three different interaction modes. The completion time of the task by each participant is shown in Figure 8-8, and the proposed system showed faster and easier interaction than the keyboard-based interaction and sensor-based interaction modes.

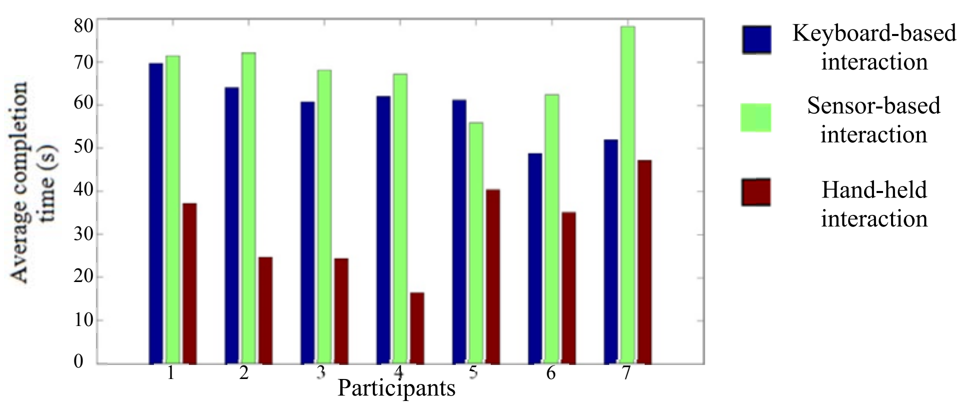


Figure 8-8 The completion time of the task by each participant

Sensor-based interaction is the slowest because this method is the most sensitive to the slight trembles from users. The users would need a longer time to adjust the location and orientation of a component especially when the component is close to its final position. Both keyboard and sensor-based interaction modes cannot allow the users to control the motion directly and manipulate virtual components naturally. In this user study, all the participants were asked to complete a post-experiment questionnaire. Four evaluation criteria as shown in Table 8-2 were used to evaluate the performance and the ease of use of the system.

Table 8-2 Evaluation criteria

Index	Evaluation Criteria
1	Ease of learning the interaction method (1~5: 1 = very difficult and 5 = very easy)
2	Ease of use of the system (1~5: 1 = very difficult and 5 = very easy)
3	Usefulness of the system in AR applications (1~5: 1 = not useful at all and 5 = very useful)
4	How immersive the experience is (1~5: 1 = not immersive at all and 5 = very immersive)

As shown in Table 8-3, the result indicates that the hand-held interaction tool is intuitive and can satisfy the requirements and needs of the participants. Participants agreed that AR-based systems can benefit more from the hand held interaction method than the other two, because the hand held interaction tool can provide a better immersive feeling to the users in a natural manner. The participants also provided a few suggestions and comments on the ARAMS module, such as "It would be better to resolve the occlusion issue of marker", and "Haptic feedback would be useful through which the user could have a sense of manipulation or interaction with the virtual component".

Table 8-3 Qualitative analysis of the user study

Methods \ Criteria	Ease of learning	Ease of use	Potential usefulness	Immersive feeling
Hand-held interaction	4.4	4.0	4.1	4.3
Keyboard-based interaction	4.0	4.1	3.6	3.3
Sensor-based interaction	3.9	3.7	4.0	3.6

8.1.2 Full version of ARAMS

8.1.2.1 Case study

8.1.2.1.1 Prototype setup

A prototype system of the full version of ARAMS module has been developed based on the methodologies presented in Section 6. The differences between this full version of ARAMS and the ARAMS described in Section 8.1.1 are as follows. Firstly, bare-hand interface is implemented to realize more intuitive manipulation from users, and a bumblebee2 camera is introduced in the setup accordingly. In addition, assembly forces calculation introduced in Section 6.2.3 is enabled to provide realistic assembly simulation process with CCH. The ARKF, ARAMS, AIM and ARTR modules have been implemented using Visual Studio 2010. The setup of the system is shown in Figure 8-9. It includes a Chameleon USB 2.0 digital camera to capture the front view of the work scene, a Bumblebee2 stereo camera to capture the top view and retrieve 3D positions of the user's fingertip, and a HMD is used as a rendering device. A marker is fixed on the assembly workbench to determine the world coordinate system, so that the camera can track its own pose and position with respect to the world coordinate system. A desktop (4GB SDRAM Memory, 3.2GHz Intel Core i5-650, ATI Radeon HD4550 512MB graphics card) is used as central processor to store, manage and process the assembly information. ARAMS works well and consistently at 20~25 frames per second for a 1024x768 frame resolution.

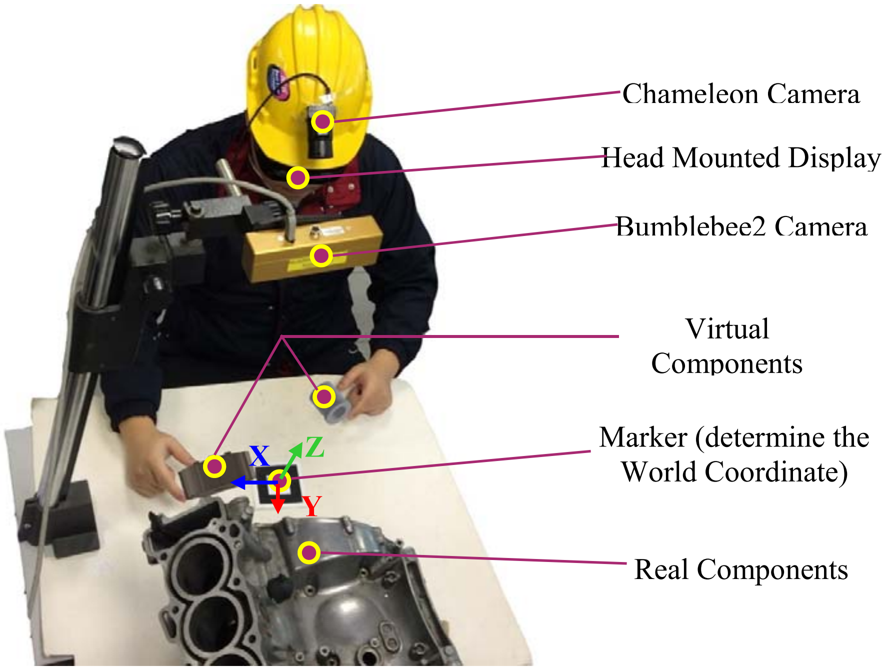


Figure 8-9 Setup of full version ARAMS

8.1.2.1.2 AR assembly simulation

This section presents a case study of a clutch linkage assembly from an automobile engine (HONDA CBR600F4i). The components involved in this case are shown in Figure 8-10. Specifically, the assembly is composed of LifterPlate, ClutchCenter, ClutchOuter, DriveSprocket, OuterGuide and MainShaft.

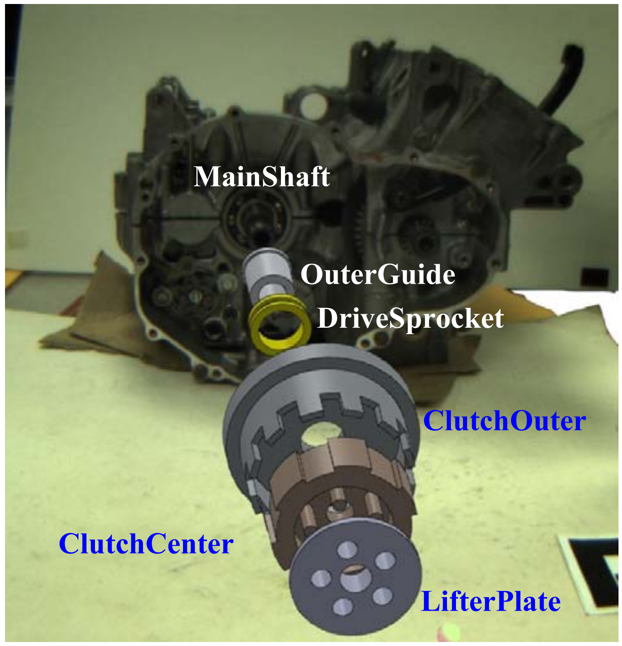


Figure 8-10 CAD models of the case study

The procedure of AR assembly simulation is summarized as follows:

1. Initialize the tracking of the existing real sub-assembly of engine. During this process, the operator needs to accomplish the registration process by selecting a set of feature points sequentially according to the ViSP manual (http://www.irisa.fr/lagadic/visp/visp.html).
2. Load CAD model of reference component into the AR environment. The geometric shape information and design data (dimensions, materials, etc.) of the component is extracted from the CAD model and sent to the AIM module for reasoning and inference during the initialization process of the component.
3. Execute EBHI to manipulate and assemble the reference component. The contact between the reference and target components, and the forces exert on the reference component are computed. The user can switch between the top view (Figures 8-11 (a-c, f)) and the front view (Figures 8-11 (d, e, g-i)).

4. At the same time, the user can record the design issues that have been identified during AR assembly simulation by inputting the pertinent information manually, e.g., ID of the surface/component that has design issue, type of the design issue, etc. The design issues can be identified by the assembly planners/designers during AR AMS process, e.g., assembly interference, improvable assembly sequence, etc.

Figures 8-11 shows the clutch linkage assembly simulation. In Figures 8-11a-b, the user assembles the virtual drive sprocket to the virtual outer guide to complete a virtual-virtual assembly task in the AR environment. After that, the user manipulates the sub-assembly to insert it to the main shaft (Figures 8-11c-d). In Figures 8-11e-f, the user grasps the virtual clutch outer and center with dual-hand gestures. When the reference component contacts other components, contact forces are created to simulate the interaction process. When the reference component is within a certain range of the target component, the virtual snapping force and torque are calculated to lead the component to its target position (Figure 8-11e), and when mating relations between *AFS*s are identified, unfeasible *DOF*s are removed by CCH (Figure 8-11f). The user manipulates and assembles the clutch center and cover in Figures 8-11g-h.

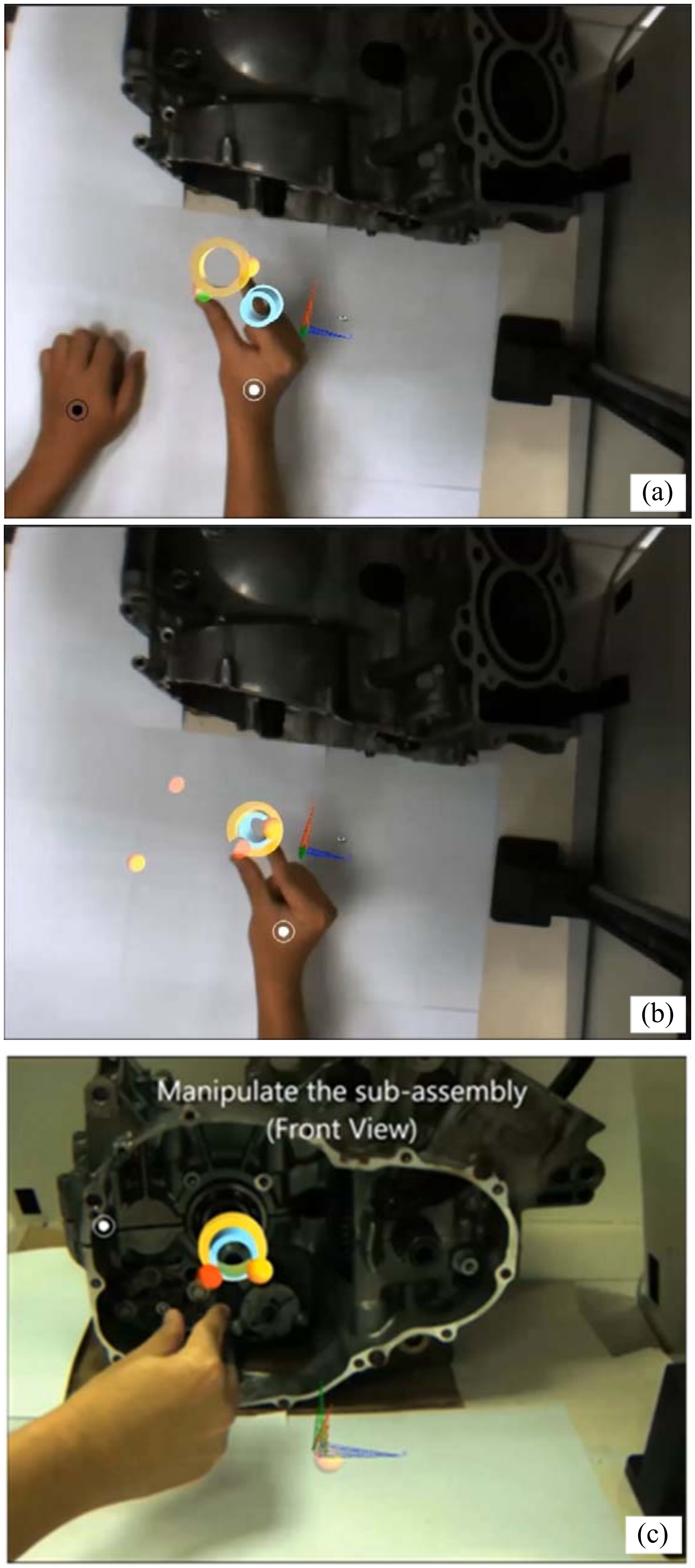


Figure 8-11 AR assembly simulation process

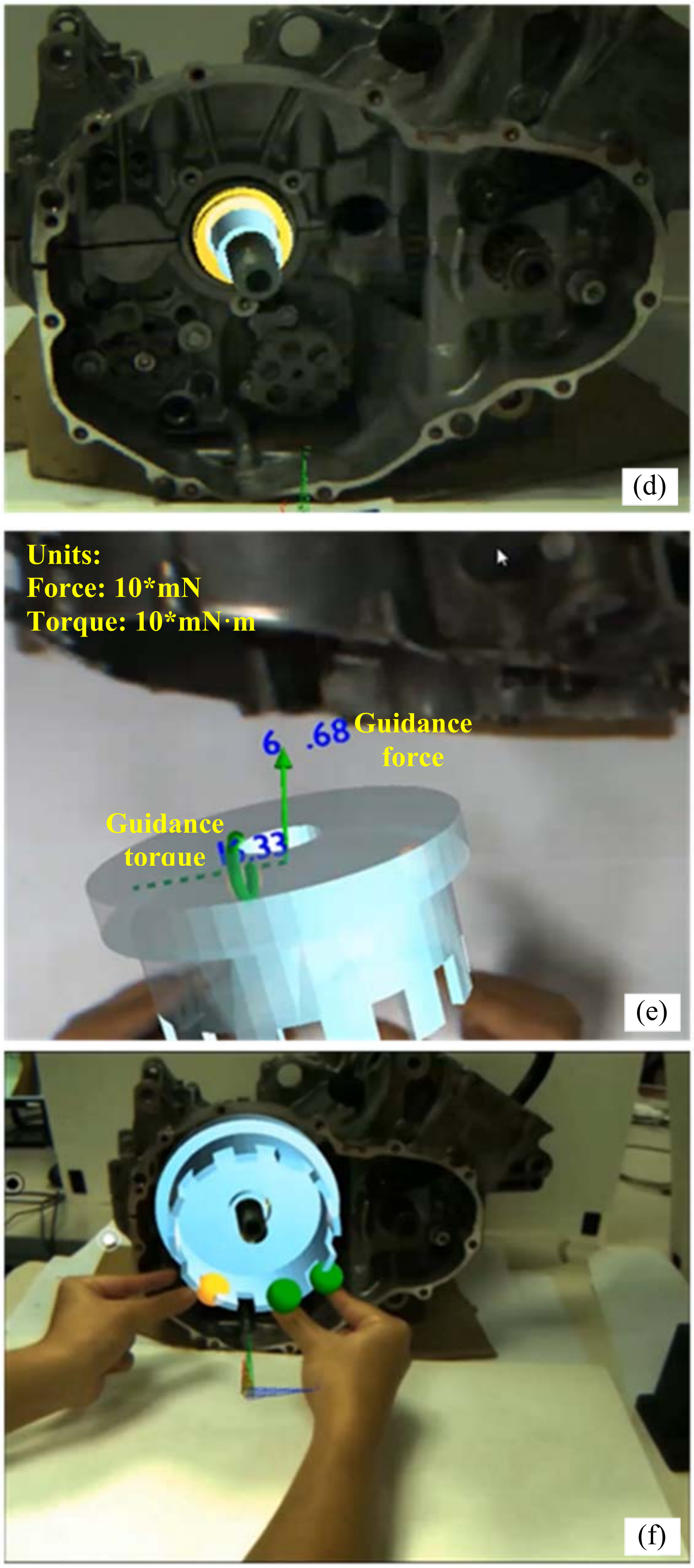


Figure 8-11 AR assembly simulation process (continued)

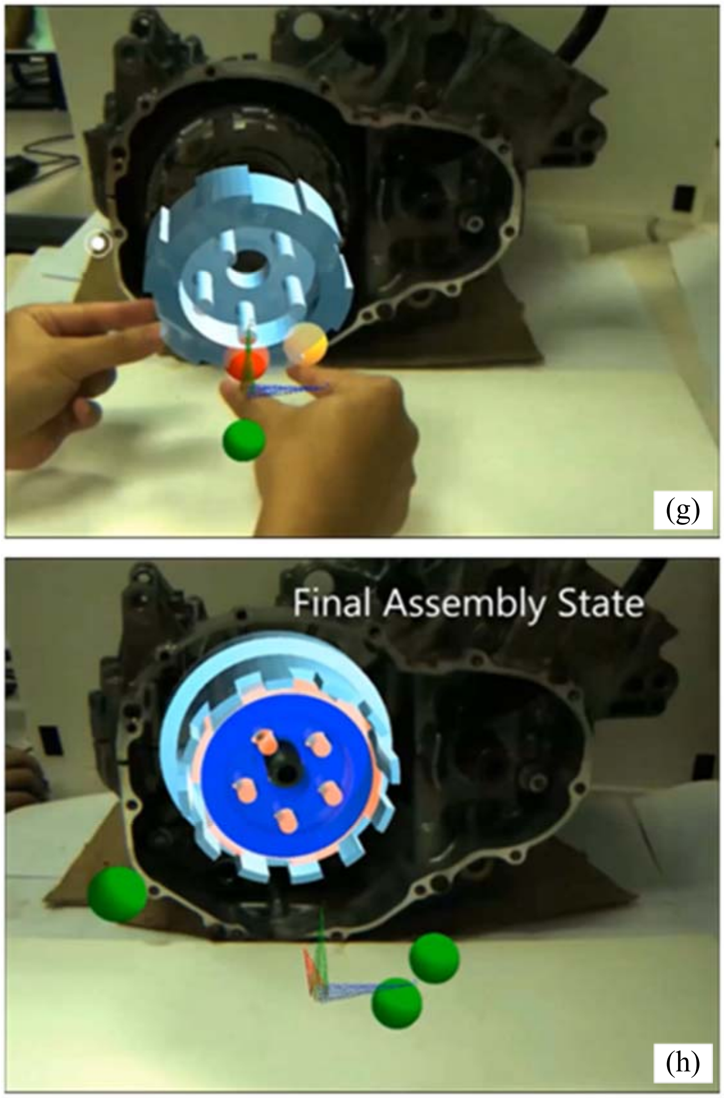


Figure 8-11 AR assembly simulation process (continued)

8.1.2.2 Force/torque calculation during AR AMS process

8.1.2.2.1 Coarse motion and virtual snapping force calculation

The objective of this section is to show how the virtual snapping force/torque is calculated during coarse motion. Figure 8-12 shows that the user manipulates a reference component (ClutchCenter) with EBHI from place to place in the AR environment without contacting the target component (the MainShaft). The corresponding translation and rotation distances (d_L and d_O)

between the mating FSs of the two components are calculated based on the pose and position of the components and the values are shown in Figure 8-13. The values for the simulation parameters are given in Table 8-4.

Table 8-4 Values of parameters in virtual snapping force calculation

k_{GL}	40.0 N·mm	ε_{0L}	20 mm
k_{GO}	35 N·mm·rad	ε_{0O}	0.35 rad

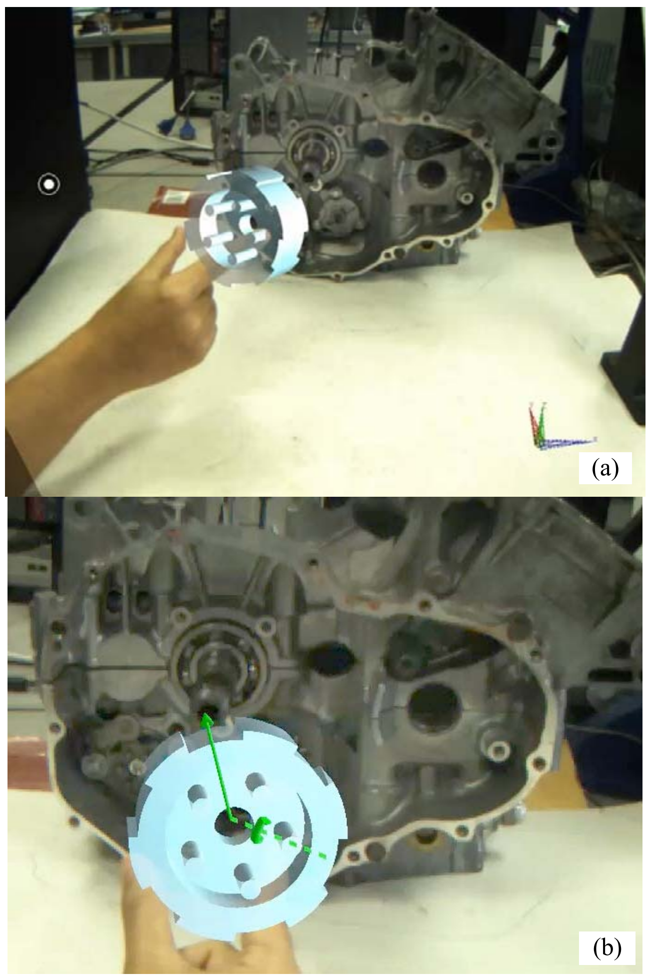


Figure 8-12 Coarse motion and virtual snapping force/torque

Figures 8-12a-b show the reference component manipulation during coarse motion. Figure 8-13 shows the whole changing process of the virtual snapping forces/torques corresponds with the user's handling positions and poses. When the reference component is in wrong orientation and/or wrong positions, i.e., not meeting the threshold of the virtual snapping force mentioned in Section 6.2.3 (d_L<120mm and d_O<40°), no virtual snapping force will be generated (Figure 8-12a). When the reference component is brought near to the target mating position gradually, the virtual snapping force ($\boldsymbol{F}_{VS}/\boldsymbol{\tau}_{VS}$) increases correspondingly. The effects of $\boldsymbol{F}_{VS}/\boldsymbol{\tau}_{VS}$ are to adjust the pose of the reference component, i.e., to reduce translation and rotation distances. The implementation of virtual snapping force can facilitate the transition phase from coarse motion to mating motion. When the reference component contacts the target component, the system will determine that the phase of coarse motions has been terminated and the virtual snapping forces will become zero. Since users cannot manipulate the components precisely, thresholds for mating *AFS*s relationship recognition have been implemented based on the human proprioceptive position sense (Van Beers, et al., 1998). Specifically, when the distance between the mating *AFS*s of reference component and the target component is within a certain threshold (translation: 15mm, rotation: 10°), the virtual snapping force/torque will disappear. The values of these parameters are chosen empirically.

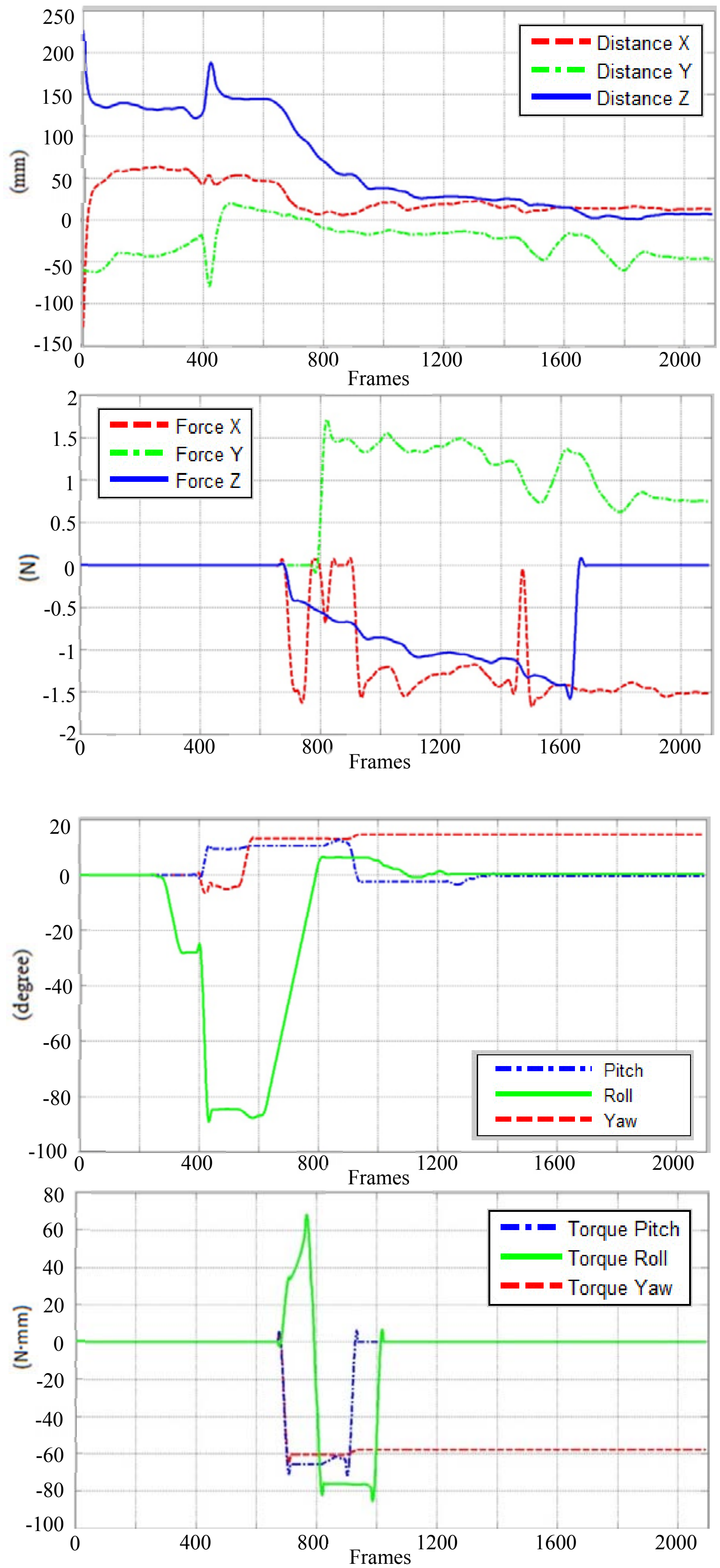


Figure 8-13 Distance and virtual snapping force

8.1.2.2.2 Force calculation in mating motion

The mating motion phase occurs when the reference component is in contact with the target component after the phase of coarse motions. In ARAMS, the interaction between the components during mating motions is considered as a series of collisions, which lead to the generation of contact forces. When the user manipulates the reference component with EBHI, the user is informed about these collisions from the visual contact forces feedback (Figure 8-14b-d). Correspondingly, the user can adjust the pose of the reference component by changing the handling pose to cause dynamic motion of reference component so that assembly operation can proceed. In Figure 8-14, the contact forces are rendered with 3D symbols (green cones). The origin of the cone represents the acting point of the force, and the vertex of the cone represents the force direction. In this section, one representative assembly task (ClutchCenter assembly) with a clearance value is selected to show the force calculation during mating motion (Figures 8-14 and 8-16), and the values for the simulation parameters are listed in Table 8-5.

Table 8-5 Values of parameters in force calculation during mating motion

EBHI:			
k_{SL}	3 N/mm	k_{DL}	3 N·s/mm
k_{SO}	115 N·mm/rad	k_{DO}	138 N·mm·s/rad
Assembly Task			
a_{stiff}	3 N/mm^2	d_{repel}	1 mm
Clutch center and main shaft		Steel	
Mass of reference component (clutch center)		0.327kg	
Main shaft		Fixed	
Hole diameter of reference component		24.023mm	
Main shaft diameter		23.993mm	
Clearance		0.030mm	
Fit type		Sliding fit	

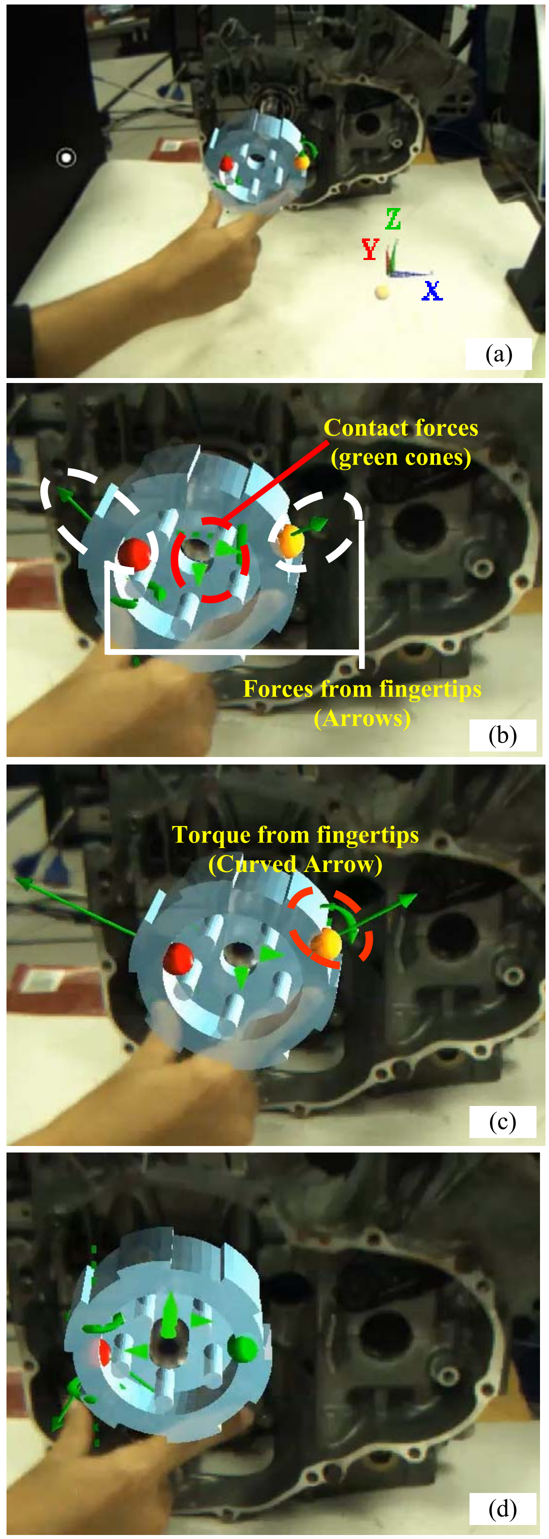


Figure 8-14 Mating motion of clutch center assembly

The basic principle is to use the positions of the reference and target components to indicate the lateral or angular errors between the components that are contacting each other. The information is rendered visually in the form of contact forces cones to support the user to make corrective motions that remove the errors and help the assembly process to advance. The magnitude of the manipulation force from the user's fingertip is represented by the length of the green arrow. The necessary geometry terms used in this case study are defined in Figure 8-15. Specifically, the insertion depth is defined to be zero just as the bottom of the clutch center reaches the tip of the main shaft.

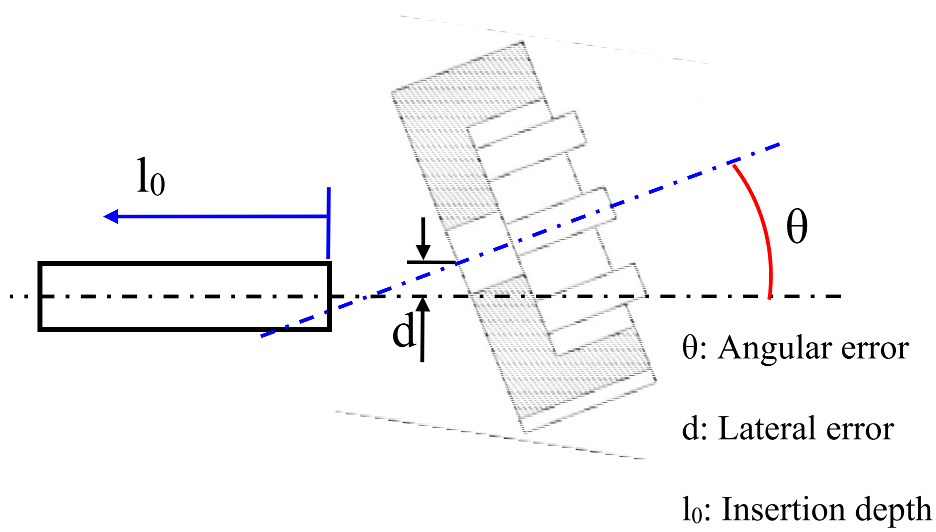


Figure 8-15 Geometry terms used in the case study

Figure 8-16 shows the forces/torques calculated based on Equations (6-5) to (6-12) during mating motions for the assembly task. The geometric relations between the reference component and the target component are illustrated by the insertion depth, lateral and angular errors in Figures 8-16a-b. The world coordinates are defined in Figure 8-14a. Figures 8-16c,e,g show the forces during mating motion, and Figures 8-16d,f,h show the torques calculated. The period from frame 1 to frame 150 represents the coarse motion phase. As the reference component is held by the user's bare hand and there is no contact between the reference component and the target component, the contact force is kept zero and the forces and torques from the fingertips are calculated using Equation (6-12). The effective force and torque are calculated with the updating pose and position of the hand with Equations (6-1) and (6-2). When the reference component contacts the target component, the mating motion phase begins and the contact forces arise. The system can detect the collisions and identify the interpenetration depth values between representing models of the contacting components by calling collision detection functions in physics engine. Based on these values and the given a_{stiff}, the contact forces can be calculated from Equation (6-5). Since the reference components typically begin mating with some relative lateral and angular errors (Figure 8-16b), the first contact occurs on the rim of the main shaft when the reference component (the ClutchCenter) is manipulated to move laterally to reduce the lateral error (Figure 8-15). The reference component is pushed laterally by the forces acting on it at the contact point. These forces help reduce both lateral and angular errors of the reference component. Between frame 150 and frame 350 in Figures 8-16, the corresponding simulation period is illustrated in Figures 8-14b-d, as the reference component advances further along the shaft, it strikes multi-patches on the outer-cylinder surface of the shaft. Due to the occurrence of multi-patches contact, the manipulation forces from the user's fingertips increase correspondingly (Figures 8-16c,e,g). The user needs to adjust the pose of the reference component with fingertips to reduce the lateral and angular errors. During this period (frame 150 to 350), the user tries to rotate the reference component with respect to the MainShaft to remove angular errors. The component is rotated by the torque created at the two contact points from fingertips (Figure 8-16d,f,h). After the frame 350, the assembly task is completed.

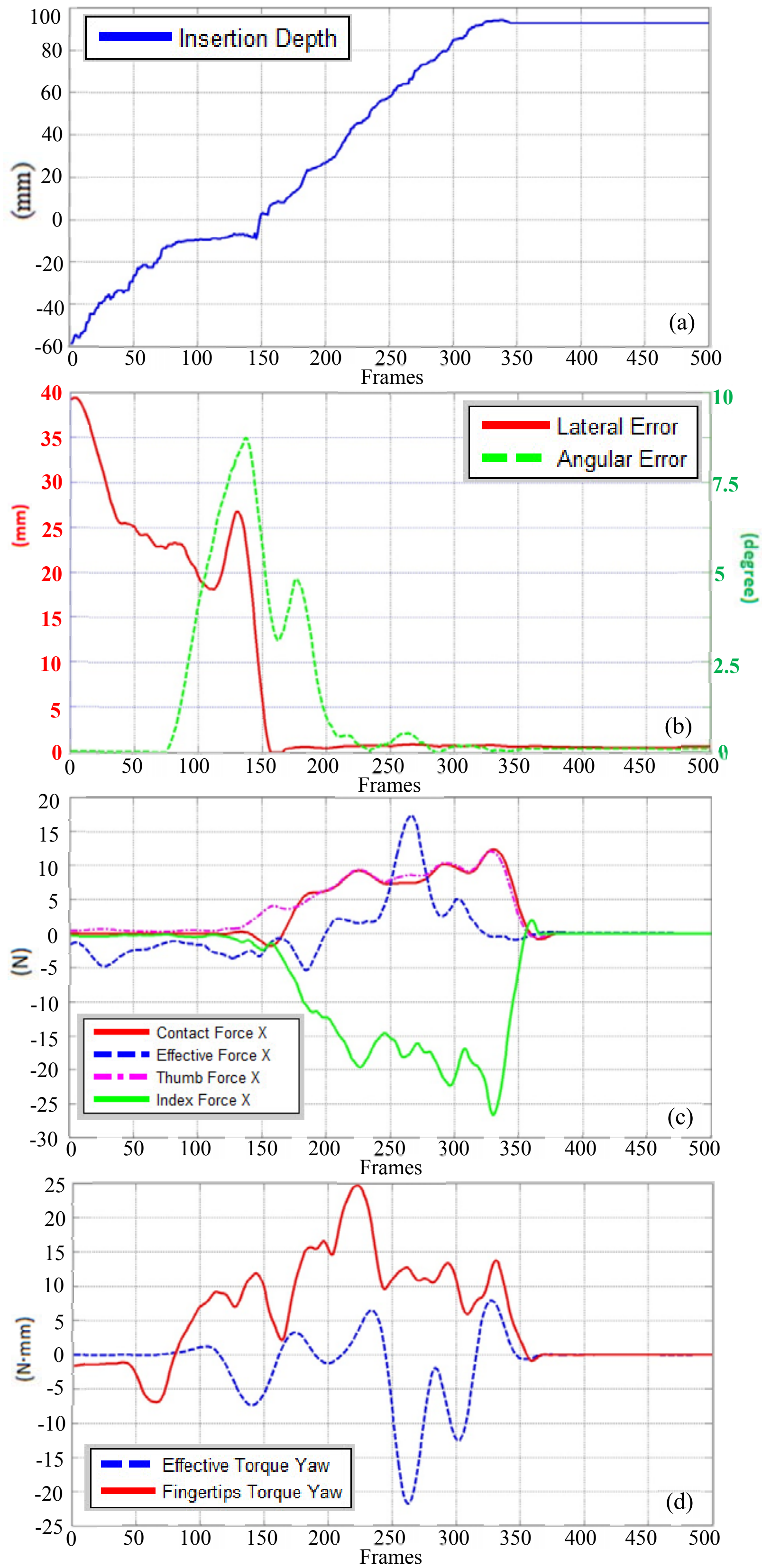


Figure 8-16 Calculated forces during mating motions

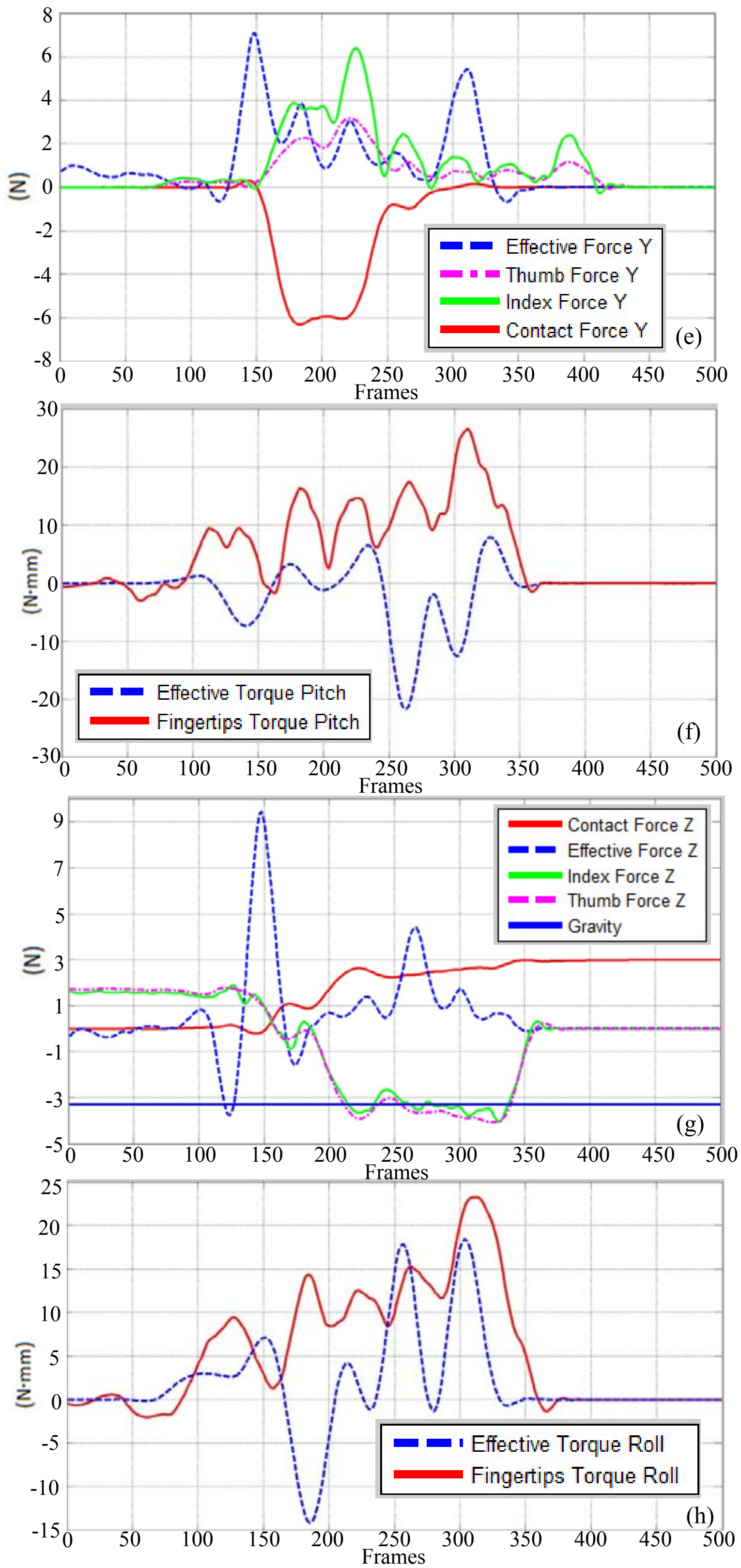


Figure 8-16 Calculated forces during mating motions (continued)

8.1.2.3 Application of ARAMS in assembly planning

Supported by the AR-assisted assembly simulation method based on interaction forces, ARAMS can assist users to identify possible design and assembly issues by carrying out assembly simulation with EBHI. Figure 8-17a shows a clutch outer assembly that cannot be completed due to a design issue in the clutch outer, where the user's hands are obstructed. Figure 8-17b shows an improved design where adequate space is provided for the user's hands. Figure 8-17c shows one situation of an unsuccessful assembly operation trial. In this figure, the reference component is stuck in the target component (MainShaft), the ClutchCenter cannot be proceeded further regardless of the amount of forces exerted. The cause of this situation is related to the initial pose of the ClutchCenter when the mating motion begins, i.e., the initial lateral and angular errors are not small enough. Figure 8-17d shows reduced initial lateral and angular errors before the mating motion happens. In this case, the assembly operation succeeds and the manipulation forces from the fingertips are much smaller than those in Figure 8-17c. Users of ARAMS can detect assembly issues in assembly sequence planning. For example, the assembly sequence in Figure 8-17f is better than the sequence in Figure 8-17e, as the latter sequence requires large manipulation forces to handle the subassembly, which may cause physical fatigue. Figure 8-17f is a better assembly sequence by assembling the clutch outer and center individually using both hands to reduce manipulation forces.

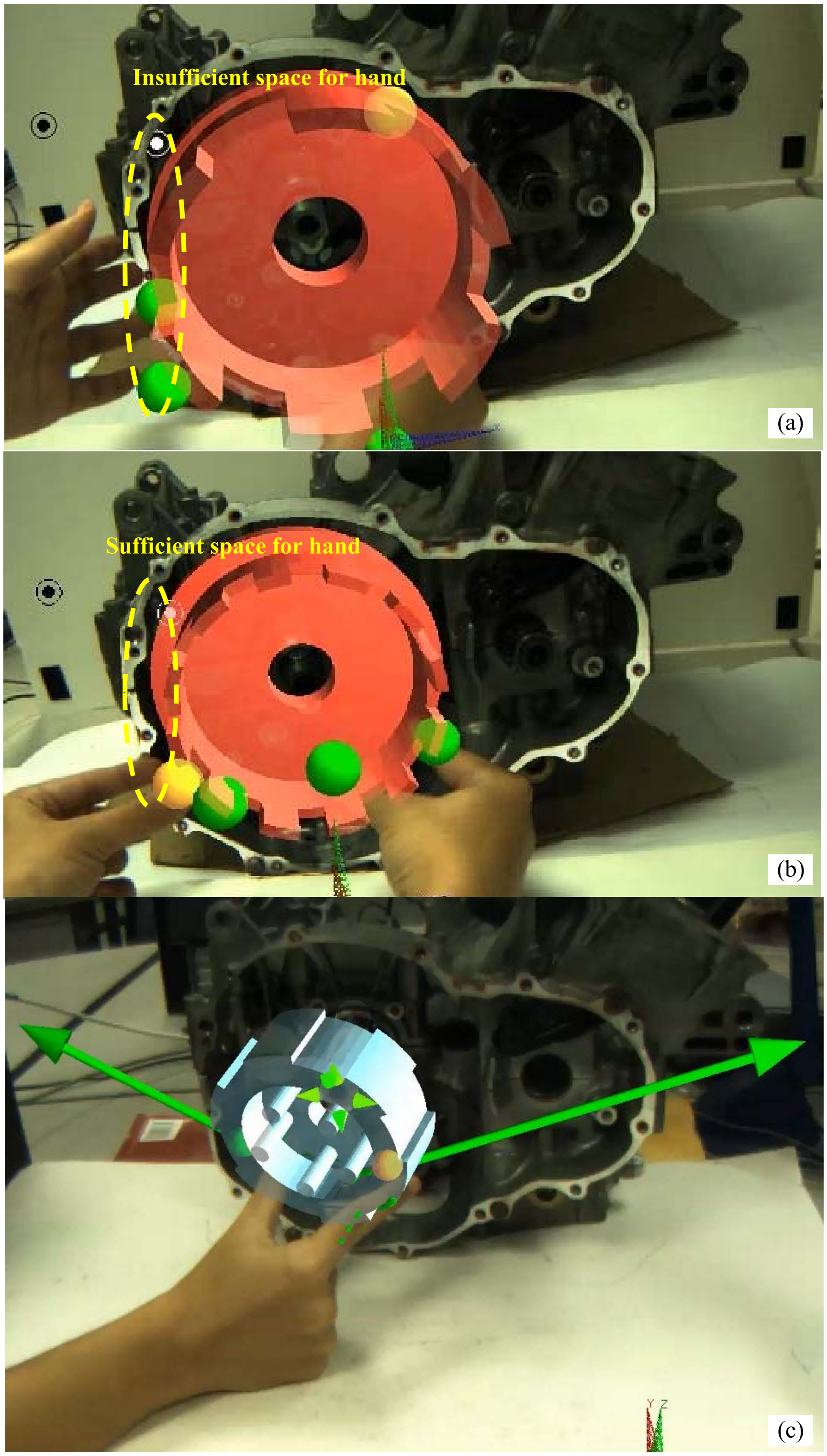


Figure 8-17 ARAMS in assembly planning

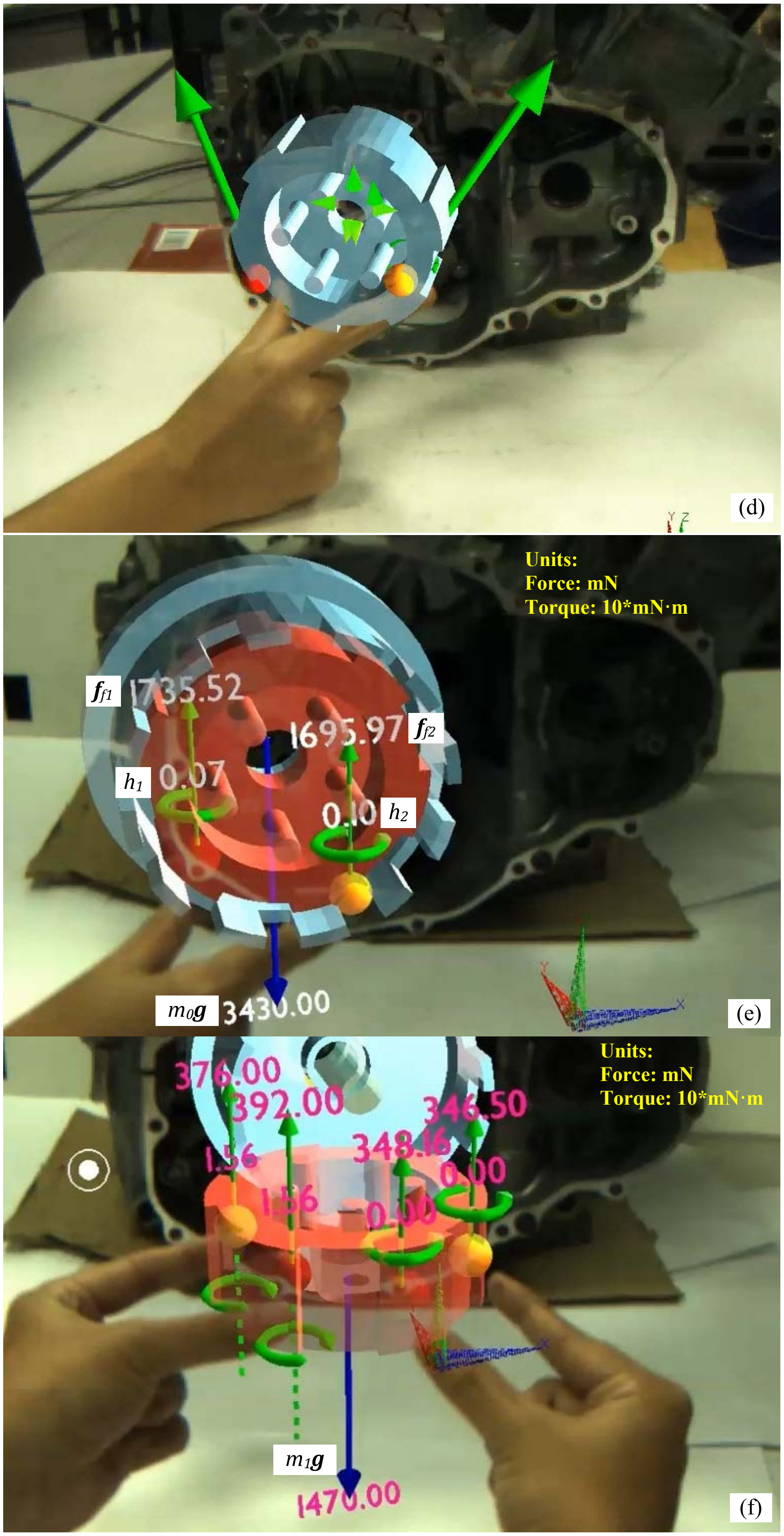


Figure 8-17 ARAMS in assembly planning (continued)

8.1.3 Discussion

ARAMS improves the intuitiveness and eliminates redundant human-computer interaction manipulations by implementing the EBHI and hand-held interaction tool. The CCH strategy works correctly in a real industrial assembly case. With the physics-based force/torque calculation during AMS, ARAMS generates physically plausible motions for the reference components manipulated by the user's bare hands. The user can identify assembly errors on the assembled product in the physics-based AMS environment, because ARAMS can simulate the assembly process from a physically plausible motion space. The delicate interaction between the user's hand and reference component is considered and the user can manipulate the reference component dexterously with the movement of his fingers.

The ARAMS has a few constraints and limitations. The experiments conducted have demonstrated that EBHI supports the user's intuitive and natural manipulation of virtual components. However, with the current EBHI, the user can only see the force feedback visually, i.e., ARAMS renders the position, direction, and magnitude of the force to the users view; the user cannot feel any tactile feedback. In order to improve EBHI, compact and portable haptic devices can be developed and worn on the bare hands to provide realistic tactile feedback. In addition, the manipulation hand gestures supported by EBHI are limited at the current stage, i.e., only the thumb and index fingers are involved in the manipulation tasks. More natural hand gestures should be explored to enhance the intuitive manipulation of the reference components.

In addition, in order to manipulate both real and virtual components in the AR-based environment, CAD models have to be prepared prior to the start of the assembly process. Necessary data is required to be extracted from these CAD models, e.g., tracking model (VRML), geometrical model (STL), and structure and geometry information which are imperative for CCH strategy, etc. The modeling of the components in assembly can be time-consuming. However, compared to the traditional AR-assisted assembly systems which require knowledge base preparation (e.g., pictures, models, videos, animation, etc.) and manual input to define mating feature surfaces, the ARAMS has advantages over these systems. This is because the hierarchical and topological information of the assembly is generated automatically instead of being prepared by the users, and the mating relations between the components are inferred based on ontology instead of being pre-defined. Although only nine types of surfaces and six types of mating relations are analyzed in the system, it can be extended to incorporate more complex surfaces and mating relations in future.

8.2 Implementation of CARAGM

A prototype system has been developed based on the methodologies presented in Chapter 7.

8.2.1 Application scenario

A set of assembly tasks for the assembly of a Mitsubishi MEO77789 motorbike alternator is used for this study (Figure 8-18), and the guidance materials are prepared based on the service manual. Two representative assembly tasks with different complexity levels are considered in the study, i.e., the assembly of the rotor (complex) and the stator (simple). The assembly of the rotor involves five components, namely, rotor-1, rotor-2, lifter bearing, bearing and rear cover. The user has to change the manipulation direction during the installation of rotor-1 to rotor-2 and installation of the sub-assembly (rotor-1 and rotor-2) to the rear cover. In addition, the user has to ensure that the installed rotor-2 fits correctly with the rear cover. The assembly of the stator involves the stator and real cover; the user needs to align the stator accurately with the rear cover.

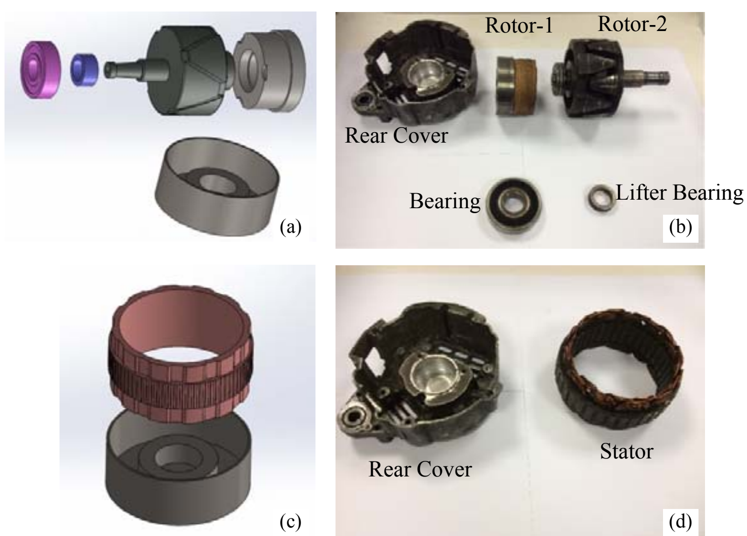


Figure 8-18 Assembly tasks in user study

Each task can be broken down into the following sub-tasks:

1. Comprehend the guidance materials;

2. Identify specific components/tools and a plan to complete the task; and

3. Execute the task (manipulation, alignment and screw fastening).

AR guidance instances have been added in the CARAGM for this case study, and they have been categorized according to the five properties of assembly guidance template (Section 7.4.2). A set of reasoning rules has been defined. The properties/sub-properties and their respective related reasoning conditions are listed in Table 8-6. For example, the modality of AR guidance should be attention-directing symbols pointing at the appropriate tools if the user is in the CognitionPhase of attention (row 5 of Table 8-6).

Table 8-6 Reasoning rules definition

Property	**Conditions**
AssemblyState	User
Component	AssemblyState
AssemblyFeature	Component, AssemblyState
Tool	User, AssemblyState, Component, AssemblyFeature
Modality	User, CognitionPhase

To evaluate the effectiveness and intuitiveness of CARAGM, a traditional AR assembly guidance system (TARAGS) based on traditional interaction tool (mouse and keyboard) has been set up. This system renders multi-media assembly instructions (e.g., 2D text instructions, images, 3D models and animations) as augmented contents in the user's view according to the user's requests. The AR environment is displayed to the user using a head-mounted display. A LCD screen based digital documentation system (SDD) is used as the baseline for this study. The instructions show 2D images of the components that need to be assembled, as well as the appearance of the entire alternator after a component has been assembled. In order to ensure the fairness of the comparison, all the three guidance systems are implemented on the same desktop, so that they have the same processing speed.

8.2.2 Experiment design

A total of eight voluntary participants (two females, six males) were recruited for the case study. The participants were interviewed on their personal experience in industrial assembly operations. Four participants work in an assembly workshop of the authors' university and conduct daily assembly activities on the equipment; the other four participants are engineering students and have assembly experience. All participants are right-handed. Hence, the haptic bracelet is attached to the left arm of the participants. The order of the tasks under the three guidance systems (CARAGM, TARAGS, SDD) is counterbalanced across participants using a Latin square approach. Participants are required to complete each sub-task as quickly and accurately as possible. Each participant is allowed to be familiarized with the three guidance systems for 10 minutes before the test. A mixed quantitative and qualitative within-subjects evaluation experiment, i.e., each participant would perform the whole set of assembly tasks (rotor and stator assembly) under the guidance of the three systems, is conducted. In the quantitative evaluation, the dependent variables are completion time for each sub-task of the assembly tasks, number of errors, and number of attention shifts. The completion time and the number of errors are recorded by an experiment assistant, while the number of attention shifts is recorded automatically. A marker-based method is employed in this research to count the number of attention focus shifts. Different markers are attached to different areas in the ARTE, e.g., the screen of the digital manual, workbench, toolbox, etc. A ray testing method is implemented to detect whether the view vector is in a certain area. This method allows the detection of the shifts of the user's view, and hence the shifts of the user focus. Thus, the number of times the user's view is switched between different areas of an assembly workspace can be measured. After completing the assembly tasks, users are asked to complete a questionnaire, and the dependent variables include the ease of use, intuitiveness and satisfaction of the system.

In order to avoid learning effects, in sub-task#2, different tools (wrench, socket, etc.) are selected to be identified for the three guidance systems. In this way, when the user performs the sub-tasks for the second time, he/she cannot perform this task based on previous experience. In sub-task#3, different sequences of fastening are prepared for the three experiment conditions. The details for the work content (denoted as W), the guidance modalities (denoted as G), and the interaction methods (denoted as I) are described in Table 8-7. The contents of the instructions provided in TARAGS, SDD, and the perception phase of CARAGM are the same regardless of their presentation mode (AR: TARAGS and CARAGM; Screen: SDD). As can be seen in Table 8-7, CARAGM provides multi-modal AR assembly guidance for different sub-tasks (different user cognition phases), while the other two systems provide identical assembly instructions throughout the whole set of sub-tasks. In addition, the interaction methods are different in the three systems (CARAGM: EBHI; TARAGS and SDD: traditional interaction tools, e.g., mouse and keyboard).

Table 8-7 Work content and guidance modalities under three assembly guidance systems

	Sub-task#1	Sub-task#2	Sub-task#3
CARAGM	W: Comprehend AR instruction G: AR instruction (text, image, etc.) I: EBHI	W: Identify related tool/component G: Marker-based tool/component recognition I: EBHI	W: Manipulation, Alignment, Fastening G: Rendered virtual component aligned with real component; on-site assembly simulation; 3D dynamic paths; dynamic illustration I: EBHI
TARAGS	W: Comprehend AR instruction G: AR instruction (text, image, etc.) I: mouse/keyboard	W: Identify related tool/component G: AR instruction (text, image, etc.) I: mouse/keyboard	W: Manipulation, Alignment, Fastening G: AR instruction (text, image, animation, etc.) I: mouse/keyboard
SDD	W: Comprehend screen-based instruction G: Digital instruction (text, image, etc.) I: mouse/keyboard	W: Identify related tool/component G: Digital instruction (text, image, etc.) I: mouse/keyboard	W: Manipulation, Alignment, Fastening G: Digital instruction (text, image, etc.) I: mouse/keyboard

8.2.3 Results analysis

8.2.3.1 Task completion times

A repeated measure ANOVA on the total completion times for each sub-task in the assembly tasks (Figure 8-19) is conducted with the participants as the random variable (Table 8-8). In order to compute the ANOVA, the assumption of sphericity needs to be verified through a Mauchly's test.

For sub-task#1, the Mauchly's test indicates that the assumption of sphericity is not violated, $\chi^2(2) = 1.310, p = 0.519$. The independent variable of guidance system does not exhibit a significant effect on the completion time for this sub-task ($F_{(2,14)} = 0.565, p = 0.581$). A post-hoc pair-wise comparison of the completion times with a Bonferroni correction (α=0.125) reveals that CARAGM (44.15s) is 3.83s faster than the TARAGS for comparison (47.97s) ($p = 1.000$), and 2.71s slower than SDD (41.44s) ($p = 1.000$, the result is not significant). The TARAGS is 6.54s slower than the digital documentation, but it is not significant ($p = 1.000$).

Table 8-8 Task completion times

Sub-task	Factor 1	Mean (factor 1)	Factor 2	Mean (factor 2)	Mean difference (factor 1-factor 2)	p-value	Significant? (95% confidence interval)
#1	CARAGM	44.15s	TARAGS	47.97s	-3.83s	1.000	No
#1	CARAGM	44.15s	SDD	41.44s	2.71s	1.000	No
#1	TARAGS	47.97s	SDD	41.44s	6.54s	1.000	No
#2	CARAGM	12.30s	TARAGS	22.71s	-10.41s	0.024	Yes
#2	CARAGM	12.30s	SDD	32.77s	-20.46s	0.020	Yes
#2	TARAGS	22.71s	SDD	32.77s	-10.05s	0.405	No
#3	CARAGM	30.73s	TARAGS	48.00s	-17.27s	0.012	Yes
#3	CARAGM	30.73s	SDD	62.62s	-31.89s	<0.001	Yes
#3	TARAGS	48.00s	SDD	62.62s	-14.62s	0.015	Yes

For sub-task#2, the Mauchly's test indicates that the assumption of sphericity is not violated, $\chi^2(2) = 3.746, p = 0.154$. The independent variable of guidance system exhibits a significant effect on the completion time for this sub-task ($F_{(2,16)} = 8.644, p = 0.004$). A post-hoc pair-wise comparison of completion times with a Bonferroni correction (α=0.125) reveals that CARAGM (12.30s) is 10.41s faster than the TARAGS (22.71s) ($p = 0.024$), which is significant, and 20.46s faster than digital documentation (32.77s) ($p = 0.020$), which is considered significant. The TARAGS is 10.05s faster than SDD, but it is not significant ($p = 0.405$).

For sub-task#3, the Mauchly's test indicates that the assumption of sphericity is not violated, $\chi^2(2) = 0.202, p = 0.904$. The independent variable of guidance system exhibits a significant effect on completion time for this sub-task ($F_{(2,16)} = 35.79, p < 0.001$). A post-hoc pair-wise comparison of completion times with a Bonferroni correction (α=0.125) reveals that CARAGM (30.73s) is 17.27s faster than the TARAGS (48.00s) ($p = 0.012$), and 31.89s faster than SDD (62.62s) ($p < 0.001$). The TARAGS is 14.62s faster than SDD, and it is significant ($p = 0.015$).

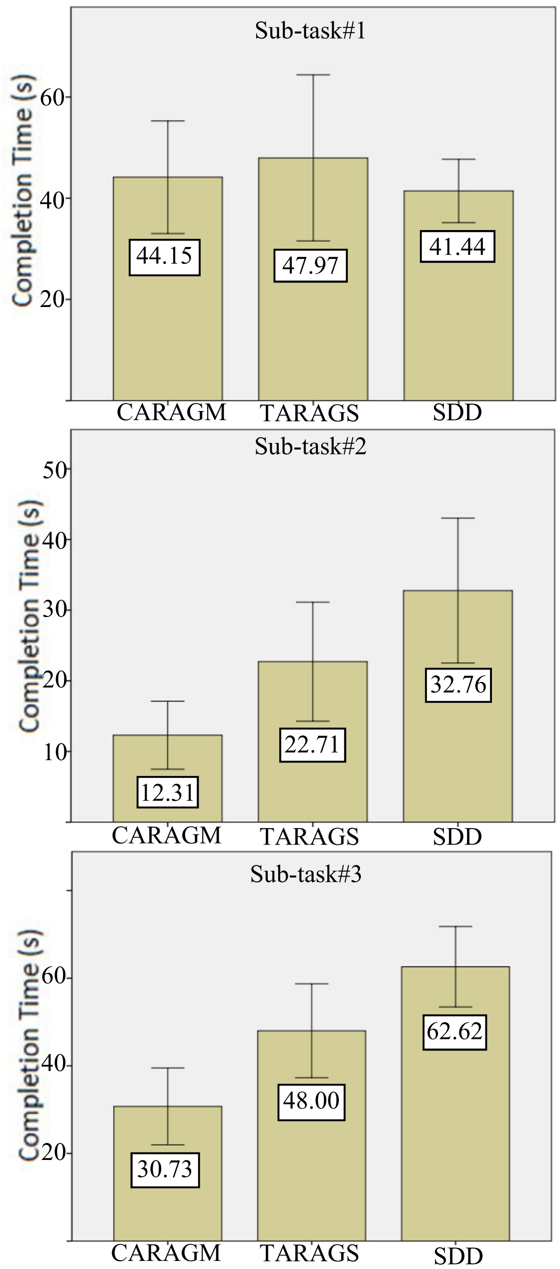


Figure 8-19 Mean completion times (s) for three sub-tasks under three guidance conditions

8.2.3.2 Shift of user focus

A repeated measure ANOVA on the number of attention shifts for each guidance system is implemented (Table 8-9), with the participants as the random variable (Figure 8-20). The Mauchly's test indicates that the assumption of sphericity is not violated, $\chi^2(2) = 4.066, p = 0.131$. The independent variable of guidance system exhibits a significant effect on the number of attention shifts for the task ($F_{(2,16)} = 25.431, p < 0.001$). A post-hoc pair-wise comparison (Table 8-9) of the number of attention shifts with a Bonferroni correction (α=0.125) reveals that CARAGM (3.875) has 0.625 less attention shifts on average than the TARAGS (4.500), but it is not significant ($p = 0.916$). CARAGM has 6.000 less attention shifts on average than the SDD (9.875), and it is significant ($p = 0.004$). The TARAGS has 5.375 less attention shifts on average than the SDD, and it is significant ($p = 0.002$).

Table 8-9 Shifts of user attention

Factor 1	Mean (factor 1)	Factor 2	Mean (factor 2)	Mean difference (factor 1-factor 2)	p-value	Significant? (95% confidence interval)
CARAGM	3.875	TARAGS	4.500	-0.625	0.916	No
CARAGM	3.875	SDD	9.875	-6.000	0.004	Yes
TARAGS	4.500	SDD	9.875	-5.375	0.002	Yes

8.2.3.3 Error rate

A repeated measure ANOVA on the number of errors for each guidance system is applied, with the participants as the random variable (Figure 8-20). The Mauchly's test indicates that the assumption of sphericity is not violated, $\chi^2(2) = 3.737, p = 0.154$. The independent variable of guidance system exhibits a significant effect on the number of errors for the task ($F_{(2,14)} = 9.877, p = 0.002$). A post-hoc pair-wise comparison (Table 8-10) of the number of attention shifts with a Bonferroni correction (α=0.125) reveals that CARAGM (0.750) has 1.625 less errors on average than the TARAGS (2.375), but it is not significant ($p = 0.056$). CARAGM has 2.500 less errors on average than SDD (3.250), and it is significant (0.034). The TARAGS has 0.875 less errors in average than SDD, but it is not significant ($p = 0.192$).

Table 8-10 Error rate

Factor 1	Mean (factor 1)	Factor 2	Mean (factor 2)	Mean difference (factor 1-factor 2)	p-value	Significant? (95% confidence interval)
CARAGM	0.750	TARAGS	2.375	-1.625	0.056	No
CARAGM	0.750	SDD	3.250	-2.500	0.034	Yes
TARAGS	2.375	SDD	3.250	-0.875	0.192	No

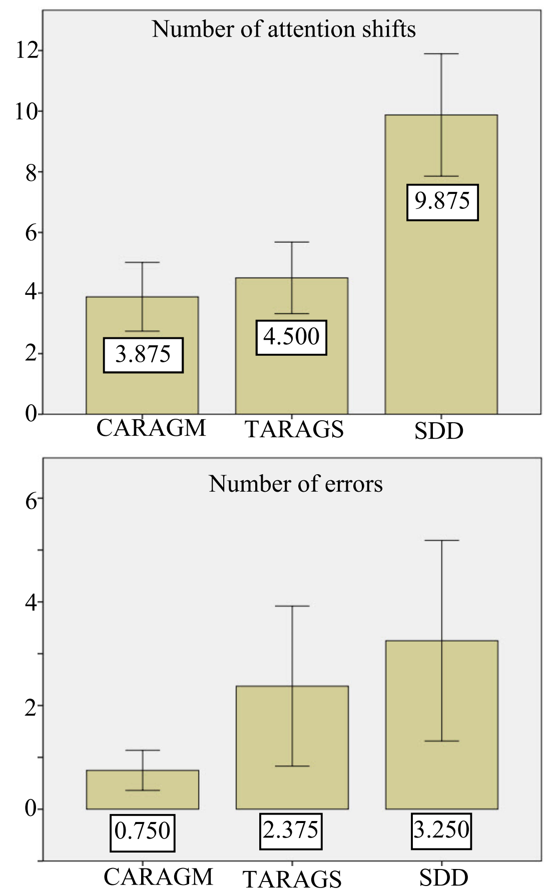


Figure 8-20 Number of attention shifts and errors in the three guidance conditions

8.2.3.4 Qualitative results

The post experiment questionnaire featured five-point Likert scale questions (1 = most negative; 5 = most positive) to evaluate the ease of use, user satisfaction level, and intuitiveness for each guidance system. The results for the eight participants in this user study are summarized in Table 8-11. The results reveal that CARAGM performs better than the other two systems for all three factors based on the average evaluation values. In addition, both AR systems (CARAGM and TARAGS) have higher average values as compared with the digital documentation for all the three factors.

Table 8-11 Qualitative analysis of the user study

Methods \ Criteria	**Intuitiveness**	**Satisfaction**	**Ease of use**
SDD	3.38	2.13	3.13
TARAGS	4.25	3.88	3.5
CARAGM	4.5	4.25	3.88

8.2.4 Discussion

Theories of cognitive psychology have been applied in assembly scenarios. They have been demonstrated to be useful in optimizing the information processing mechanisms of guidance systems for manual assembly, and these systems supports the user adaptively (Stork and Schubo, 2010; Henderson and Feiner, 2011). The CARAGM extended the results presented in literature by exploring specific modalities of AR guidance for each phase of the user cognitive process, and further analyzed the reciprocal effect of the various cognitive phases through realistic assembly operation of an industrial product. For instance, the guidance for the execution phase can reduce the cognition load during the perception and attention phases, because the users can learn through the AR guidance on-site. The CARAGM prototype system can facilitate users to perform assembly tasks more quickly and accurately as compared with the other two guidance systems (TARAGS and SDD), especially in locating of pertinent components/tools (attention phase), and execution of the real assembly tasks (execution phase).

In sub-task#1, the SDD performs best among the three guidance systems. This can be attributed to the factor that the SDD is the most frequently used mode by the assembly operators in the daily assembly operations. However, the comparison results are not statistically significant. Participants using CARAGM (44.15s) shows competitive performance compared with participants with TARAGS (47.97s) and SDD (41.44s). The majority of the participants stated that the AR display method (TARAGS and CARAGM) allow the operators to experience less head movement, leading to less attention shift during the perception phase. In addition, the participants stated that the EBHI is more intuitive and natural to control the rendering contents than the traditional interaction tools (mouse and keyboard), especially in a messy environment of industrial assembly platform. In sub-task#2, the results showed that CARAGM enables faster selection and localization of the pertinent components/tools than TARAGS and SDD. This can be explained by the strength of CARAGM in the attention phase of the user cognitive process through reducing attention switching between the documentation and toolbox. This can be demonstrated in the results of the number of attention shifts during the task, where CARAGM performs better than SDD (statistically significant) and TARAGS (not statistically significant). In sub-task#3, i.e., the execution phase, CARAGM improves the guidance significantly as compared with the other two systems. This is due to the accurate spatial alignment of the virtual components in CARAGM with the physical components, and the user knows the accurate translational and rotational motion to align the manipulated component; whereas for the TARAGS and SDD, there is no information that indicates the way to align a component because the physical components and assembly workbench are not tracked in real time. The user can interact with the physical/virtual components when using CARAGM, e.g., manipulating the physical/virtual components in 3D and see the alignment relation between physical and virtual components from different view-angles. The implementation of haptic feedback bracelet also contributes to the improvement of the error rate of the task. From the qualitative evaluation, most of the participants mentioned that CARAGM enhances the transfer from guidance to practice. The feature recommended most is the on-site simulation. The participants stated that CARAGM enhances the intuitive interaction between the user and the system with a completely hands free interaction approach. In addition, some of the participants mentioned that the provision of AR notes is useful as they do not need to memorize a long list of work steps, warnings and instructions, such that they can focus on the task execution.

9. Conclusions and recommendations

The primary objective of this research is the application of the AR technology for AMS and AOG. By integrating interaction strategy between real and virtual objects in the AR environment (CCH strategy and assembly forces calculation), IARAE provides an adaptable and effective solution to the ARAMS problem. In addition, by considering the user cognition process during an assembly task, IARAE provides appropriate and timely multi-modal assembly guidance for a user's needs. An IARAE system has been developed to implement the approach and case studies have been conducted for validation purposes.

9.1 Research contributions

This thesis has made contributions in the following aspects.

9.1.1 A pipeline to incorporate both real and virtual objects into the AR environment

A methodology has been proposed and developed for the incorporation of both real and virtual objects into the AR assembly environment to support the interaction between real and virtual objects. One key contribution of this method is the proposal of a modified hybrid real component tracking method in which the model-based tracker (MBT) is combined with the Kanade-Lucas-Tomasi (KLT) tracker to reduce the noise caused by the inaccurate measurements and extraction of the features during the implementation of the original MBT. In addition, an algorithm for occlusion detection and handling is proposed to enhance tracking stability and robustness, comprising three steps, namely, occlusion detection, occluded key features removal and lost key features recovery. The proposed hybrid tracking method is robust against key feature occlusions, resulting, on average, in an accuracy of 3.4281 pixels, while the average accuracy of model-based tracking is 17.4135 pixels.

9.1.2 An ontology based assembly information management method

In IARAE, two ontology-based information management models, namely, Ontology-based Assembly Information Model (OAIM) and Ontology based Assembly Task Process (OATP), are implemented to support assembly information management in the reasoning of component movements from the assembly relationships among the components, and the reasoning of assembly guidance information during an assembly task, respectively. These ontology models, comprising assembly information relations map, reasoning rules for pertinent information, and information instances, are independent of programming languages and enable reasoning using first order logic.

9.1.3 A component contact handling strategy to calculate the merging of degree-of-freedom

A component contact handling (CCH) strategy has been proposed and implemented to model and determine all the possible movements (i.e., all the feasible *DOF*s) of the reference components at any time instance throughout the entire assembly simulation when these reference components interact with other components during assembly simulation. The CCH strategy provides realistic components motion simulation corresponding to user manipulation. Interaction between multiple components can be inferred during the AR-aided assembly process and all valid DOF_t can be determined in real time; manual input to set the appropriate contact information is reduced as much as possible, i.e., the user is only required to load the pertinent component file to the system, and then the system will extract and infer related information automatically. The results show that the users can perform stable assembly operation simulation with the assembly system implementing CCH with average time of 27.5s and standard deviation of 10.7s (average time of 35.5s and standard deviation of 17.1s for the system without CCH).

9.1.4 Assembly forces calculation

This research presents a real-time AR-assisted assembly simulation platform to facilitate assembly planning and design issues identification during early product design. The methodology implemented considers actual constraints and interactions from real components in a real assembly environment, and the dexterous component manipulation associated with different assembly operations during assembly simulation. EBHI facilitates AR assembly simulation with natural gestures and an intuitive physically plausible interaction approach. A method to calculate the contact forces and the corresponding manipulation forces has been developed, and the quantitative results can be rendered in real time. In addition, a method is implemented to calculate the virtual snapping forces based on constraints analysis, so as to improve the efficiency of the assembly process. The ARAMS module is based on assembly and manipulation forces calculation, and advances the study of interaction process during assembly motion simulation.

9.1.5 Multi-modal AR assembly guidance based on human cognition

In this research, a novel human cognition based interactive Augmented Reality assembly operation guidance module (CARAGM) has been implemented through integrating the enhanced bare-hand interface (EBHI) to facilitate the multi-modal interaction between the user and the rendered contents. A within-subject controlled user study is performed, where CARAGM is tested against two baseline conditions. The results reveal that CARAGM is able to facilitate users through the whole user cognitive process by providing various modalities of guidance, so that the users can perform tasks more quickly (sub-task 1: CARAGM 44.15s, TARAGS 47.97s, SDD 41.44s; sub-task 2: CARAGM 12.30s, TARAGS 22.71s, SDD 32.77s; sub-task 3: CARAGM 30.73s, TARAGS 48.00s, SDD 62.62s; attention shifts: CARAGM 3.875, TARAGS 4.500, SDD 9.875) and accurately (Error rate: CARAGM 0.750, TARAGS 2.375, SDD 3.250) as compared with the other two guidance systems. In addition, CARAGM has been shown to be the most intuitive, easy to use, and satisfactory guidance system among the three guidance systems based on the median values. The user study has demonstrated the system features clearly. Thus, we conclude that, in order to improve the effectiveness and efficiency of AR assembly guidance system, multi-modalities of guidance should be provided to present appropriate information for various cognition phases of the user.

9.2 Recommendations

For further exploration, the following aspects can be investigated for improvement and enhancement.

9.2.1 Advanced 3D reconstruction techniques

The system should be able to capture the 3D workspace scene with depth information so that real-time 3D reconstruction can be achieved with high precision to facilitate the interaction between virtual and physical objects in the workspace. In future, the prototype system can be improved by employing depth sensing to unlock new possibilities for AR-aided assembly. Currently, the AR assembly process is based on CAD models of the real components, which are usually not available in advance. With depth sensing, the system will be able to re-construct and track the real components in the AR-based environment. As a result, a deeper fusion of real and virtual components can be obtained.

9.2.2 Intelligent assembly information management

Knowledge representation and management strategies would need to be investigated to support the development of context-aware systems that can understand and induce operator workflows, such that the system can consider the operators' mental status to provide instructions fit for their cognitive process. It is imperative to investigate the user cognition during general industrial assembly tasks. A more appropriate user cognition model should be proposed with the consideration of assembly tasks with different complexity and difficulty.

9.2.3 Collaborative interface for AR assembly

Collaborative AR assembly systems, with intuitive and natural interaction methods (e.g., bare hand, 3D referencing), should be investigated to support the concurrent product development process. Gesture-based interactions in AR systems have already been discussed in this research, and studies of natural gesticulation in the description of 3D objects and the creation of free-form shapes using augmented reality interfaces give an indication of how these interfaces can be used as an alternative for assembly designers, planners, and/or operators to communicate their ideas in 3D space. The portable and ubiquitous nature of bare-hand interfaces in AR make them ideal for collaborative product design processes.

9.2.4 Further research of IARAE

The calculations of assembly forces are based on physical laws and the modelling of the interaction between contact components. These calculations are used for the assembly process simulation and have not been validated by measuring the real interaction forces between two real contact components because the real situation is complicated and the forces are difficult to measure. In future work, the validation of the assembly forces calculations is necessary, and, in order to get more realistic assembly force calculations, more complicated modelling of the forces are required. To enrich the manual assembly simulation, assembly tasks using power tools will be investigated. In this research, components used for assembly simulation tasks are primarily cylindrical/symmetric objects, as these objects are representative and frequently used in manual assembly tasks. The use of objects with other geometric and/or asymmetric shapes is recommended for future work. One important aspect of the proposed AR technology is the performance of the hybrid marker less tracking system under variable lighting conditions. This is currently one of the most important drawbacks that does not allow a wider adoption of AR in industrial settings. Therefore, the investigation of lighting conditions for industrial AR system should be emphasized in next step. Furthermore, the proposed IARAE is potential to be integrated with MES (Manufacturing Execution System) in order to allow operators to dynamically receive AR based support during the execution of their tasks.

List of Publications from this Research

Wang, X., Ong, S.K. and Nee, A.Y.C. (2015), "Real-Virtual interaction in AR assembly simulation based on component contact handling strategy", *Assembly Automation*, Vol. 35 No. 4, pp. 376-394.

Wang, X., Ong, S.K. and Nee, A.Y.C. (2016), "A comprehensive survey of augmented reality assembly research", *Advances in Manufacturing*, Vol. 4 No. 1, pp. 1-22.

Wang, X., Ong, S.K. and Nee, A.Y.C. (2016), "Real-virtual components interaction for assembly simulation and planning", *Robotics and Computer-Integrated Manufacturing*, Vol. 41, pp. 102-114.

Wang, X., Ong, S.K. and Nee, A.Y.C., "Multi-modal augmented-reality assembly guidance based on bare-hand interface", *Advanced Engineering Informatics*, accept (2016 May).

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Appendix A Questionnaire on CARAGM

(This survey consists of three parts, i.e., a pre-test questionnaire, a demo shown on the assembly workbench, and a post-test questionnaire.)

Please complete the following contact information identifying the person completing this part of the Statistical Report. This will help if questions arise in interpreting the data.

Name:________________Age:___________________ Gender: ________________ Education level: ____ Occupation: ____ Date: ____ Interviewer: ____

Pre-Test Questionnaire

1. Have you had any experience of performing assembly or maintenance operation?

__ A. No

__ B. Yes, for __________________ years

2. Have you had any experience of using digital guidance system for such operations?

__ A. No

__ B. Yes, for a few times

__ C. Yes, with strong knowledge

(Please describe the system you use:

____

____

______)

3. Did the digital guidance system fulfill your intention?

__ A. Yes

__ B. Not always (Please

specify____

____

_____)

4. Do you think the user interface of the digital guidance system is convenient to use?

__ A. Yes

__ B. No (Please

specify____

____

______)

5. Do you think the guidance contents can be associated with the real assembly environment?

__ A. Very easily

__ B. Easily

__ C. A little difficult

__ D. Very difficult

6. Have you had any experience of using AR systems?

__ A. No

__ B. Yes, but seldom

__ C. Yes, quite often

__ D. Yes, every time

7. Have you had any experience of performing assembly operation supported by AR systems?

__ A. No

__ B. Yes, but seldom

__ C. Yes, quite often

__ D. Yes, every time

8. Usually your intention of implementing AR in mechanical assembly is

__ A. To guide the assembly process

__ B. To simulate and plan the whole assembly process before the real assembly operation

__ C. Others (Please

specify____

____

___)

[Test: Show the subjects how the *in-situ* system works.]

Post-Test Questionnaire

I. Intuitiveness

9. Do you think the system offers you an opportunity to fully interact with the instructions and explore the knowledge in the *in-situ* assembly environment?

__ CARAGM

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ TARAGS

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ SDD

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

10. Do you think the guidance provided is easy to understand and helpful for different phases of an assembly task?

__ CARAGM

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ TARAGS

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ SDD

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

11. Do you think, the system can facilitate the execution of your on-going task in addition to show you an instruction on the task steps?

__ CARAGM

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ TARAGS

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ SDD

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

II. Satisfaction level

12. Do you think the system provides various and enough modalities of guidance for each stage of an assembly task?

__ CARAGM

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ TARAGS

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ SDD

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

13. Do you think the system is the one you would most like to choose for assembly operation guidance?

__ CARAGM

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ TARAGS

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ SDD

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

III. Ease of Use

14. Do you think the system is easier to use when you work on an industrial assembly task comparing with other systems?

__ CARAGM

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ TARAGS

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

__ SDD

-Strongly Disagree

-Disagree

-Neutral

-Agree

-Strongly Agree

IV. Comments

15. Do you have any comments on the system?

____

____

____

____

____

____

Signature________________________________Date________________________

____

We appreciate your time and effort for this survey. The data received will be consolidated and appeared in my thesis, but NO personal data will be released. Thanks a lot!