Assembly Design and Evaluation in an Augmented Reality Environment

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***Abstract* — The technologies and methodologies of assembly design and evaluation in the early design stage are highly significant to product development. This paper looks at a promising technology to mix real components (e.g. physical prototypes, assembly tools, machines, etc.) with virtual components to create an Augmented Reality (AR) interface for assembly process evaluation. The goal of this paper is to clarify the methodologies and enabling technologies of how to establish an AR assembly simulation and evaluation environment. The architecture of an AR assembly system is proposed and the important functional modules including AR environment set-up, design for assembly (DFA) analysis and AR assembly sequence planning in an AR environment are discussed in detail.**

Keywords: Augmented reality, assembly simulation, design for assembly.

I. INTRODUCTION

It has been well proven that the technologies and methodologies of assembly design and evaluation in the early design stage are highly significant to industrial product development [1-2]. Traditionally, physical prototyping is the main method for assembly design and evaluation. With physical prototypes, users can easily obtain useful feedback (visual, audio, tactile and force, etc.) during assembly operations and identify any unexpected drawbacks to improve the product design. However, physical prototyping is very time-consuming and expensive even though in the past twenty years, Rapid Prototyping (RP) techniques have been widely used. In addition, once made, physical prototypes are either difficult or impossible to modify.

Potentially, virtual prototyping (VP) can be used to simulate and evaluate assembly in the early design stage. The concept of VP stems from the virtual reality (VR) technology, which generates immersive, interactive computer worlds using a combination of 3D graphics, motion tracking technology, and sensory feedback. VR attempts to replace the user's perception of the surrounding world with an artificially generated 3D environment. By adopting VR techniques, the duration and cost of prototyping are reduced greatly and the modification of the design can be performed in a very fast, economic and efficient manner. However, a shortcoming of VR as a medium for assembly evaluation is the limited "realism" experience while manipulating virtual objects due to a lack of suitable sensory feedback. In addition, although currently the computers are very powerful, the simulation of a complex assembly environment in a pure virtual environment requires a great deal of computation resources and is often difficult to satisfy the requirements of a real-time simulation. In addition, certain workspace and assembly parts cannot be completely defined and are difficult to be simulated. Thus, the VR environment does not completely provide the intuitive manipulation capability for assembly evaluation.

A promising alternative is to mix real objects (e.g., physical prototypes, tools, machines, etc.) with virtual objects to create a mixed reality interface. This mixed prototyping (MP) concept is a powerful potential methodology for assembly evaluation and product development in the next manufacturing generation. The underlying technology is called Augmented Reality (AR) [3] and has the goal of enhancing a person's perception of the surrounding world rather than replacing it with an artificial one. In an AR interface, it would be possible to realize the concept of mixed prototyping, where a part of the design is available as physical prototypes and a part of the design exists only in the virtual form. With such an interface, it would be possible to combine some of the benefits of both physical and virtual prototyping.

II. RELATED WORK

One of the most well-known applications of AR in the assembly domain is the assembly of cable harnesses at Boeing [4]. In the field of automobile production, applications have been introduced for assembly guiding of car doors [5]. The coordinating research project ARVIKA (www.arvika.de), which is sponsored by the German Federal Ministry of Education and Research, uses AR technologies to implement a user-oriented and application-driven support for working procedures in the development, production, and servicing of complex technical products and systems. WebShaman Digiloop

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system [6] augments digital virtual prototypes with physical objects to examine the functionality and features of products through assembly operations in an AR environment. A framework of an AR system for rapid evaluation of product prototypes through mixed prototypes was presented by Balcisoy et al. [7]. Fiorentino et al. proposed a Spacedesign system [8], which is an innovative AR system addressing the aesthetic design of free form curves and surfaces. Bernd and Blandine [9] presented an AR system for training and assisting the maintenance of equipment in an industrial context. Klinker et al. [10] at TU Munich reported an interesting project to analyze the information generation, retrieval, transmission, and visualization process in the context of maintenance procedures performed in nuclear power plants. Both the Fata Morgana [11] system developed by TU Munich and BMW and an AR-based product design system presented by Gausemeier [12] were used to investigate the AR presentation for automobile design evaluation. Sharma's group investigated an information presentation scheme [13-15] for AR stimuli in assembly sequence planning. In addition to assembly, an application to support dismantling processes has also been reported [16].

In the last ten years, a few research groups have developed virtual assembly systems. The VADE system [17] used constrained CAD models within a VR environment that represents the assembly area, and an expert human assembler can manipulate virtual parts and the assembly tools using both hands and dexterous finger tip-based manipulations to perform realistic assembly operations. The CODY Virtual Constructor [18] is a knowledge-based system that enables the interactive assembly of 3-D visualized mechanical parts in a virtual environment. BMW and IGD co-operated to investigate the steps needed to apply virtual prototypes to verify assembly and maintenance processes [19-20]. Ye's group [21] at the University of Illinois at Chicago investigated the potential benefits of a VR environment in supporting assembly planning using the CAVE system. Ma et al. [22] proposed a hierarchically structured and constraint-based data model for intuitive and precise solid modeling in a virtual assembly environment. Steffan and Kuhlen [23] developed the MAESTRO system for interactive assembly simulation in a virtual environment. The DPM assembly system by the Delmia Corporation (www.delmia.com) is a commercial VP system providing similar functions (including: collision detection, assembly sequence and collision-free paths generation, etc.) as the VADE system.

III. AR ASSEMBLY SYSTEM ARCHITECTURE

An AR assembly environment is a very complex environment supporting assembly design and evaluation. The proposed architecture of an AR system is shown in figure 1. In this system, we will integrate an existing CAD system with the AR environment, since:

- CAD systems are very popular and successful in industrial applications, and
- Most of the information required for simulating and verifying the assembly operations can be exported from a CAD system.

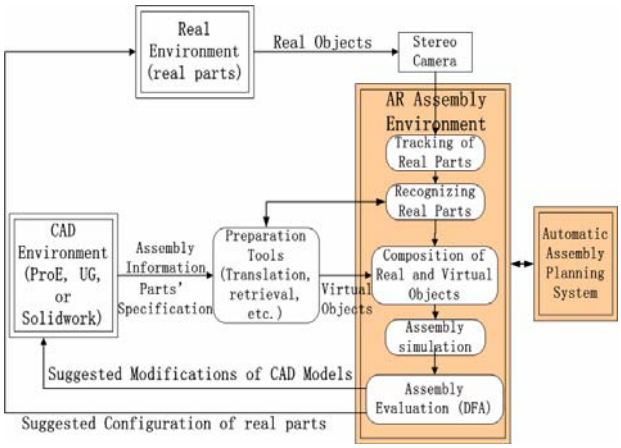

Figure 1. AR assembly system architecture

As shown in figure 1, design information is defined in a CAD system, and the solid model information and assembly information are translated into an AR environment automatically using some preparation tools. In the AR environment, stereo cameras are used to capture the real assembly scene and real assembly prototypes. These real components are rendered with virtual components from a CAD system to simulate and evaluate the assembly operations. The evaluation information from an AR assembly environment can be used for assembly sequence planning, assembly training, robot path planning, etc.

A. Augmented Reality Module

A portable head-mounted display (HMD) is suitable for an assembly operation environment. Basically, there are two HMD systems: optical see-through and video see-through. The present system will opt for the video see-through HMD because of the following considerations:

- The optical see-through HMD offers an almost instantaneous view of the real world but a delayed view of the virtual object. This information lag will confuse the collision information in some assembly processes.
- In assembly feasibility and ease evaluations, accurate registration is necessary. The video see-through HMD is easier and more reliable to control the registration error than an optical see-through system.
- In a video see-through HMD, collision information is easily presented since the real image and the virtual object are overlaid in the video stream.

- Although an optical see-through HMD is better for safety consideration because it provides a direct view of the real world even if the power is cut off, we can adopt some methods to ensure a continuous power supply for the video see-through HMD, and thus eliminating the safety problem. Even though power is cut off for a while in a video see-through HMD, it may still be safe for most of the assembly operations.

Based on these considerations, currently the video see-through HMD is a suitable choice for the AR assembly system.

The AR assembly system uses computer vision techniques for tracking and registration. At the early stage, the marker-based tracking, registration and object recognition method was adopted since it is reliable and easier to operate. The marker-based tracking and registration software framework was developed based on the ARToolkit [24]. Since the marker-based method has its limitations, e.g., limited tracking range and reduced flexibility due to marker visibility requirements, in the later research stage, we will try to develop markerless methods to establish the AR environment.

B. Design for Assembly Module

Using AR technologies, users can render real and virtual prototypes in the AR environment. The Design for Assembly (DFA) Evaluation modules extends the AR module basic functions to simulate and evaluate the feasibility and ease of assembly operations using mixed prototypes and improve the product design based on the verification information. It includes two main functions: Assembly Operation Simulation and DFA Analysis. Figure 2 shows the configuration of this module.

1) Assembly Operation Simulation

The simulation of assembly operations in an AR environment is a fairly complex process. Generally, the following basic features and capabilities are necessary to support assembly operations.

- *Virtual Objects Selection and Manipulation*
  Some interactive devices (dataglove, etc.) are involved in this function to provide the interactive capabilities to select and manipulate the virtual objects in an AR assembly environment.

- *Guidance to Target Position*
  This feature is used for assembly guiding and capturing the design intent, and thus eases the assembly operations in the AR environment. The system will obtain prior knowledge of the target positions and orientations and provide guidance in the AR environment to assist in the assembly operations. This feature also uses constrained motions along the axes and planes to simulate realistic interactions during the assembly process.

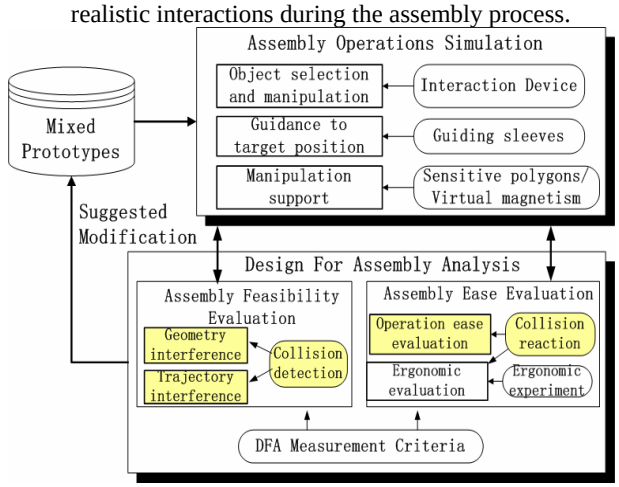

Figure 2. DFA Module in AR assembly system

- *Artificial Support Mechanisms*
  This function includes sensitive polygons and virtual magnetism. Sensitive polygons are shown in figure 3(a): if the parts move into certain sensitive polygons, they are automatically oriented. Figure 3(b) shows the "virtual magnetism": it provides a snap function to aid the exact alignment of objects at arbitrary locations. Since accurate placements, movements and alignments of 3-D models are difficult to realize in an AR environment, the "virtual magnetism" (snap-function) will be helpful to overcome this.

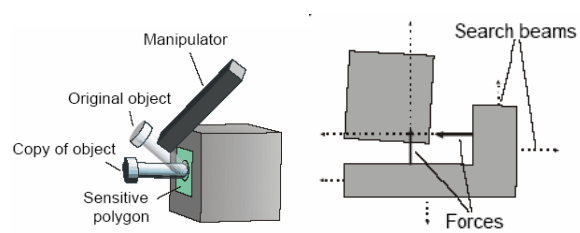

Figure 3. (a)Sensitive Polygon (b)Virtual Magnetism [23]

2) Design for Assembly Analysis

Using the features provided in the Assembly Operation Simulation, users can manipulate the mixed prototypes to simulate the assembly process. The DFA Analysis module will detect the collision information during the simulation process. This module also provides the function to simulate the collision reaction feedback (tactile and force feedback) to give users a feel of how difficult the assembly operation is. The related DFA guidance information is presented interactively in the AR environment to help users improve the product design based on the collision and reaction information. There are three types of collision in an AR environment: collision between virtual objects, collision between virtual and real objects, and collision between real objects.

C. Assembly Sequence Planning Module

Assembly sequence planning for complex products has always been a difficult task for engineers. Although many automatic systems have been attempted to automate the sequence of the planning process, it is very difficult to formalize the assembly planners' knowledge. However, automatic sequence planning systems [25-26] are able to generate a set of feasible sequences based on identified constraints. Assembly constraints have been systematic studied [26-27]. Some constraints, such as geometric constraints, are easily identifiable and definable. However, certain constraints, especially the component constraints and the soft constraints, are difficult to identify without a good realistic feel of the assembly process. An AR interface mixing the real prototypes and virtual prototypes provides a better intuitive environment for users to experience the realistic feeling of assembly operation and identify the assembly constraints.

The AR assembly environment can be integrated with an automatic assembly planning system. The methodology used for assembly sequence optimization is shown in figure 4. Firstly, as many constraints as possible are identified through the AR assembly environment. Next, these initial constraints are imported into the Automatic Assembly Planning System to generate the feasible sequences. Planners can view and verify the feasible sequences in the AR environment to identify new constraints and decide whether there is a need to change the optimization criteria (e.g., minimal cost, minimal number of orientations, etc.). Next, the users go back to the Automatic Assembly Planning System to re-plan the sequences. The planners repeat this process until they find a satisfied sequence.

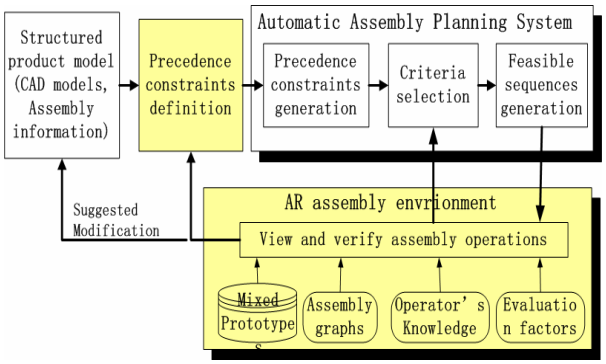

Figure 4. Sequence Planning in AR Assembly System

IV. RELATIONSHIP BETWEEN REAL AND VIRTUAL COMPONENTS

In the mixed prototyping concept, some important questions need to be clarified: (1) Which are the parts that should be real prototypes? What should be virtual? and (2) How much manipulation of the virtual parts is feasible and needed, etc.? Although the answers to these questions are very context dependent, basically we can make a decision based on the following aspects.

- *Design Strategy:* In order to obtain economies of scale in customized productions, standard components of products have become very popular in the manufacturing industry. In the mixed prototyping concept, these standard parts should be real components normally since they can be found easily in stocks. For some fixed designs that do not need to be changed much, we prefer to use real components through conventional RP technologies. For the customized parts, which need to be evaluated and revised many times, we would use virtual prototypes since virtual prototypes are flexible for modification.
- *Assembly Operations:* During an assembly process, some obvious considerations would help in the decision making process. For example, it would be impossible to connect two real components using a virtual component to obtain realistic feedback. In addition, we cannot stack a real component on a virtual component. Using the largest component of an assembly as a virtual part would not be ideal if several other real and virtual parts are connected to it. Hence, a part where several components are to be assembled, such as the base part, would serve better if they are real.
- *Components Properties:* Certain workspace and assembly parts (spring, flexible cable, etc.) cannot be completely defined and are difficult to be simulated. For these components, we would try to use real components as much as possible.
- *Prototyping Cost:* If the prototyping cost of some components is very high, we would try to use virtual prototypes even though their designs are already fixed.
- *Sensory Feedback:* Normally, users can obtain a more realistic feedback based on real components as compared to virtual components. For some assembly parts, if the sensory feedback is very important for making decision, it is better to use real components.

For the specific cases, it is difficult to obtain an obvious optimal solution of all these aspects. We need to consider the trade-off of these aspects carefully in terms of our application and requirements to define a proper strategy for assembly evaluation based on mixed prototyping.

V. DISCUSSION AND CONCLUSION

This paper describes the potential of setting up an AR assembly environment for assembly design and evaluation based on the mixed prototyping concept, which can combine the benefits of RP and VP. The

establishment of an AR assembly environment is extremely complex and needs to consider many interdisciplinary issues of AR technologies, assembly and manufacturing knowledge. In this paper, we propose an AR assembly architecture, which supports assembly design and evaluation in an AR environment, and the important issues of the system set-up are discussed in detail.

Although researchers have done some work in the AR assembly domain, the research in this area is still at the infant stage. Currently the limited research in AR assembly is focused on the methods to present instructional information to guide the assembly process (operation, planning, etc.) and the methods to simply superimpose a virtual shape on a real platform for aesthetic evaluation or space checking. We believe the physical interaction between real and virtual objects in an AR assembly environment, which includes collision detection and reaction, is significant for a comprehensive assembly evaluation. Collision detection is the foundation for assembly feasibility evaluation and collision reaction information is very important for assembly "ease" evaluation. Thus far, the reported research [28-30] on these problems is limited and the techniques are far from mature. If an efficient and robust solution for these problems cannot be found, the AR assembly system can only be used for simple assembly evaluation. In addition, it is important to realize that most interactions in an AR environment are currently one-directional, i.e., real objects can affect the virtual objects, but the virtual objects cannot usually affect the real ones. Hence, as a start, only the reaction from a real prototype to a virtual prototype is studied. The other way of reaction from VR to RP is interesting and significant for future AR applications.

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