Facilitating Mechanical Design with Augmented Reality

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Abstract — **By enhancing a real scene with computer generated objects, Augmented Reality (AR), has proven itself as a valuable Human-Computer Interface (HCI) in numerous application areas such as medical, military, entertainment and manufacturing. It enables higher performance of on-site tasks with seamless presentation of up-to-date, task-related information to the users during the operation. AR has potentials in design because the current interface provided by Computer-aided Design (CAD) packages is less intuitive and reports show that the presence of physical objects help design thinking and communication. This research explores the use of AR to improve the efficiency of a design process, specifically in mechanical design.**

Keywords — **Augmented Reality, Computer-aided Design, Mechanical Design, Technical Drawing**

I. INTRODUCTION

By enhancing a real scene with computer generated objects, AR, has proven itself as a valuable HCI in numerous application areas such as medical, military, entertainment and manufacturing. On-site tasks can be better performed with a seamless integration and presentation of up-to-date task-related information to the users during the operation. For example, overlaying real-time ultrasound images on a patient can assist the doctor to perform minimally invasive surgery [3] or superimposing step-by-step assembly instructions can reduce errors during assembly operations [3]. Comparative studies such as [19], have shown that a guided process yield better performance when the instructions are presented via AR. AR has also been widely used for training and teaching purposes where annotations of components' name, location, and operational steps, are placed in the real scene as guides to new users. Neumann and Majoros [15] suggested that AR can be used to support concurrent training and performance which greatly reduces the need for training as a distinct process. This research explores the use of AR for improving the efficiency of design processes, specifically for mechanical design.

For the rest of this paper, Section 2 explains the motivation for product design in physical environments which is the research motivation for integration of AR in design. An in-depth description of the design scenarios considered in this research is covered in Section 3. Section 4 gives an overview on the fundamentals of AR. A brief description of the system architecture is presented in Section 5 and Section 6 exhibits some of the results. The last two sections describe some observations on the system performance and conclude the paper respectively.

II. MOTIVATION AND RELATED WORK

A design process is typically an iterative process consisting of the following steps, i.e., identification of needs, goal statements, performance specifications, conceptual design, detailed design, prototyping and production. During conceptual design, ideas are generated through sketches or drawing on paper. This will later be translated into 3D models and scaled physical mock-ups to provide better visualization and understanding of the design. Most industries use commercial CAD packages for designing new products as this is a cost effective and efficient approach. However, the interface provided to the users through desktop-based Graphic User Interface (GUI) is less intuitive and presentation of a design on a 2D flat screen does not provide the user with "natural feel" [16]. Virtual Reality (VR) has been developed where digital models are presented with utmost realism in expensive viewing setups such as CAVEs or large projection walls [13]. Despite the fact that this immersive approach will allow more natural interaction with the design entities, recent observational study shows that the presence of physical object during the design process helps in enhancing design thinking and communication [4]. This finding is supported with the argument that a physical object is appreciated by at least two of human senses and its behavior and limitations can be better understood with its presence. This will allow the user to make connections between objects and also to recall an episode of the component in usage.

There are quite a few systems supporting design in physical environments as highlighted in [11] where physical design environments support the users in spatial, physical, and tangible act of creation. In the paper, they assembled a panel to debate on how different approaches can result in different visions of what a creative environment should be. Another research [7] also highlights the benefits of mixed reality in providing the users with a better perception of a design. Their system, AR CAD, features a more natural mode for changing views of a model and completely understanding the model content, which helps to improve communication and shared perception of designs. This system is also promising to lay the foundation for further application of mixed reality technology to the design, construction and maintenance phases of a product life cycle. The research in [15] had described the potential benefits of AR to users which analyzed from the cognitive psychology perspective.

In recent years, there are more reports on the adoption of AR in design related tasks by the industries, mainly automotive and building industries. For example, at Volkswagen, due to the possible large variations of components, building a prototype for every design alternative is costly. Their platform strategy has cut down production costs by building several models using common chassis and components [9]. AR aids in the assembly of virtual new parts onto a platform in the early design for visual evaluation and assists the designers during the decision making process. This strategy also supports ergonomics evaluation of the new design. Similar strategies had also been reported in [16] where AR enhances designers' perception of the real world by overlaying 3D objects on the real scene. This allows the users to exploit the flexibility of digital models and, at the same time, the advantages of physical mockups. A typical automotive design evaluation scenario involves comparisons of a previous generation car with the mockups of new candidates placed on turn tables in a large show room [13]. With AR, new digital models of the car can be virtually placed side-by-side with real car to ease the designer making evaluation as if they are looking at a physical mockup. SpaceDesign bypasses the cycle of common practice for aesthetic design in industry; building physical mock-ups using rapid prototyping techniques and updating the original CAD data via reverse engineering techniques after the review phase, where adjustments and modifications are carried out directly on the models using traditional workshop tools [8]. This results in an increase in efficiency in terms of cost and cycle time.

III. DESIGN SCENARIO

Most of the researches stated in the previous section focused mainly on design evaluations based on the appearances of the designs. The exact geometric information might not appear to be as crucial. However, despite the advancement in 3D modeling technology, traditional industries, such as those involved in chemicals and power plants, still rely on 2D technical drawing [2]. By merging the technical data to the real environment of the plant, the electronic information is presented to the user for facilitating work on-site. Similarly, geometric information is important in mechanical design, as it often involves combinations of new designs and standard components such as bearings, gears, fasteners, shafts, flanges, gaskets, etc. Design information, in the forms of blue-prints and CAD models, can be correctly aligned to the physical object corresponding to the viewpoint that the user is looking at for reference in design and redesign works. This will help a designer makes better and faster judgments based on the electronic information and physical constraints from the real environment. It will also save the designers from the search of annotated drawings. Such an in-situ design scenario is also valid as the digital information available might be out-of-date or there is information that is not considered in the previous design steps. Thus, conducting and configuring a mechanical design with the presence of physical objects and virtual objects in AR will result in a more efficient process. The following are the design scenarios considered in this research:

A. Component selection/assembly and design

Design information is used for the retrieval of appropriate components from a database. These components can be presented to the designers as a short-listed electronic catalog where he/she can interactively select and fit the components to the real scene, creating a design that is a mixture of real and virtual components. Besides that, the designer can also plan out the assembly process concurrently and check for fitting and interference.

B. Design information verification and updating

By superimposing design information onto a real scene, verification of digital design information can be made by taking some on-site measurements using measuring tapes or calipers. This is an essential step, specifically in redesign work, as it will influence the outcome of the design [6]. Changes to the design information can be implemented using an interaction stylus, for selecting design entities, coupled with other means of input methods, such as a keyboard.

C. System design – shop floor planning/design

Typically, spatial relationships of various parts may not be indicated in the CAD model which usually only contains individual part information. The connections between the machines (cabling/piping) or components vary from case to case. Overlaying of the blue-print of a shop-floor and CAD models can assist the industrial engineers to make on-site decisions on the planning and verification of a shop-floor design. Virtual machines and in-between connections can also be identified and virtually assembled at the same time. Similar application in planning of a shop-floor has been reported in [5], [10].

IV. FUNDAMENTALS OF AR

There are two main components in realizing AR, namely tracking and registration.

A. Tracking

Tracking establishes an understanding between the computational and real environments. Many types of sensors have been used to track the position and orientation (pose) of a user's body and head in a real world, e.g., ultrasound, magnetic and inertial [1]. This information will be used for rendering virtual objects to the real scene. However, current tracker-based systems are limited in terms of the range application and the vulnerability in dealing with possible noise and disruption. With the rapid development of the digital imaging technology, many recent developments in AR are based on the optical and vision techniques. Such systems are highly dependent on computer vision and image processing techniques to obtain estimated poses of the user or objects in the real scene.

B. Registration

Registration is the process of overlaying computer generated objects onto a real scene based on the pose estimation given by the tracking system. The estimated pose will specify where and what needs to be rendered to the real scene. Therefore, it is clear that the accuracy of the registration depends greatly on the accuracy of the estimated pose. The virtual objects are presented to the users using four means, projection onto the real scene [18], projection onto retinal [17], head-mounted displays (optical see-through and video see-through) [3] and on a computer screen or a Personal Digital Assistant (PDA).

Besides that, other supporting technologies such as wireless communication, database technology and various analysis engines also add more value to this interface.

One prominent achievement in AR came through the development of the ARToolKit from the Human Interface Technology Laboratory (HITLab) [12]. Due to the availability of ARToolkit in the public domain and its simplicity, a large number of AR applications are based on it. The pose estimation is achieved through establishing a relationship between a square marker and the camera, based on image processing and associating the feature in the images to known sizes and patterns of the markers. Next, the virtual objects are superimposed on the images using OpenGL.

V. SYSTEM ARCHITECTURE

Basically, the architecture of the system consists of three main subcomponents as shown in Figure 1.
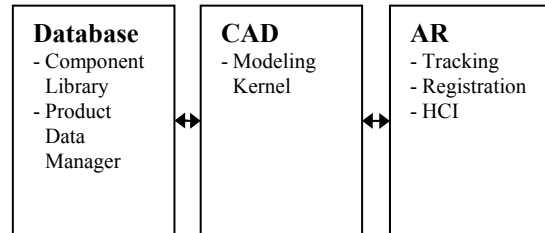

Figure 1: System architecture

The AR subcomponent will deal with AR-related features, such as tracking, registration and HCI. Currently, the AR subcomponent is based on ARToolkit, C++ and OpenGL. In order for the system to make use of functionalities from CAD package, an interface is built to enable communications between a CAD package and the AR subcomponent, where AR sends sets of drafting instructions or invocations and CAD returns design information that can be rendered using OpenGL in AR. The database supports the overall system, serving as a repository for all the necessary standard components and product information that are required in a mechanical design process. The information in the database is retrieved via AR through CAD as most CAD packages are readily equipped with database support.

VI. SOME RESULTS

This section highlights some of the initial result of this system, namely an interactive selection box and a function for superimposing design information on the physical objects.

A. Interactive Selection Box

This feature allows a user to interactively select a region as a bounding box to display and render only the information related to that bounding box. On the other hand, this feature can also be used to suppress information so that the user's viewpoint is not cluttered with information. A 3D bounding box can be specified to the system by recording two 3D points as shown in Figure 2. The selection region is rendered as a thin wire frame cube.

Note that those 3D points can be obtained by relating two markers where the marker "Hiro" is the world coordinate system (WCS) and the other marker is the position of the interaction stylus. The smaller marker is used for interaction purposes, where by occluding it, the location of the tip of the interaction stylus is recorded with respect to the WCS. The details of the transformations are described in the Appendix.
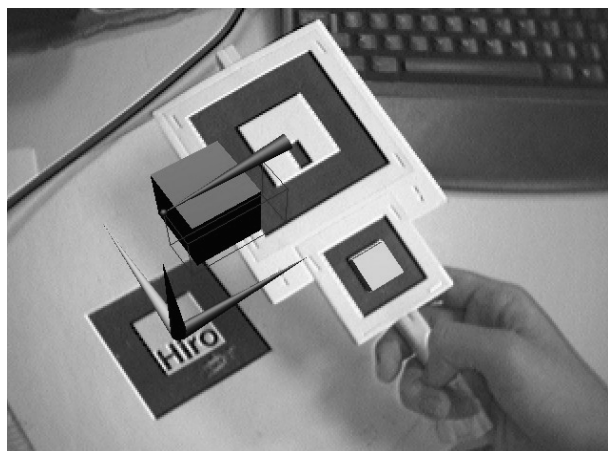

Figure 2: 3D bounding box for selective information presentation

This approach can be used for other features such as a 3D virtual panel for selecting components, invocating drafting instructions, etc.

B. Superimposing design information on physical objects

Most common practices in the industry still depend on the information stated in a technical drawing. As shown in Figure 3, the blue-prints are correctly aligned according to the viewpoint of the users in order to correctly present the design information. This can be achieved by making a simple distance approximation between the marker and the camera, and each of the markers corresponds to the information of the viewpoint. The marker that the user is looking at will be the closest. Other design information related to the other viewpoints is therefore suppressed to avoid cluttering of information.

Given any technical drawing, preprocessing is required before it can be rendered and presented to a user. Information in the technical drawings, such as lines, circles, dimensions, etc. can be extracted by interpreting the .dxf files, which is a standard drawing exchange format developed by Autodesk Inc.
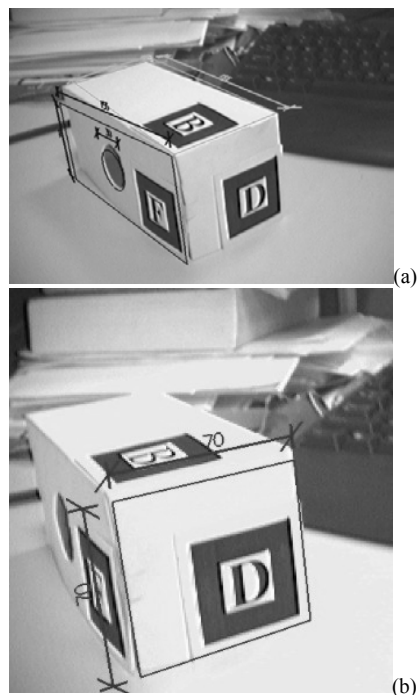

(a)

(b)

Figure 3: Two different viewpoints (a) and (b) showing only viewpoint-relate design information

VII. SOME OBSERVATIONS

The current work is a proof-of-concept. More works is required before it can be implemented in the industry. During the development process, the limitations of ARToolkit in terms of accuracy and stability were observed. It is not suitable for precise manufacturing applications as it is designed neither for precise applications nor 3D measurements, but mainly for overlaying virtual objects in a real scene. When the marker size is relatively small compared to the screen size, instability can be observed in the registration of virtual objects as the detection of the marker is less accurate. Tests had been conducted to quantify the accuracy of ARToolkit in [12], [14].

VIII. CONCLUSIONS AND FUTURE WORKS

Motivated by the findings that physical objects can assist the thinking processes in a design work, this research looks into facilitating mechanical design in AR to yield a more efficient design process. Some preliminary works have been reported in this paper and more features will be added before a real implementation in the industry, such as setting up a comprehensive database of components, and filters to assist the short-listing of component for the ease of the selection process. As the shortcomings of ARToolkit have been observed, there is a possibility of improving the system through implementing feature recognition for tracking and intelligence to perform associations so that relevant design information can be retrieved from the

database and presented to the users.

APPENDIX

Figure 4 shows the coordinate frames transformations in obtaining the relationship of the tip of the stylus to the WCS. It can be denoted as:

$$_{s'}^{w}M = _{c}^{w}M \, _{s}^{c}M \, _{s'}^{s}M \qquad (1)$$

Where, w is the WCS frame,
          c is the camera coordinate frame,
          s is the stylus coordinate frame,
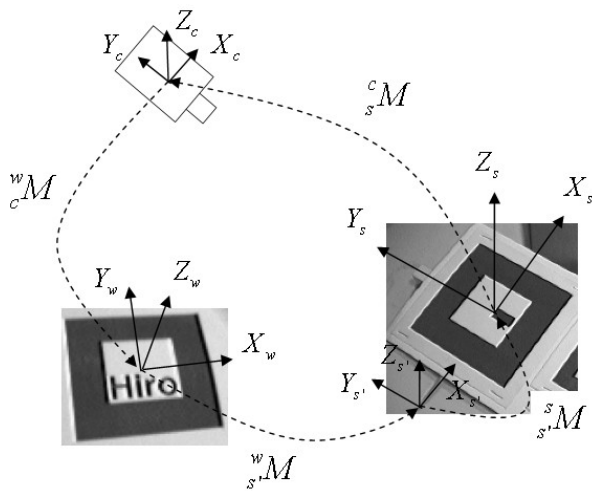 s' is the stylus's tip coordinate frame.

Figure 4: Transformations between camera and markers

The transformations $_{w}^{c}M$ and $_{s}^{c}M$ are obtained using ARToolkit and $_{c}^{w}M$ is the inverse of $_{w}^{c}M$.

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