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Augmented reality applications in design and manufacturing

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ABSTRACT

This paper reviews the research and development of augmented reality (AR) applications in design and manufacturing. It consists of seven main sections. The first section introduces the background of manufacturing simulation applications and the initial AR developments. The second section describes the current hardware and software tools associated with AR. The third section reports on the various studies of design and manufacturing activities, such as AR collaborative design, robot path planning, plant layout, maintenance, CNC simulation, and assembly using AR tools and techniques. The fourth section outlines the technology challenges in AR. Section 5 looks at some of the industrial applications. Section 6 addresses the human factors and interactions in AR systems. Section 7 looks into some future trends and developments, followed by conclusion in the last section.

1. Introduction

Manufacturing is the process of transforming raw materials and information into finished commodities with good value-added for the satisfaction of human needs. It has been a key contribution to a nation's economic growth for the last few centuries and will continue to do so in the future. In the current highly competitive and dynamic business environment, the manufacturing industry is facing new challenges, which require a holistic perspective on the four main classes of manufacturing attributes, i.e., cost, time, quality and flexibility [30]. Manufacturing companies should be producing innovative products at low cost and reduced time-to-market. High product-mix with low volume, customisation to meet the individual demands of the customers, increasing legislation of environmental and other issues have further made manufacturing processes more complex and demanding. In addition, the increasing trend of globalized manufacturing environments requires real-time information exchanges between the various functional units in a product development life cycle, e.g., design, setup planning, production scheduling, machining, assembly, etc., as well as seamless task of collaboration among them. Manufacturing processes have to be more responsive and systematic in order to be efficient and economically competitive. On top of that, the increasing demand for goods results in an increasing demand for natural resources and energy. However, since resources and energy are finite, new ways of producing more with less ought to be found [33].

Due to the recent advancements in information technology (IT), manufacturing research has entered a new level of product planning, analysis and trouble shooting. Digital manufacturing has been considered, over the last decade, as a highly promising set of technologies for reducing product development times and cost as well as for addressing the need for customization, increased product quality, and faster response to the market [31]. Digital manufacturing has become a common trend worldwide as computer-integrated manufacturing systems have eliminated data handling errors and enhanced decision making. Computer simulation using CAD modelling tools and finite element analysis has assisted manufacturing engineers to reach decisions faster and free from errors. In just over a decade, augmented reality (AR) technology has matured and proven to be an innovative and effective solution to help solve some of the critical problems to simulate, assist and improve manufacturing processes before they are to be carried out. This would ensure that activities, such as design, planning, machining, etc., are done right-the-first-time without the need for subsequent re-work and modifications. AR is a novel human–computer interaction tool that overlays computer-generated information on the real world environment. The information display and image overlay are context-sensitive, which means that they depend on the observed objects [8,9]. This novel technique can be combined with human abilities to provide efficient and complementary tools to assist manufacturing tasks. AR has already been demonstrated to be a solution in many applications, both in manufacturing and other fields. Several successful demonstrations have been made in the medical domain, military training, tele-robotics, entertainment, maintenance, and manufacturing [107,177].

Research in the manufacturing applications using AR technology is a strong and growing area. The challenge is to design and implement integrated AR-assisted manufacturing systems that could enhance the manufacturing processes, as well as product and process development, leading to shorter lead-time, reduced cost and improved quality.

2. Hardware and software systems in AR

Developing successful AR applications is a challenging task. Despite recent advances in the AR technology in the last ten years, most of the AR systems developed so far are laboratory-based

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implementations. Extensive research has been carried out worldwide in addressing some of the critical issues in AR technology. Real-time tracking and computation are crucial since synchronization between the real and the virtual worlds must be achieved in the shortest possible time interval.

AR applications are both hardware and software intensive. Special equipment, such as head-mounted displays and accurate trackers are required. Commercial hardware and software tools are widely available.

2.1. Hardware devices

In this section, hardware devices employed in AR applications are reviewed, including display devices, user tracking devices, and haptic and force feedback rendering devices.

2.1.1. Display devices

Head-mounted display (HMD) devices have been applied widely in AR applications as the eye-level display facilitates direct perception of the combined AR scene. However, wearing HMD devices is uncomfortable and may cause headaches, dizziness and nausea, especially after prolonged usage. Recently, researchers have also explored the application of other display devices, such as projectors and handheld devices.

2.1.1.1. HMDs. Table 1 lists a number of current HMD models in the market in an ascending order of the weight of the model (excluding accessories, e.g., head bands, goggle frames, controllers, batteries, etc.). Compared with earlier HMD models, most of these new models are light-weight with a large field of view (FOV), and support high resolution display, such as SVGA (800×600) or SXGA (1280×1024). Some HMD models have embedded cameras and sensors to facilitate image capture and display using head movement. In addition, many manufacturers provide customization service so that the user can specify the HMD to be optical see-through (OST) or video see-through (VST), compatible with different video input configurations (VGA, DVI, composite, etc.).

Besides the products listed in Table 1, there are HMDs in the design and development stage that have been reported in the literature. Researchers have investigated technologies for the purpose of achieving high FOV for the HMDs, such as the research of applying freeform prisms and lenses by Cheng et al. [27], and the design of an off-axis optical system using relay lenses with polynomial surface by Zheng et al. [185]. Caruso and Re [23] focused on the development of visualization and interaction methods in a design review system. A video see-through HMD was designed with two motor-driven video cameras that can adjust the camera convergence automatically. This self-adjusting mechanism solves the problem encountered in common VST HMD that the visualization of a virtual prototype (VP) may be distorted if it is too close to the designer.

2.1.1.2. Handheld devices. Research in AR applications is towards mobility using handheld devices (HHD) that are either commercially available products or specially designed for the applications [55,156,174]. Higher processing power and hardware, such as high resolution camera, touch screen and gyroscope, etc., have already been embedded in these mobile devices. A tablet PC-based sketching tool was developed as a design platform [174], where 3D designs are facilitated. The 3D design space is defined based on the "napkin" metaphor, and a virtual plane is rendered on a set of ARTag markers. A mobile device, namely MARTI, was developed incorporating a UMPC and a camera [156]. The MARTI device provides a two-handed gripping structure to ensure comfortable handling of the device.

Researchers have used off-the-shelf mobile phones in AR applications. Due to the limited processing capability and internal storage of the mobile phones, some researchers have applied a client-server architecture to obtain real-time performance. Hakkarainen et al. [55] reported a study on the possibility of using mobile phones for an AR-assisted assembly guidance system. A client–server architecture was set up using a Nokia mobile phone and a PC. Considering the limited processing capability of the mobile phone, the PC handles the rendering of complex CAD models, and static rendered images are sent to the mobile phone for fast rendering. Similarly, Ha et al. [53] applied a client-server model for real-time tracking applications using an Android mobile phone. The mobile phone handles image capturing and virtual information rendering, while a server is applied for image analysis and object recognition.

2.1.1.3. Projectors. Projectors have been utilized in certain AR systems so that the users do not have to wear HMDs to view the augmented scene, and this projector-based AR configuration has been named spatial augmented reality (SAR). Application of projectors in AR applications can be categorized into two groups according to the installation of the projector, namely, fixed installation and portable installation. Saakes and Stappers [131] applied AR technologies using a fixed SAR configuration during the early design stage. Texture captured from real objects can be mixed with digital images, and this new texture can be projected onto a physical model to evaluate the design. Kitagawa and Yamamoto [74] applied a 3D LCD projector in the application of 3D puzzle assembly guidance on a desktop. A portable projection device has

Table 1
Summary of HMD models in the market (based on the specifications listed by the manufacturer unless otherwise specified).

Manufacturer – model	Type		Features
Vuzix – Tac-Eye LT	Video	Monocular	• 51 g; 30° FOV
Liteye – LE 750A	Optical	Monocular	• 80 g; 24-28° FOV
Vuzix – Wrap™ 920AR	Video	Stereo	• 85 g (Vuzix Wrap 920 review); 31° FOV • Embedded two cameras and a 6-DOF motion tracker
Vuzix – Tac-Eye Binocular	Video	Stereo	• 7.3 oz (about 200 g); 35° FOV • Support 3D stereoscopic viewing
eMagin – Z800 3DVisor	Video	Stereo	• 8 oz (about 225 g); 40° FOV • 3-DOF head motion tracking
Trivisio – ARvision-3D HMD	Video	Stereo	250 g; 42° FOV • Embedded two cameras
Trivisio – ARvision-S HMD	Video	Stereo	• 250 g; 42° FOV
Cybermind – hi-Res800 (2D/3D)	Video	Stereo	• 700 g; 26° horizontal FOV • Integrated with InterTrax™ head tracker (optional); • Support 3D stereo display
Cybermind – Visette45 SXGA	Video/Optical	Stereo	• 750 g; 45° horizontal FOV • Support SXGA display; high resolution (1280×1024)
NVIS – nVisor ST60	Video	Stereo	• 1300 g; 48° total horizontal FOV • Support SXGA display; high resolution (1280×1024)
NVIS – nVisor SX111	Video	Stereo	• 1300 g; total 102° horizontal FOV • Support SXGA display; high resolution (1280×1024)

Table 2
Summary of mini projector models in the market.

Manufacturer – projector model	Type	Pros	Cons
MicroVision – Pico projector	Optical	• Low cost	Low light intensity
AAXA – P1 Jr Pico projector	Optical		
AAXA – P2 Pico projector	Optical		
Pico projectors using DLP technology	DLP	• High light intensity (8–300 Lumens) • Filter-free, lamp-free • Superb readability	Relatively expensive for high intensity display

been developed and applied in liver surgery using AR technologies [52]. Löchtefeld et al. [91] proposed the design of projector phones using off-the-shelf mini projectors integrated with mobile phones while the axis of the projection is aligned with the optical axis of the camera inside the phone. Discussions on the FOV and field of projection (FoP) were presented. Willis [172] discussed the application of a similar device in the application of games. The SixthSense project [151] developed a user interface where a mini projector is attached to the head of the user. Table 2 lists a few off-the-shelf projector models in the market. In addition, researchers have developed projection systems to be used in AR applications. Yoshida et al. [175] developed RePro3D using retro-reflective projection technology to generate motion parallax for the user to view 3D images without wearing special glasses.

2.1.2. User tracking

In most AR applications, the movement of the user needs to be tracked with reference to a given environment map so that position-based digital contents can be retrieved and rendered interactively. There is a trend in AR applications to use software-based tracking instead of using hardware-based tracking due to the requirement of most AR applications to provide less restriction caused by bulky hardware. Currently most of the AR systems have either applied computer vision (CV)-based tracking methods (Section 2.2), or combined CV-based methods with sensor-based tracking technologies, including inertial, magnetic, and acoustic sensors, and more recently the radio frequency (RF) technology. Table 3 lists some of the tracking products in the market that have been used in AR applications.

Researchers have applied RF technology in the tracking and localization of assets, inventories and personnel in dwellings, industries, groceries, logistic facilities, nursing homes and hospitals, using RFID tags, ZigBee modules, etc. Usually the user needs to carry an RF reader, while a number of RF modules need to be installed in the environment. There are mainly two methods to apply the RF technology in user tracking. In the first method, the user needs to be in contact with an environmental RF module, which carries its coordinates in a given application frame. The position of the user is thus determined to be equivalent to that of the environmental module. In the second method, which is called the fingerprint-based positioning technology, the position of the user is determined by mapping the received signal strength (RSS) to a pre-determined RSS map. The fingerprint-based tracking method is still in the research and development stage; most of the reported works were accomplished by researchers and laboratories. In addition, one disadvantage of using RF-based tracking methods is that a number of RF modules would need to be pre-installed in the environment.

2.1.3. Haptic and force feedback

Haptic and force feedback have been considered in AR applications to enhance the immersive and interactive sensation for the user. Researchers have applied wearable datagloves for mobile applications and for desktop operations, such as in assembly, design, etc. Valentini [164] focused on the interaction mechanism using a dataglove during virtual assembly in an AR environment. The research focused on the grasping and manipulation of virtual assembly components based on the identification of three typical manipulation gestures. Haptic devices have also been applied for path planning of a virtual robot [26]. Table 4 lists several haptic devices in the market.

2.2. Software systems

The essential components of AR include combining of real and virtual objects, registration in 3D and real-time interaction [8]. In the past years, various algorithms and systems have been developed to address tracking and registration issues in AR. Based on these algorithms, several well-known AR software platforms have been developed to facilitate the development of various specific AR applications.

Tracking and registration is the basic enabling technology of AR. Without accurate tracking and registration, the virtual and real objects cannot be merged seamlessly. Various sensors have been used to track the head of the users so as to calculate their viewpoints, which is crucial to support static and dynamic registration. These sensors have been introduced in Section 2.1. In this section, CV-based tracking and registration will be focused

Table 3
Summary of tracking products in the market.

Manufacturer – product model	Methodology	Pros	Cons
Ascension – driveBay	Magnetic	• Miniaturized passive sensor • 6DOF movement tracking • No inertial tracking, no distortion caused by metals	• Limited tracking area (up to 78 cm)
InterSense – InertiaCube BT and Wireless InertialCube3	Inertial	• Small in size • Wireless data connection Un-restricted user movement	• Only tracks 3DOF movement (yaw, pitch, roll)
Xsens MTx	Inertial	Small in size • Drift-free orientation data Provides kinematic data	• Only 3DOF orientation data (yaw, pitch, roll) is ready for use Needs serial port connection
InterSense – IS-900	Inertial + ultrasonic	• Handle-shape design for easy manipulation • 6DOF user movement tracking (X, Y, Z, yaw, pitch, roll)	• Restricted tracking area depending on the installation of ultrasonic transmitter • Needs RS-232 or Ethernet connection
InterSense – IS-1200	Inertial + optical	• Small in size • 6DOF user movement tracking (X, Y, Z, yaw, pitch, roll)	• Needs to install markers in the environment • Needs USB or RS-232 connection for the camera embedded

Table 4
Summary of haptic devices in the market.

Company – product model	Type	Pros	Cons
CyberGlove – CyberTouch	Vibro-tactile actuators	• Actuators on each finger and the palm to provide tactile feedback • Flex sensors to provide real-time joint-angle data Wearable and light in weight Wireless connection	• Expensive • Only tracks finger flexing motion; no hand movement data
CyberGlove – CyberGrasp	Exoskeleton	• Adds on to CyberGlove to provide force feedback to each finger • Lightweight	
Sensable – PHANTOM OMNI		• To touch and manipulate virtual objects using the handler • Provide force feedback • Small in size and lightweight	• Need firewire connection

on as these tracking methods analyse the images captured by a video camera to estimate the camera pose. The existing tracking and registration algorithms in AR systems can be roughly classified into marker-based tracking, natural feature-based tracking and model-based tracking.

Fiducial markers have been widely used in AR applications. These markers have geometric features or unique patterns which make them easy to be detected and identified in a video stream. Marker-based tracking provides a robust and stable solution for the prepared environment. Based on feature detection and pattern matching, different markers can be recognized and camera pose can be estimated. ARToolKit [7,70] is the most well-known tracking library in this field. In this platform, square markers with asymmetric patterns are designed and detected to augment virtual objects seamlessly. It is an open-source and free platform and numerous ARToolKit-based applications have been developed, such as the assembly [108,113], design [143], robot programming [29,106], CNC machining [182,183], education [14], etc. Integrating ARToolKit library with the powerful OpenSceneGraph advanced graphics libraries, osgART [111] has been developed to support marker tracking and AR rendering. In addition, various libraries based on ARToolKit have been developed considering various programming platforms. FLARToolKit [47] has been designed to develop web-based AR applications. FLARManager has been developed to support the building of AR application for Flash. SLARToolKit [152] is a library to support the development of AR applications with Silverlight.

ARTag [25] is an open source platform developed several years after ARToolKit. ARTag uses more complex image processing and digital symbol processing methods. ARTag outperforms ARToolKit in stability and resistance to illumination changes. In ARTag, 2D barcode markers are implemented, such that there is no need to train any markers or load any pattern files. ARMES [5] is a commercialized marker tracker SDK that is based on unique circular markers.

Natural feature tracking can enhance the tracking stability and extend the tracking range. With natural feature tracking, AR applications can be developed for the unprepared environment. Most current natural feature tracking methods are based on the robust point matching approach. Various feature descriptors, such as Binary Robust Independent Elementary Features (BRIEF), ferns features, Scale Invariant Feature Transform (SIFT) features, Speeded Up Robust Features (SURF), etc., have been explored to facilitate feature detecting and matching.

Parallel Tracking and Mapping (PTAM) [76] is a notable platform for estimating camera pose in an unknown scene. Through the methods of processing the two tasks, namely, tracking and mapping, in parallel threads and keyframe-based mapping, detailed maps of the unknown environment can be reconstructed with many landmarks. With the detailed maps, virtual objects can be registered onto the real world. This platform only supports the tracking of static and limited environments. Parallel Tracking and Multiple Mapping (PTAMM) [24] was developed as an extension of PTAM. PTAMM is able to use multiple independent cameras and create multiple maps in which different applications can be created in individual maps. In this platform, the cameras can switch automatically between maps by comparing the descriptors between the keyframes and the camera image. With this scheme, PTAMM supports the exploring of large environment with multiple mapped workspaces.

ARToolKitNFT is another C/C++ software library that supports natural feature tracking with which virtual objects can be augmented onto textured surfaces. It is compatible with the ARToolKit library. BazAR [82] is a library that supports feature points detection and matching based on computer vision. In this library, a keypoint-based approach has been developed. The authors formulated the wide-baseline matching of keypoints between the camera images and those in the model images as a classification problem to shorten the on-line computing time significantly. In this approach, issues such as large perspective and scale variations have also been addressed with a simple and fast keypoint detector.

Instead of using fiducial markers, model-based tracking matches the detected features with the natural features available from pre-created models, such as appearance, texture, motion, etc. Open Tracking Library (OpenTL) [114] is a model-based tracking library that provides user-friendly APIs and handles multiple objects tracking. This library uses the multi-threading method and GPU-based computing to achieve real-time performance. It is not specifically developed for AR applications, but for general purpose model-based object tracking.

With powerful computing capability and ubiquitous properties, AR applications based on handheld devices have attracted increasing attention in recent years. NyARToolkit [103] is an optimized version of ARToolKit library that supports multiple programming languages and operating platforms. It can also be used to develop AR applications on Android handheld devices. Android ARToolkit (AndAR) [3] is a Java-based software library and supports the development of AR applications on the Android platform. There is also a version of ARToolkit for iOS for supporting the development of AR applications on Apple's iOS platform. Layar [79] is a mobile platform to display digital information of the environment in the vicinity of the user. Different versions of Layar are provided for Android, Symbian and iOS platforms. Qualcomm Augmented Reality (QCAR) [122] SDK supports the development of AR applications on Android 2.1, 2.2 and 2.3 devices. Three kinds of objects can be tracked in this library, namely, image targets, multi targets and frame markers. Image targets are texture images with good contrast. Up to five image targets can be tracked simultaneously. Multi targets refer to objects with multiple image targets and targets have fixed spatial relationship. Other image targets can be detected based on the relationship if one of the targets is detected. A frame marker is a special fiducial marker with a unique ID encoded into a binary pattern along the border of the marker image. Any image can be placed in the center area of marker. With this design, the markers look more natural.

3. Major AR research in design and manufacturing

Manufacturing is one of the most promising fields where AR can be used to improve the current techniques and provide solutions in the future [107]. With new advances in computer and manufacturing technologies, there is a growing trend of allowing users to interact directly with the manufacturing information associated with the manufacturing processes. AR has the ability to integrate these modalities in real time into the real working environment, which is useful for manufacturing activities, particularly assembly, training, and maintenance. It can provide the user with an intuitive way to interact directly with information in manufacturing processes. It also allows the operators to use their natural spatial processing abilities to obtain a sense of presence in the real world with virtual information. Many researchers in the manufacturing industries, academic institutes and universities have started exploring the use of AR technology in addressing some complex problems in manufacturing.

3.1. VR and AR research in design

3.1.1. VR-based design

Before addressing AR in product design, it is useful to mention the role of virtual reality (VR) in design. Many VR approaches have been used in creating product design. They provide very intuitive interaction with the designers in terms of visualization and the interfacing with downstream processes.

Stark et al. [153], Wiese et al. [171] and Israel et al. [67] developed a hybrid immersive modelling environment by merging desktop-CAD with VR technologies at IPK, TU Berlin and Berlin University of Arts. They noted that the current modelling media are that of papers and CAD systems. Although they are complementary to some extent, there is still the lack of fluid and intuitive interaction. On the other hand, digital media has the advantage of allowing a direct integration of a developed product model with the capturing of dimensions and other associated properties. In addition, some downstream processes, such as planning and fabrication can be integrated. Fig. 1 shows a student sketching a wine bar as part of a design activity. Fig. 2 shows the transformation of a sketch of a ceiling lamp to a final product using rapid prototyping. The schematics of the online integration of a CAD system with a VR-based sketching tool is shown in Fig. 3.

Perkunder et al. [119] addressed a similar problem by considering automatic shape creation using sketches as input to an immersive CAD environment in the early phases of product design. FiberMesh and ImmersiveFiberMesh, which are desktop systems for freeform modelling, were adopted. FiberMesh creates and changes a 3D model from 2D input strokes interactively.

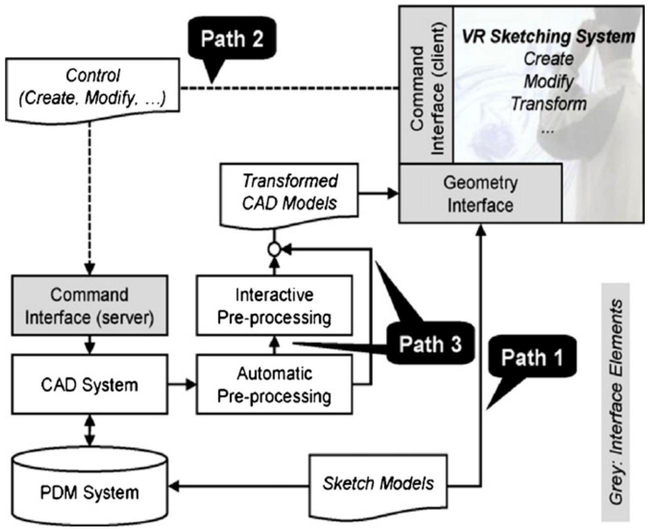

Fig. 3. Schematics of CAD and VR sketch tool [153].

3.1.2. AR-based design

A few AR applications in design and other areas are shown in Fig. 4. AR-based systems support information visualization through augmenting virtual objects onto the real world. As far as product design is concerned, AR is becoming a major part of the prototyping process. For example, in the automotive industry, AR has been used for assessing interior design by overlaying different car interiors, which are usually only available as 3D-models in the initial phases of development, on real car body mock-ups [50]. However, only a few systems support product creation and modification in an AR-based environment using 2D or 3D interaction tools. In Construct3D [71], which is developed for mathematics and geometry education, constructions of primitives can be created and displayed in a 3D space, as shown in Fig. 5. However, complex parts combining these primitives cannot be created as this system does not support modelling functions.

Park [116] presented an AR-based re-formable mock-up system for design evaluation, where interactive modification of shapes as well as colours, textures, and user interfaces can be carried out, in tangible design evaluation. Physical mockups of handheld Portable

Fig. 1. Student sketching a wine bar [153].

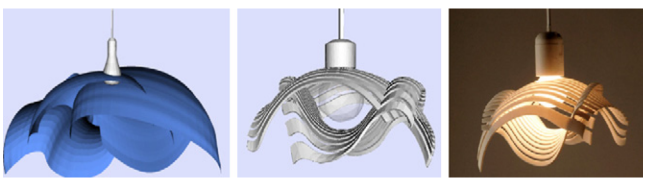

Fig. 2. Example of a ceiling lamp from sketch (left) to the refined model (middle) and the final prototype (right) [153].

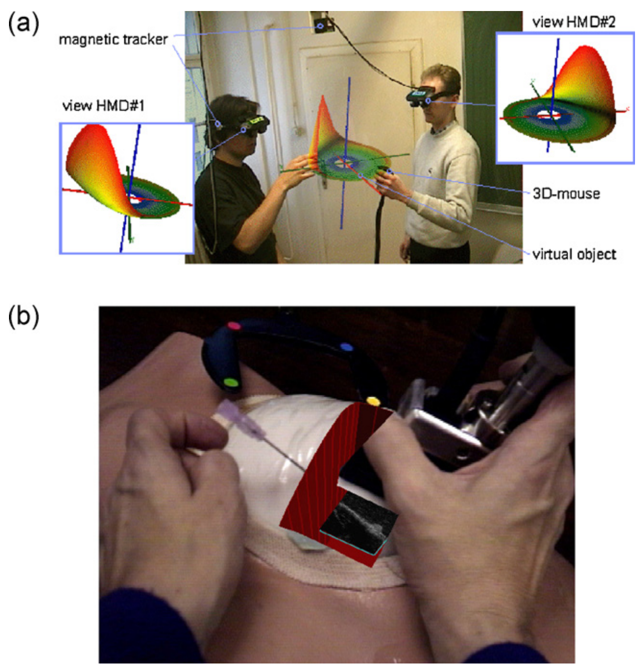

Fig. 4. AR application areas: (a) scientific visualization [138] and (b) medicine [154].

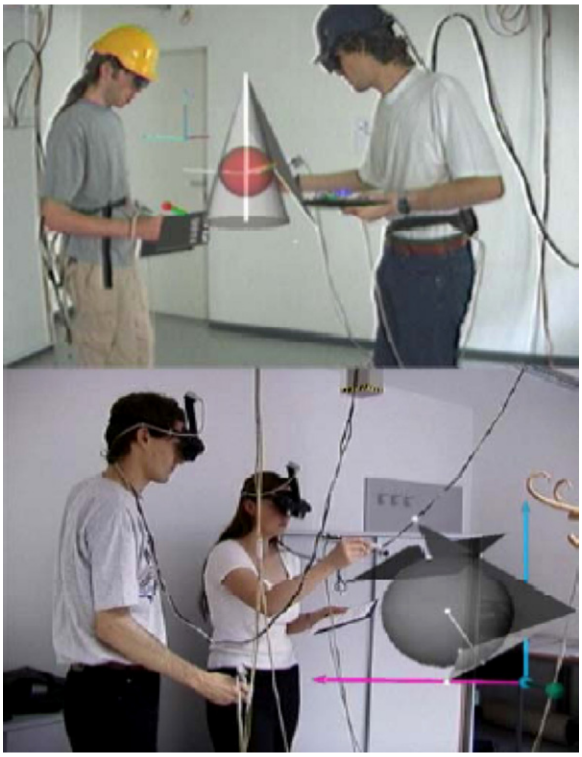

Fig. 5. Working in Construct3D [71].

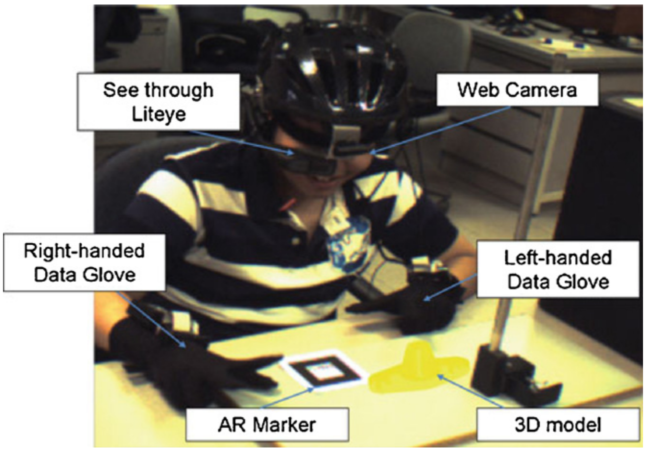

Fig. 7. GARDE setup [102].

Media Players were used and through the use of AR, the users could experiment with changing characteristics of the product such as their colour and even use their interfaces (e.g., small touch screens). In addition, the users could decide on a design model that they wanted to evaluate and construct the mock-up by assembling body parts. Skin region overlay was used to exclude the additional visual information from the presented images and eliminate the overlaying of added images, e.g., from the user's fingers. On the other hand, everyday objects were used in the research by Ng et al. [101] to facilitate interactive design. An AR computer-aided design environment (ARCADE) has been developed to facilitate interactive design for a layman [101] (Fig. 6), where the users can create new designs through modifying and combining both virtual and real objects. The user can generate and modify solid models using marker-based interaction methods. This approach of design generation allows the users to create designs, and visualize and contextualize them in a real design space. Solid models can be generated from everyday objects for the user to modify and to combine with other models.

Ng et al. [102] presented a gesture-based AR design environment, GARDE (Fig. 7). Using gestures, the designer can visualize a 3D model in an AR environment, evaluate the design and make modifications, which will be reflected in the model and also in a conventional CAD software application in real time. This allows the user to contextualize the design in the working environment and make use of the spatial information of the real environment in modifying the design. GARDE can be considered as a form of augmented prototype and it enjoys the benefits of both physical prototypes and virtual prototypes, such as realism, ease of modification and contextualization.

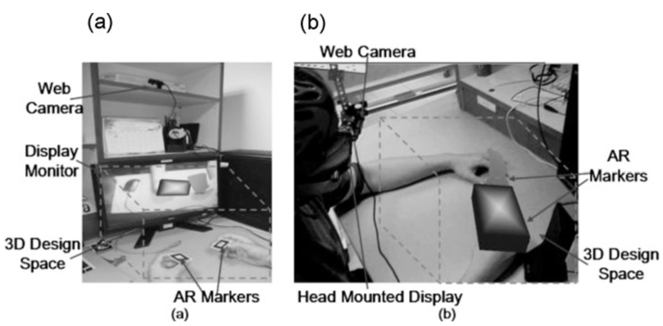

Fig. 6. (a) Desktop setup, and (b) HMD setup for ARCADE [101].

3.1.2.1. AR-based collaborative and distributed design systems. With virtual information augmented onto a real scene, AR can improve a user's perception of the real world and facilitate the human computer interactions. AR-assisted single-user systems have been reported to facilitate design tasks [108,113,143]. In this section, several existing collaborative VR/AR systems are reported.

In collaborative VR/AR systems, the 3D models that are displayed to each user in a collaborative design session have to be consistent. Some of the co-located systems [75,126,127,155] have been designed to share the same central database. In some collaborative systems [130,138], the virtual models displayed are kept consistent by propagating the modifications through Internet communication. In the integrated VR framework presented by Alexopoulos et al. [2], the users participating in a collaboration session can view and modify the attributes of the geometrical model, while any design changes are distributed in real-time to the models viewed by all the participating users.

AR-based collaborative design systems can be further divided into two classes, i.e., visualization-based design systems and co-design systems. Visualization-based design systems have been used to provide an AR-based environment to the designers, in which the designers can visualize, annotate and inspect the 3D products collaboratively. In co-design systems, the designers can create and modify 3D models collaboratively in a 3D space.

3.1.2.2. Visualization-based AR collaborative design systems. Most of the existing AR-based collaborative systems are visualization-based design systems. In these systems, the virtual information and virtual product models are augmented and displayed to the designers to facilitate the decision-making process. Besides the virtual product models, certain information regarding the virtual objects, such as shadows [130], predefined symbols [75], meta-data [18], design information and annotations [69], is also augmented and displayed to facilitate the decision-making process in these collaborative systems.

In TransVision [130], the shadows of the virtual objects act as effective visual hints and allow the designers to perceive their positions and sizes with ease. Some abstract information, such as the stresses and loading of a part, can be augmented and taken into account in the Virtual Round Table [18] system. In SeamlessDesign [75], geometric constraints defined between the primitives of the virtual objects are displayed using predefined symbols to facilitate the users' understanding of the design. It is found that although the shadows and predefined symbols can be used to render the abstract information, textual information is still the main format.

Annotations are used in collaborative systems to provide product information as clear virtual labels linked to the virtual/real objects. In Studierstube [138], annotations are created using the Personal Interaction Panel, which is a physical representation of pen-and-panel with an augmented virtual interface. In MagicMeeting [126,127], the virtual objects in a scene can be annotated with different colours using real annotating cards to facilitate discussion. The annotating colour, the person attaching the annotations and the virtual model itself will be recorded in a central database. However, annotation using colours would limit the annotating content to be predefined, as only certain information that is understood by all the users can be expressed in one colour. In IMPROVE [136], annotations were created using a tablet PC and pasted onto an object as notes. In this system, annotations are used as a command input. Jung et al. [69] have developed an annotation system to allow collaborating designers to attach text annotations on the surfaces of a 3D model and draw on plane surfaces in a 3D environment. They aimed to communicate design decisions through annotations. However, the system works in an asynchronous discussion mode. These AR-based collaborative systems are co-location setups in which the users are in the same room. In face-to-face communications, gaze and gestures can focus the collaborators' attention and facilitate the discussion. It is also quite easy for the users to know the activities of the other collaborators.

In distributed systems [1,13,133], various non-verbal channels developed using the AR technology have been explored to make the local user aware of the presence of the other users.

In the system developed by the European Computer-Industry Research Center (ECRC) [1], distributed AR for collaborative design is supported for furniture positioning in a room. This distributed application environment is based on the Facile distributed language. Facile is an experimental concurrent functional programming language developed at ECRC [162] that allows distributed application issues, such as concurrency and communication, to be addressed separately from the rest of the application. In this system, modifications made to the model representations in one view can be propagated to the other connected views. For a local user of the system, the selected furniture is rendered with a bounding box to provide feedback of the manipulation and the remote updates would cause the furniture to "self move", which in essence, is moved by the remote user. At the end of a collaboration session, the furniture selection can be recorded and used to fill out an order form. In the system developed by Billinghurst and Kato [13], AR is used to support remote collaboration, and provide gaze and non-verbal communication cues. In this system, the FOV of the remote user is augmented with the real workspace of the local user, and the augmentation appears as a live virtual video window attached to a real card. No further information besides the remote users' appearance is displayed to the local user in this system. In the projector-based collaborative design system developed by Sakong and Nam [133], synchronized turntables and virtual shadows were used to provide cues for the awareness of other users. The synchronized turntables allow the users to visualize the manipulations of the virtual objects by the other users. The virtual shadows can enhance the communication between the users by providing the locations and gestures of the other users. However, the shadows cannot locate the vertical position and can only provide an approximate pointing direction. Therefore, it is not easy for the user to pick a specific feature of a complex model. A collaborative design environment including VR and AR-based visualization functionality has been suggested by Chryssolouris et al. [32]. In a case study of the textile industry, 3D models of carpets were seamlessly integrated in the digital view of the real world through the use of marker tracking, which detects the paper marker in the image and uses it as a reference to place the virtual model data in the correct perspective.

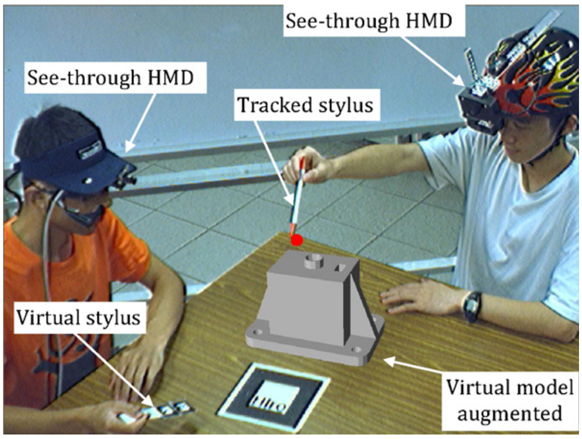

Fig. 8. The working scenario of the co-located users [109].

Fig. 8 shows a system developed at NUS [109,142,143]. In this system, each user wears a HMD with an IEEE1394 camera mounted on his/her head. The users can freely walk around in order to observe the augmented environment from different perspectives. The users can be in the same room or distributed at different locations. A real scene in the current context is the working environment of a designer. A designer may have a real product in hand, together with his tools, such as machining cutters, measurement and inspection gages, etc., and these form part of the real scene. Other members of the design team also form part of the real scene. The system framework is shown in Fig. 9. The main components of this system are (1) Clients representing the views of the users, e.g., designers, machinists, etc., in a product life cycle; (2) A server for product modelling, collaboration management and constraints management; (3) Interaction techniques to manipulate the virtual product models and features in the views of the clients; and (4) An embedded modelling kernel for solid modelling and geometric information extraction to support precise product modelling and modification in the AR environment.

One advantage of this system over existing VR/AR modelling systems is the use of the AR technology, where modifications made to a part design can be displayed dynamically before the CAD model is updated. With 3D model visualization, users can

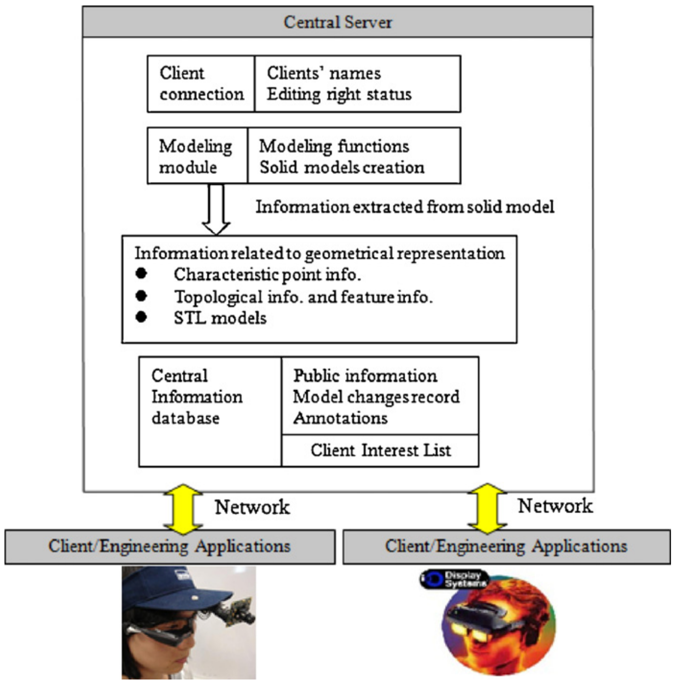

Fig. 9. System framework [142].

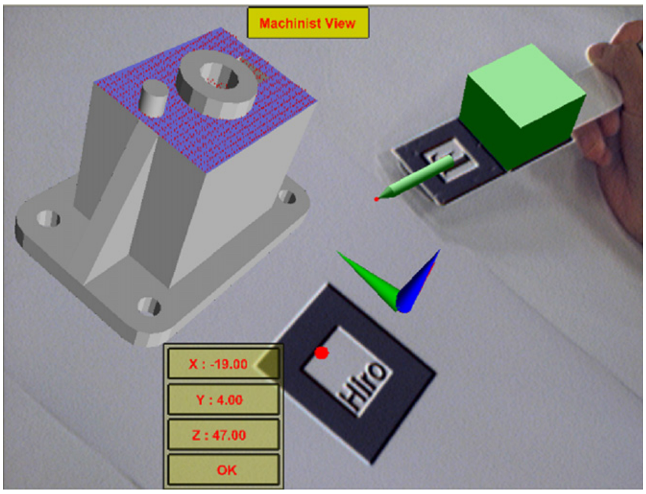

Fig. 10. Feature adding process [142].

determine easily whether the updated display is what they desire. The CAD model will only be updated using the modelling module in the server after the user is fully satisfied with the modification. This can reduce the amount of information exchange between the editing client and the server. It can also reduce the amount of modelling operations on the server side. Currently, the system supports modelling display in near real-time.

Using this system, a new extrusion feature that is being added to a part can be classified into two types, i.e., additive feature or subtractive feature. When creating an additive feature, the user defines a primitive feature from the system's feature library with the required parameters, and it will be created at the correct position and displayed in the 3D space, as shown in Fig. 10, where a cylinder with the user-defined radius and height is displayed at coordinates (−19, 4, 47). Using the hardware Z-buffer, the depths of the pixels of the features are obtained and compared. For the pixels at the same screen position, OpenGL only displays the pixel with the smallest depth value. Therefore, the feature created and the existing features can be displayed correctly when the user changes his viewpoint.

3.2. AR in robotics

VR has been proven to be useful in medical robots for surgeries [19], tele-robotics [48], etc. Liu et al. [89] developed an off-line feature mapping algorithm for arc-welding robots that aims to achieve welding tasks efficiently in the cases when the workpieces or fixtures are redesigned or the robot workstation layout has been changed. Chen et al. [26] modelled a six-DOF virtual robot arm driven by the PHANToM joint based on the structural similarity between the PHANToM haptic device and a six-DOF articulated robot arm. They proposed a workspace mapping method based on robot kinematics analysis to enable the virtual robot arm to interact haptically with virtual prototypes in a virtual environment. The haptic-based virtual robot arm is used in interactive modelling in free path planning and constraint based assembly path planning operations in the virtual assembly system. In both planning processes, the user can edit an assembly path interactively with the guiding forces as feedback. The proposed haptic-based virtual robot arm provides a new Human Computer Interaction (HCI) method for VR-based robot path planning and virtual assembly systems. However, the main constraint in VR-based robot programming is the need to construct the entire Virtual Environment (VE), and this requires full *a priori* knowledge of the workpieces, working area and thus more computational resources. This is not suitable for semi-structured or loosely structured working conditions.

In robotics, AR has been applied in various applications as shown in Table 5. AR application in these robotic systems offers the

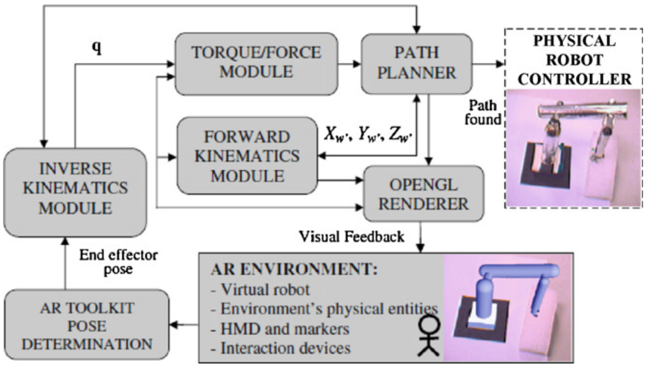

Fig. 11. RPAR system architecture [106].

users visual aids through augmenting illustrative and informative elements over the real workspace via a video stream. An AR cueing method was reported by Nawab et al. [99] and Chintamani et al. [28] to assist the users in navigating the end-effector (EE) of a real robot using two joysticks. The visual cues, which associate the orientation and translation of the end-effector with the movement of the joysticks, allow the users to navigate the robot in a tele-operation task intuitively under display-control misalignment conditions. These studies showed positive effects of using AR on operator performance in ad hoc tele-robotic tasks.

Some studies have reported the use of AR in robotic systems to address human–robot interaction and robot programming issues. Equipped with proper interaction tools, operators can interact intuitively with the spatial information during the robot programming process. The use of virtual robot models enables the operators to program the robot by guiding the virtual models without having to interact physically with the real robot manipulators. Zaeh and Vogl [179] introduced a laser-projection-based approach where the operators can manually edit and modify the planned paths projected over the real workpiece through an interactive stylus. Reinhart et al. [128] adopted a similar human–robot interface in robotic remote laser welding applications. In this system, the production cycle efficiency for the welding process is significantly improved with reduced set up and programming time. Chong et al. [29] and Ong et al. [106] presented a methodology to plan a collision-free path through guiding a virtual robot using a probe attached with a planar marker and developed the RPAR (Robot Programming using Augmented Reality) system. The methodology is interactive as the human is involved in obtaining the 3D data points of the desired curve to be followed through performing a number of demonstrations, defining the free space relevant to the task, and planning the orientations of the end-effector along the curve (Fig. 11). A piecewise linear parameterization algorithm is used to parameterize the data points using an interactively generated piecewise linear approximation of the desired curve. A curve learning method based on Bayesian neural networks and reparameterization is used to learn and generate 3D parametric curves from the parameterized data points. Only a small number of good demonstrations (3–5) are required to achieve good performance (this is also dependent on the sampling rate). Fig. 12 shows the RPAR system planning the orientation of the end-effector and a successful collision-free geometric path.

The application of AR also provides the operators with various simulation options in robotic planning [17]. The simulations are mainly conducted to test whether the planned path(s) are reachable and collision-free without considering the motion constraints (e.g., joint velocity and joint acceleration).

3.2.1. RPAR-II AR environment

The setup of the RPAR-II system [41,42] is shown in Fig. 13. It includes a SCORBOT-ER VII manipulator, an electrical gripper, a robot controller, a desktop-PC, a desktop-based display, a stereo camera, and an interaction device attached with a marker-cube.

Table 5
Major AR research in robotics and tele-robotics.

Groups/projects	Institutes	Area	Methodology/feature
Ergonomics in Tele-operation & Control Laboratory [123]	University of Toronto (Canada)	Industrial robot	(1) Stereo-vision method (2) Human-tele-robotic interaction (3) Virtual tape-measure (4) Stereoscopic graphics and video
Centre for Medical Robotics and Computer Assisted Surgery [147–149]	Carnegie Mellon University (USA)	Medical/surgical robot	(1) Marker-based tracking method (6-DOF) (2) Intra-operative collection of tracking data in image-free systems (3) Shape-based registration (4) Patient-specific 3D template method
da Vinci Surgical System [58,63,161]	Intuitive Surgical Inc. (USA)	Medical/surgical robot	(1) Master-slave system (2) Optical 3D location sensation and digital video processing (3) Calibration/registration using optical marker
Robotics Intelligence Lab [93,173]	Jaume I University, Castellón (Spain)	Net-robotics (educational robot)	(1) Web-based system controlling online robot (2) Predictive display using AR (3) AR assistance on robot programming and monitoring (4) Remote programming (5) Multi-users management (6) Distributed architecture
Inami Laboratory and Tachi laboratory [146,157,158]	The University of Electro-communications; University of Tokyo (Japan)	Medical/surgery robot;	(1) Real-time sensing (2) Haptic display (3) Synchronized interaction (4) Retro-reflective projection for tele-communication with robot (5) Projector-based tracking system
Anthropomorphic Robot Assistants Project (MORPHA) [15–17]	KUKA Robot Group (Germany)	Industrial robot (welding, painting, assembly, etc.)	(1) Monitor-based visualization with various simulation options (2) Optical tracking (with marker) and mechanical tracking (without marker) (3) Occlusion model (4) KUKA AR viewer (5) Instantaneous/real-time visual feedback
Augmented reality in assembly planning ([128,179]	German research Foundation; Technical University Munich (Germany)	Industrial robot	(1) Laser projection and VST-visualization (2) Tracking with retro-reflective markers (3) Pen-like input and interaction tool (4) Trajectories planning and editing
AVILUS [84]	Federal Ministry for Education and Research (BMBF)	Industrial robot (heavy industry and SMEs)	(1) Integration of CAD/CAM models in product lifecycle management process (2) Tracking of large measuring volume in the size of a factory (3) Tactile interaction metaphor (4) System ergonomics issues (5) Extension to mobile platforms
SMErobot [62,100]	EU initiative	Industrial robot (SMEs)	(1) Robot programming by everyone (2) Multimodal interaction: e.g., tactile, verbal, visual (3) Speech interaction: better signal to noise ratio (4) PDA integrated with KUKA Teach Wand (5) Touch screen based programming

The augmented environment consists of the physical entities that exist in the robot operation space, e.g., the manipulator, workpieces, etc., and a virtual robot model which includes the virtual EE to replicate the real robot.

A virtual SCORBOT-ER VII manipulator is modelled in SolidWorks®, where the geometries of the coupled joints and links are modelled separately according to the kinematic parameters of the manipulator. The links are built with both functional and geometric features to enhance the visualization effects. The virtual robot model can be assembled and augmented onto the real environment. In addition, it can be scaled up or down for different robot configurations.

3.2.2. RPAR-II system architecture

Fang et al. [41,42] 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 (Fig. 14), a collision-free geometric path can be generated

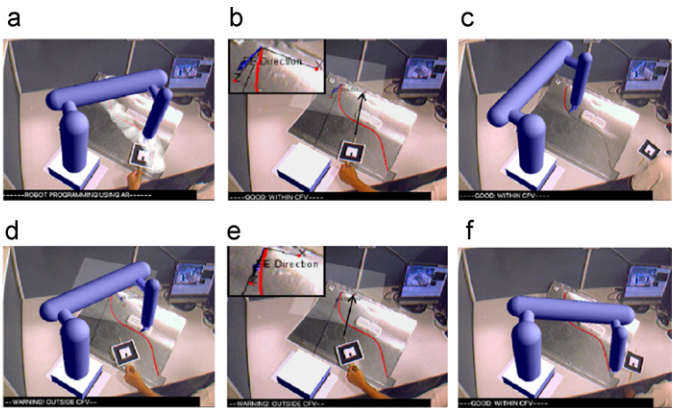

Fig. 12. Planning the orientation of the end-effector and a successful collision-free geometric path [106].

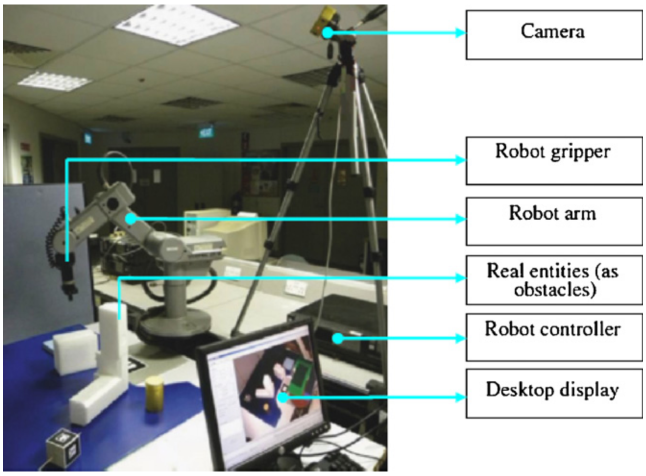

Fig. 13. Physical layout of the experimental set-up [42].

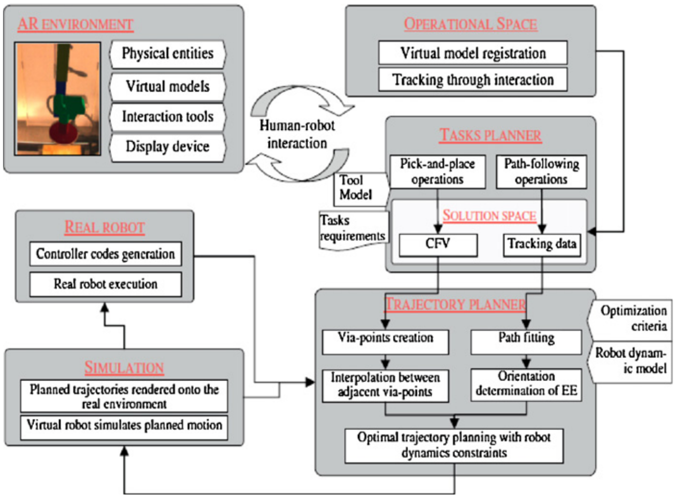

Fig. 14. Architecture of the RPAR-II system [42].

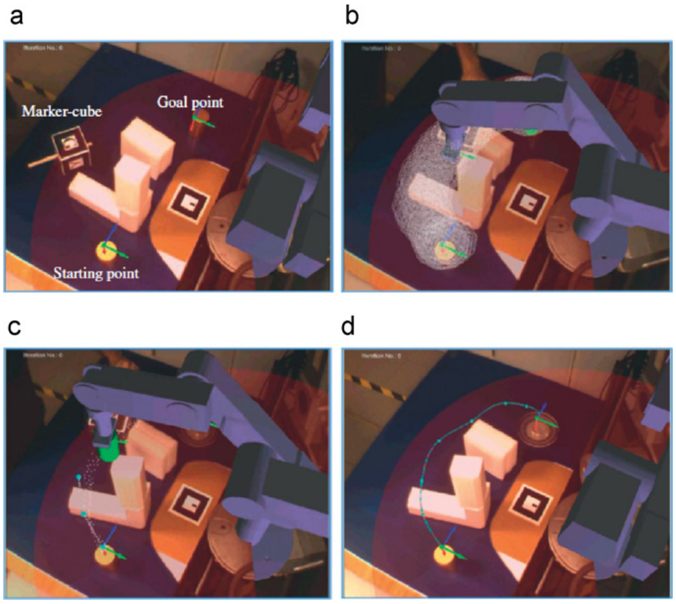

Fig. 15. Geometric path planning in the RPAR-II system [42].

through human–virtual robot interaction in a real working environment for a pick-and-place task, as illustrated in Fig. 15. Fig. 15(a) is the setup for a robotic task, which is to transfer an object from a start point to a goal point. The foams represent the obstacles. With the start point and goal point known *a priori*, after generating a collision-free volume (CFV) in the workspace (Fig. 15(b)), the user proceeds to create a series of control points within the collision-free volume using the interaction device (Fig. 15(c)). Using these points as inputs, a cubic–spline interpolation is applied to generate a smooth path automatically (Fig. 15(d)). In this example, a total of six control points (excluding the start point and goal point) are created, and each is assigned an unequal (normalized) spaced time stamp, such that a path with smooth curvature distribution can be finally achieved.

3.3. Factory layout planning (FLP) systems

Before the emergence of AR-based systems, VR simulation systems have been applied widely for solving FLP tasks. In fact, VR Factory Layout Simulation (FLS) is currently one of the most well received tools for FLP. These systems are often known as plant simulation or manufacturing simulation software. As shown in Fig. 16, commercial products, such as the Tecnomatix Factory FLS by Siemens [160], Teamcenter Manufacturing Plant Simulation by UGS [159] and MPDS4 Factory Layout by CAD Shroer [20], have their own market shares.

These VR systems [21,65,180] are quite similar as they provide a visually appealing on-line layout planning platform to the users. As tools designed to simulate the layout plan, these VR FLP systems are used to refine the theoretical results before implementation. The tedious design process, however, cannot be improved with these systems. Moreover, as the entire plant environment is simulated virtually, any deviation from reality will reduce the usefulness of the solutions of these systems. Other shortcomings of the VR FLP systems include time-consuming modelling of the entire factory floor space and all the facilities in detailed 3D. This is not very productive as only specific locations or equipment of interest are required to be studied.

A number of studies on AR-based FLP systems have been reported. These systems allow the users to lay out virtual objects in the real environment, during which human intuitiveness is explored in the immediate evaluation of the resulting layout arrangement. It is an attempt to integrate human intuitiveness with the layout design process. However, as the AR technology had not matured then, many of the reported systems were at the conceptual design stage.

In the “Build-it” system [124], a Tangible User Interface (TUI) was built to perform FLP tasks. With the TUI, when the user moves the bricks, augmented virtual objects projected on the front wall will be moved correspondingly. The interaction between the real and the virtual worlds in the system refers to the manual manipulation of the bricks by the users. This can be regarded as one of the most preliminary AR-assisted space planning tools. Gausemier et al. [51] replaced the bricks with markers and the result can be viewed on a monitor with the use of a web camera. There are other reported systems [37]. Some of these systems are shown in Fig. 17. Although these systems appear to be novel, they basically follow the same concept of the VR FLP systems. As a well-developed field both commercially and academically, current VR FLP systems outperform these AR-assisted systems.

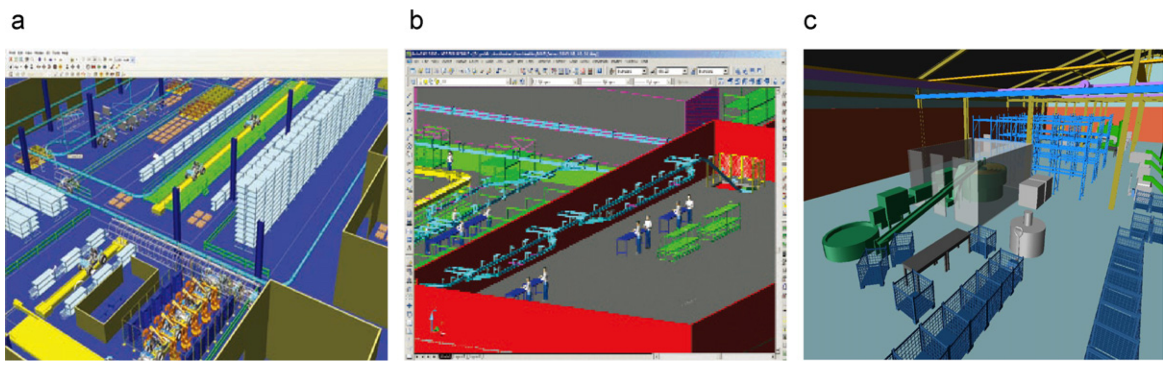

Fig. 16. VR layout simulation software, (a) tecnomatix factory layout simulation [160] (b) teamcenter manufacturing plant simulation [159], (c) MPDS4 factory layout [20].

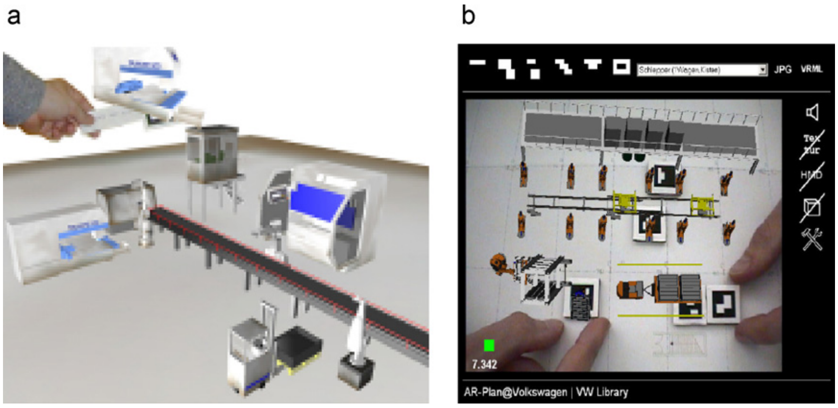

Fig. 17. AR-assisted FLP systems, (a) AR-planning tool [51], (b) ARVIKA [37].

Poh et al. [120] introduced a method to set up physical constraints via markers (Fig. 18). Specifically, their system works in two steps, component identification and layout design. In the first step, components are registered to different markers in a way similar to those that have been reported. In this system, some markers, which have been registered to objects that are to be arranged, are subject to physical constraints. Markers with physical constraints play an important role in acquiring the information of the real world. As shown in Fig. 18, when markers are pasted onto the walls, floors and other possible constraints in the environment, they help to set up an interactive interface between the virtual and real worlds. Many of the evaluation criteria addressed in their work depend heavily on this interactive interface. Electrical losses, fluidic losses and the total cost are related to the distances between the components and the physical constraints. While the attempt to acquire the information from the real environment is of great value, heavy dependence on markers and the cumbersome registration process would make this system impractical in a real industrial environment.

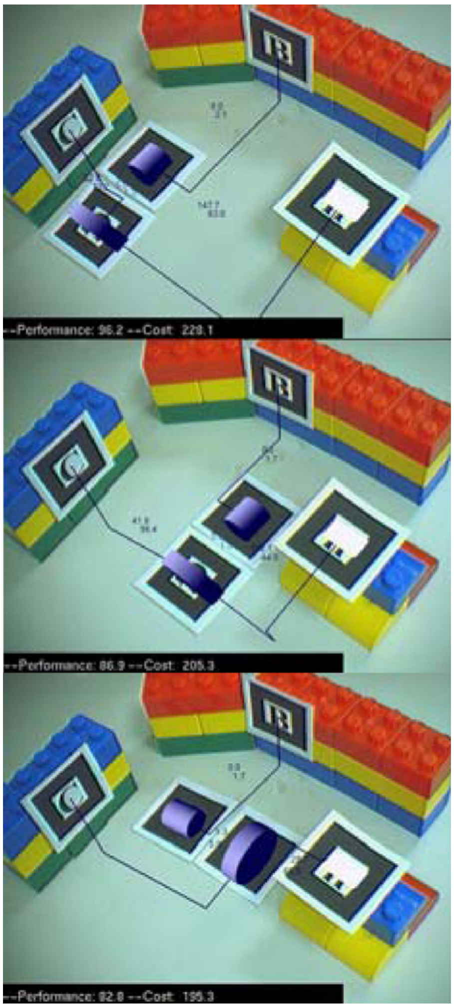

Fig. 18. AR-assisted SLP system [120].

Siltanen et al. [150] developed a system using AR technology for space reservation. In FLP, when new machinery is installed into an existing space, the designer is aided to ensure that there is enough space for the designed machinery. Modelling can be avoided by making visual inspections and even automatic collision detection in AR instead of VR (e.g., desktop based FLP). Furthermore, the authors stated that "AR enables the real time communication between mechanic and designer" allowing the implementation of "last moment changes" in the models. The architecture of a VR-AR based system, which could be used to support the planning process of complex manufacturing systems has been also suggested [34]. The proposed system assists the user in modelling, validation of the simulation model, and subsequent optimization of the production system.

3.4. AR-assisted maintenance systems

Maintenance activities, e.g., preventive and corrective maintenance, are performed according to pre-defined procedures of the maintenance tasks. Maintenance workers need to be trained in the respective procedures, and they sometimes need to seek help from supporting systems and experts when they are on site. The training of maintenance tasks can be achieved using traditional 2D printed materials and VR-based simulation systems [4]. However, VR technologies cannot be applied for maintenance guidance where interactions with real machines are required. AR technology shows merit in the maintenance applications in two aspects. Firstly, user interfaces can be rendered in a ubiquitous manner so that the worker perceives the instructions with less effort. Secondly, user interactions in the AR environment can facilitate maintenance data management and allow remote collaboration to be achieved intuitively. Table 6 summarises a few AR-assisted maintenance systems.

Wang et al. [167] proposed an infrared-marker based AR system for industrial maintenance. The tracking system is comprised of a camera fitted with an infrared filter and infrared markers which are projected onto the scene. Since the markers are infrared and thus, invisible to the naked eye, there is no visual disturbance for the user. One of the presented applications is the maintenance of the gear box of a milling machine. Through AR, gear models are overlaid on the images to indicate the function of the real gear-box, and the actions that the technician must do are presented through animated 3D models. The most noticeable challenge presented by the authors is the jitter when the line of sight of the marker projector is blocked.

Table 6
AR-assisted maintenance systems.

System	Display device	Tracking technologies	Data management		Human–system interaction		User collaboration
			Data retrieval	Data record	Office-based user	On-site user	
KARMAR [44]	HMD	Sensor-based	Knowledge-based	NA	NA	Head motion	NA
Etälä [57]	HMD	Marker-based	Virtual model-based	Virtual model-based	Mouse, keyboard	Mouse, keyboard	Microphone, remote laser pointer
ARVIKA [49]	HMD	Marker-based/ sensor-based/hybrid (marker and sensor-based)	Scenario-oriented/ process-oriented	Scenario-oriented/ process-oriented	Mouse, keyboard	Microphone	Microphone, remote laser pointer
STARMATE [140]	HMD	Marker-based	Scenario-oriented/ process-oriented	NA	NA	Microphone, virtual pointing device (VPD)	NA
AMRA [36]	HHD	Marker-based/hybrid (marker and CAD model-based)	NA	NA	NA	Touch screen	NA
ARTESAS [6]	HMD	CAD model-based	Scenario-oriented/ process-oriented	Scenario-oriented/ process-oriented	Mouse, keyboard	Microphone	Microphone, remote laser pointer
PLAMOS [137]	HHD	Marker-based/WLAN	Scenario -oriented/ Process-oriented	Scenario -oriented/ Process-oriented	NA	Touch screen	NA
ARMAR [59,60]	HMD	Hybrid (marker and sensor-based)	Knowledge-based	NA	NA	Opportunistic control	NA
AROMA-FF [80]	HMD	Marker-based	Scenario-oriented/ process-oriented	NA	NA	Digital camera	NA

Henderson and Feiner [59,60] developed an opportunistic control model and applied it in the development of a TUI for maintenance applications. According to their user study, the opportunistic control-based user interface improves the performance with shortened task completion time. Lee and Rhee [81] developed a ubiquitous car service system using AR technology with three layers for the manipulation of interaction, context and service, respectively. User context, such as the preference profile of the user, was considered. Marker-based tracking and information retrieval from product technical information system was applied in the system. The system was implemented for the scenario of a user who needs to repair his mal-functioning car on the road.

Authoring is an important step in remote collaboration applications as experts need to provide instructions to the maintenance worker. Zhu et al. [187] developed an online authoring tool where online authoring is performed by the experts on still keyframes. Using PTAM as the tracking and registration framework, the highlighted objects in the environment can be tracked so that the authored information can be displayed in consistency with the objects (Fig. 19).

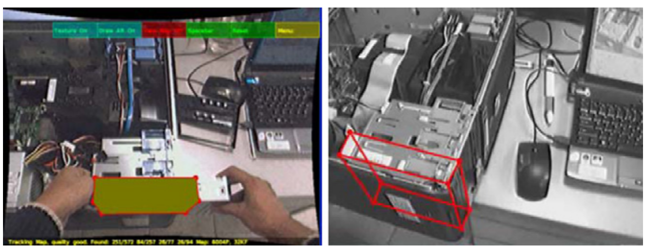

Fig. 19. An AR-assisted remote maintenance system [187].

3.5. AR-based CNC simulation

Researchers have developed methods and algorithms for both geometric and physical simulations, and there are many commercially available 3D graphics-based CNC machining simulation systems, such as DELMIA Virtual NC [35], EASY-ROB NC Simulation [39], hyperMILL by OPEN MIND [64], etc. On the other hand, the ability for humans to analyse machining information and make spontaneous decisions can be complemented using high speed computers equipped with 3D graphics simulation capabilities and instant access to databases. Combining the physical experience of the human operators and a rich knowledge database would constitute a mutually beneficial system. AR technology enables this through rendering virtual information (texts, images, sounds, or even videos) onto a real environment, thus providing a real world supplemented with rich information to the users.

In an AR-based machining simulation environment, the users can retain an awareness of the real CNC machine, while the augmented 2D or 3D information, e.g., cutting parameters, CNC programs, etc., can enhance the users' visual, aural and proprioceptive senses. The advantages of applying AR in these applications are that the user can accumulate knowledge and information when operating on real machines, and the switching of context with the use of computer-based and VR-based simulation systems can be avoided.

Many studies in applying AR technology to the information-intensive and time-consuming tasks in manufacturing have been conducted. Comparatively fewer applications have been developed that apply AR technology in CNC machining. This is probably due to the fact that the processing procedures are machine-centric and fewer human factors are involved during this stage. The ASTOR system [104,105] applies a projection-based AR display mechanism to allow users to visualize machining data that is projected onto a real machining scene. The system first obtains the machining process data and the resultant cutting forces, and displays the information onto a holographic optical element window, which is installed on the sliding door of the lathe. Weinert et al. [169] developed a CNC machining simulation system for 5-axis CNC machines. In the system, ARToolKit-based tracking was applied to track the movement of the cutter with respect to the machine table, and dexel boards were applied to model the workpiece. The simulation module in the system can estimate the cutting forces and predict collision between the head stock and the workpiece.

An AR-assisted *in situ* CNC machining simulation system, namely, the ARCNC system, has been developed [181–183] for machining operations on a 3-axis CNC machine. The system architecture and setup are shown in Fig. 20 and Fig. 21. This AR-assisted *in situ* CNC simulation system consists of three main units, namely, a CNC machine, specifically a 3-axis vertical CNC machine in this research, a display device, and the AR-assisted human-machine interfaces, which include a Firewire CCD camera, and a high-end PC (for image processing, virtual information generating and rendering, CNC simulation, etc.). Either a head-mounted display or a monitor can be used in the *in situ* system as the display device.

To achieve *in situ* CNC simulation, the position of the cutter is registered in the machining coordinate system using a hybrid tracking method and constraints extracted from given NC codes.

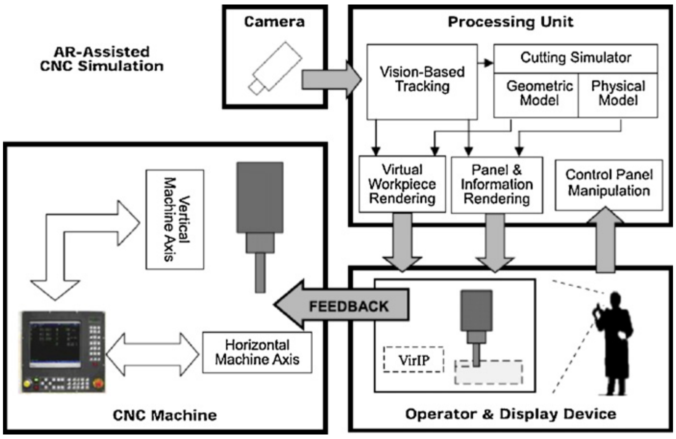

Fig. 20. System architecture of AR-assisted CNC simulation system [181].

Fig. 21. The experiment set-up using a monitor-based configuration [183].

The system is designed to be used by novice machinists, who can use the system to alter NC codes and observe responses from the CNC machine without possible tool breakage and machine breakdowns. According to the simulation results, alarms can be rendered in the augmented display to notify the users of dangers and errors (Fig. 22).

In the ARCNC system, machining simulation is performed between a real cutter and a virtual workpiece and displayed to the users using a video see-through scene rendering mechanism (Fig. 20). Simulations of material removal processes are displayed to the user to assist in the inspection and evaluation of the machining processes before performing real machining, thus reducing material wastage and power consumption. In addition, the user can inspect the physical aspects of the machining processes based on the estimated machining conditions, which are augmented onto the scene, e.g., machining forces, etc. The application of the video see-through technology in the proposed system allows different users to focus on different information and

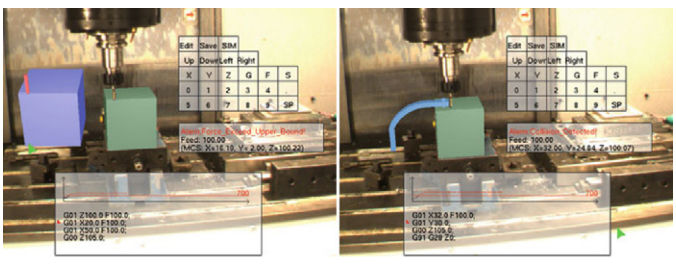

Fig. 22. An *in situ* CNC machining simulation system [183].

tasks, which can be useful during training when several trainees are involved.

During an *in situ* simulation, a virtual cutter is registered with the real cutter in near real time. A virtual workpiece is either rendered onto a worktable or aligned with a fixture on the worktable. Simulation of the machining process can be achieved according to the movements of the virtual cutter and the workpiece (which moves together with the worktable). Both geometric and physical simulations can be performed and displayed. To the operator, it would look like a real cutter machining a virtual workpiece. The operator can interactively observe the simulation as it proceeds, with NC codes, cutter coordinates, and estimated physical cutting conditions provided on a virtual interaction panel (VirIP [176]). Feedback from the operator to the machine tool can be included in the architecture. When certain values in the physical simulation, e.g., cutting forces exceeding certain limits, an alarm can be displayed to the operator, who can respond accordingly, such as pressing an emergency button on the virtual panel to stop the machine tool.

The AR-assisted *in situ* simulation system may perform better than 3D graphics-based simulation systems in several aspects. First of all, the cutting simulation is presented to the operator with a heightened sense of reality, and he can operate the CNC machine and observe the simulation simultaneously. The system can be used with any CNC machine that the operator is familiar with or is trained for. The selection of a machine tool will not affect the simulation procedures as long as initialization is conducted accordingly. For example, the parameters applied in a physical simulation may be different from machine to machine. Thus, calibrations should be performed first and stored in the physical model module. Scene rendering time and effort in this AR-assisted system is reduced as compared to the graphic-based simulation systems, since only a few virtual objects are modelled and updated geometrically and spatially. Furthermore, the movements of the cutter and the worktable are obtained from vision-based tracking and registration. Hence, the simulation can reflect the real dynamic tool movements, rather than an ideal model of the machine in 3D graphic-based simulation systems.

3.6. AR in assembly design and operations planning

Given a set of assembly components, an optimal assembly operations sequence needs to be achieved to reduce the assembly completion time and effort; the assembly operators need to be trained to carry out the manual assembly operations; cues and guidance may need to be provided to the assembly operators during the manual assembly process; and finally the product and components may need to be evaluated and redesigned taking into consideration assembly requirements and constraints.

VR and VP techniques [45,92] have been very popular in simulating and evaluating assembly operations in the early design stages of a product design. Many VR-based virtual assembly systems have been reported so that the human motions can be considered during assembly design and assembly operations planning [141]. VR systems have been developed that can be used in the design of assembly processes from the point of view of ergonomic analysis [94,95,115]. These systems employ real users to perform tasks regarding manual welding or assembly and their movements are ergonomically assessed or their interactions are mapped onto digital mannequins. Even with elaborate VR systems, the assembly planning experience seldom goes beyond a pure VE as there is a lack of real spatial feel and perceivable sensory feedback. A complex assembly process would consume a great amount of computing resources for a near-to-real-life simulation in a pure VE. In addition, intuitive assembly operations cannot be achieved in VR-based assembly planning systems as the planner is not able to have a realistic sensory feedback in handling the parts. As a result, the effort that is needed to handle certain assembly components cannot be estimated and considered as one of the parameters in solving the optimization problem.

The application of AR in augmented assembly (AA) in an augmented environment (AE) can be created where virtual objects are combined with the real environment to enhance the assembly design and planning process. In an AE, physical parts, real feedback and virtual contents are used to analyse the behaviour and properties of planned products, allowing the benefits of both physical and virtual prototyping.

Many AR applications in assembly have been reported, e.g., AR has been applied in manual assembly station planning [129], products assembly guidance in product assembly [132,178], augmenting digital virtual prototypes with physical products [56], data glove-based virtual assembly [164] and replacing physical manuals with augmented virtual contents [170]. Ong et al. [108] and Pang et al. [113] proposed a methodology using AR for assembly product design planning (PDP) and assembly workplace design and planning (WDP) to improve the efficiency and quality of assembly design and planning at the early design stage (Fig. 23). Their methodology is implemented in an AR assembly environment, where engineers can design, evaluate and plan a product assembly and its assembly sequence through manipulating virtual prototypes in a real assembly workplace. In this AR environment, WDP information are fed back to the designers and engineers in real-time to aid them in making better decisions in assembly design and planning. Fig. 24 shows the evaluation of assembly design alternatives using this system. In the application reported by Salonen et al. [134], when the assembly phase is going on, the application displays the part which belongs to that work phase and shows the required action. The parts of the component to be assembled are initially placed in bins and when the work phase starts, the system displays an arrow the bin from which the next part should be taken and animates the 3D model of the part being mounted showing its position on the assembly together with its posture.

Assembly information, such as assembly features, predefined assembly constraints, etc., have to be extracted from CAD data in several reported AA systems. This requirement has limited their applications as time-consuming preparation is needed for each application [110]. There is also rather limited interaction between the users and the systems. In addition, in order that the correct assembly steps and instructions are augmented at the right sequence onto the right components to the assembly operators, the assembly components being handled need to be recognised, mapped to the assembly features in the assembly structures and tracked in order to determine the state of an assembly process. To enhance the interaction between the assembly operators and the AA systems and reduce the need to model and recognize assembly components, sensors, such as RFID, have been coupled with AR to track assembly components so as to determine the state of the assembly in order that the right assembly instructions and steps can be extracted from the assembly structures and augmented to the assembly operators at the correct time onto the correct assembly components. Zhang et al. [184] presented an RFID-assisted assembly guidance system in an AR environment for assembly information management, assembly activity detection, and assembly activity-oriented information rendering, especially the rendering of CAD models in the assembly coordinate system to assist the assembly operators during the assembly process. On the other hand, Yuan et al. [176,178] proposed the use of a Virtual Interaction Panel (VirIP) to enhance the interaction between the assembly operators and the AR-assisted assembly guidance system during the assembly information navigation process. The VirIP is developed based on CV technologies and it can be customized to the types of assembly applications required. The VirIP is an easy-to-use tool that can be used to control AR systems interactively. The VirIP is composed of virtual buttons, which have meaningful assembly information that can be activated by an interaction pen during the assembly process. Fig. 25 shows the use of two VirIPs for assembly operations and motion control.

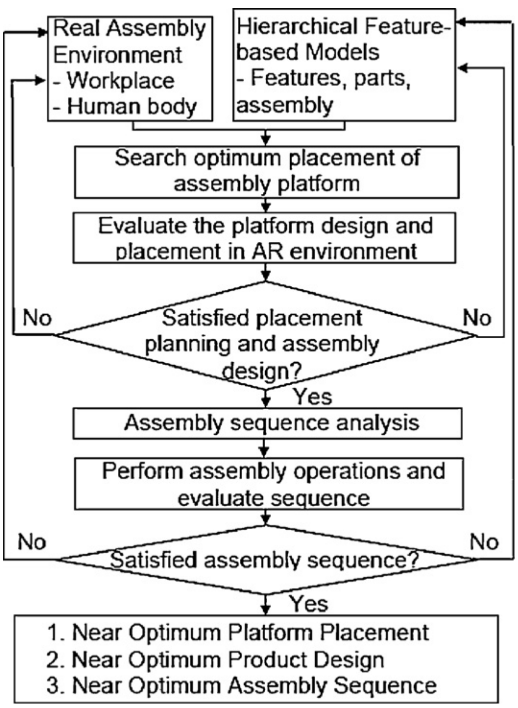

Fig. 23. AR in assembly product design and planning and workplace design and planning [108].

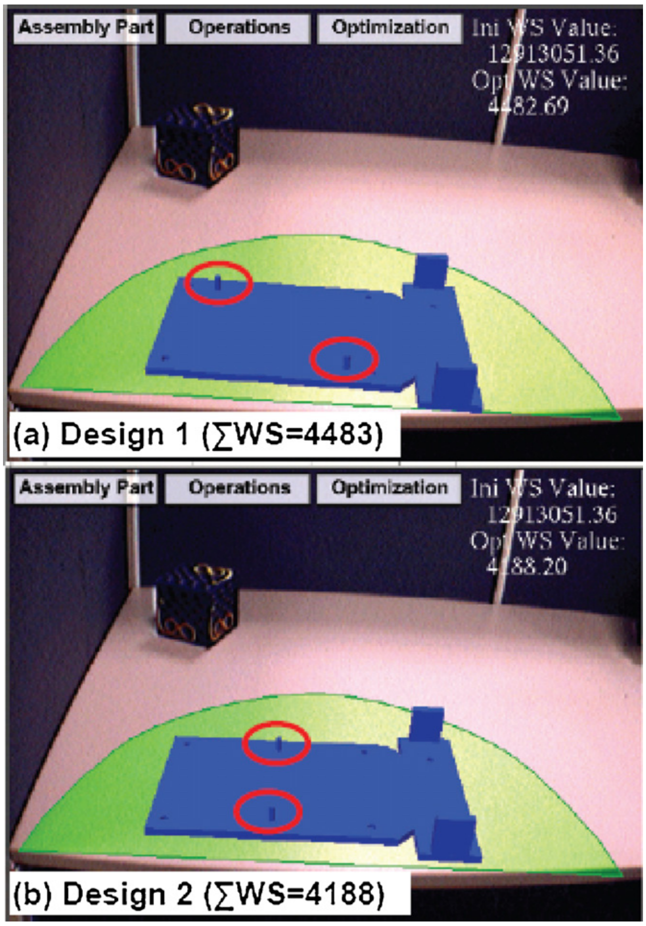

Fig. 24. Evaluating different design alternatives [108].

3.6.1. Bare-hand interaction method in AA

Many tasks in AA systems are manipulative in nature and with high DOFs. This has led to higher dexterity requirement in manipulating the virtual objects using conventional interaction

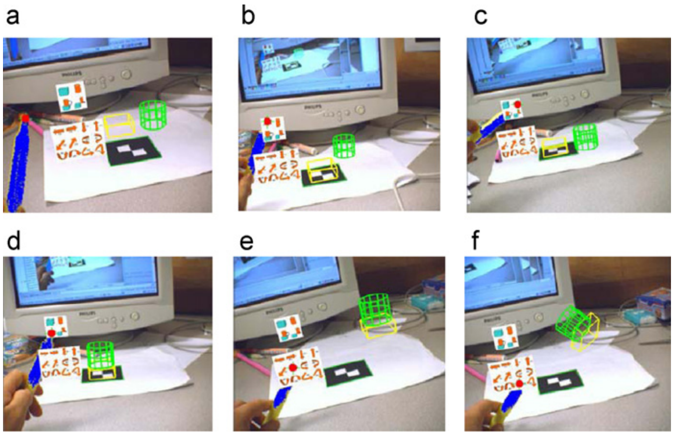

Fig. 25. Examples using two virtual control panels for assembly operations and motion control [176].

tools such as a mouse. In order to achieve high natural and more intuitive HCI, human bare hands can be used as interaction tools in an augmented environment. Bare-hand is less intrusive and more convenient for the users to interact with virtual contents and explore the 3D AEs since using one's hands is most natural. HCI devices, such as data-gloves have been used to capture hand motions in VR/AR applications. Equipped with sensors on the data-gloves, spatial positions of the hands and joint angles of the fingers can be captured quite easily. Data-gloves, however, are often quite uncomfortable and can be rather costly.

CV-based human-hand detection and tracking methods can identify and extract bare-hand gestures from video streams and use them as input commands [77,144].

Ong and Wang [110] presented an AA system which can interpret a user's manual assembly intent, support on-line constraint recognition, and provide a robust 3D bare-hand interaction interface to allow visual feedback during assembly operations (Fig. 26). A 3D natural bare-hand interaction (3DNBHI) method has been developed [110] to implement a dual-hand AA interface for users to manipulate and orientate components, tools and sub-assemblies simultaneously. This allows close replication of real world interactions in an AE, making the user feel that he is assembling the real product, and hence the AA process becomes more realistic and almost comparable to the real process. A tri-layer assembly data structure (TADS) is used for assembly data management in this system. An interactive constraint-based AA using bare-hand has been developed to increase the interaction between the user and the virtual components to realize the active participation of the users in the AA process. Fig. 27 shows the architecture of a bare-hand interaction augmented assembly (BHAA) system.

The users' bare hands are tracked in the 3DNBHI method to extract the hand contours, determine the palm centres and detect the position of the fingertips. The thumb tips and the index fingers of both hands can be differentiated automatically to achieve

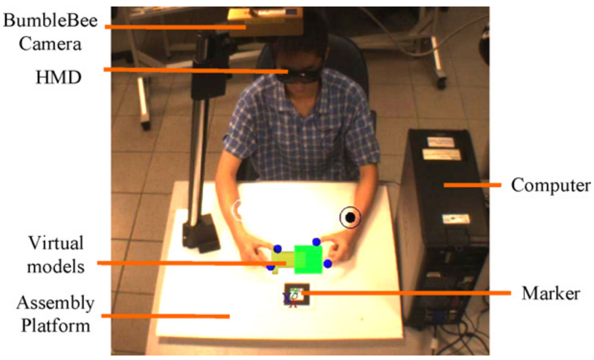

Fig. 26. BHAA system setup [110].

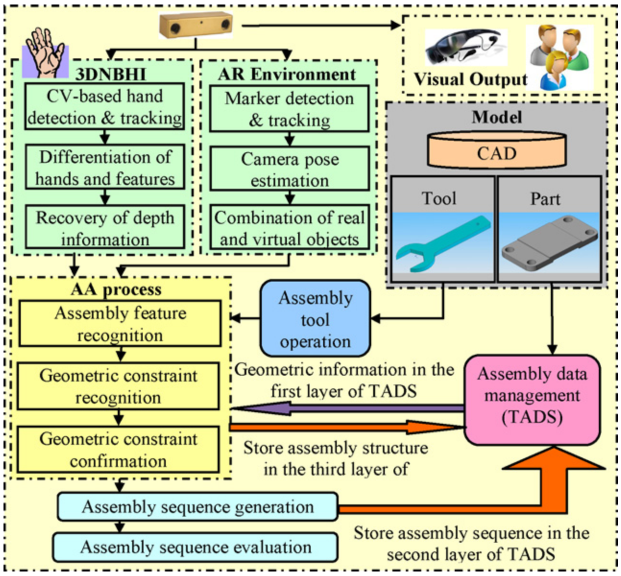

Fig. 27. Architecture of BHAA system [110].

interactions between the fingers and the virtual objects. Both hands can be identified and differentiated in the camera's view in the 3DNBHI method. After they have been differentiated, a matching algorithm is used to track the hand centres and this minimizes their displacement over the next two successive frames, so that these two hands can be differentiated from the live video stream.

A small virtual sphere is rendered on the fingertips to achieve interaction between the bare hands and virtual objects. The V-Collide algorithm [165] is applied to detect any collisions between the spheres and the virtual objects. The virtual sphere on each fingertip becomes highlighted when the virtual object is manipulated by a user. Fig. 26 shows the user moving a virtual cube using the tips of the thumb and the index finger of both hands.

The BHAA system developed can work well and quite consistently at around 15 frames per second for a 512×384 frame resolution. The accuracy is determined by the fingertip detection method which has a RMS error of 1–2 mm in all the three axes.

The exploded view of a pulley bracket shown in Fig. 28 is used as a case study. In Fig. 28(a), the user first grasps the pulley with his right hand and the left bush with his left hand and assembles the two parts together. If the parts collide, the system will analyse the surface information in the contact list and detects any possible constraints. In this case, a cylindrical fit constraint has been recognised. Next, the position and orientation of the pulley in the user's right hand is adjusted automatically to ensure that the cylindrical fit constraint has been met precisely and the assembly operation is then completed. In Fig. 28(b), the user next assembles the right bracket with the base. After the two co-planar fit constraints have been recognized, it is realised that the right bracket can only be translated on the base. In Fig. 28(c), the user then proceeds to fasten the two bolts using a standard spanner for fixing the right bracket onto the base. In the final step shown in Fig. 28(d), the user assembles the left bracket on to the base. After a coplanar-fit constraint has been recognized, the motion of the right bracket is constrained in the planar surface of the base.

This case study, although quite simple, has demonstrated the use of bare-hands for assembly simulation. It has good potential for training a novice worker in assembling parts together. After several training sessions, the worker can operate without further AR guidance, while the initial learning curve can be shortened considerably. Work is underway to implement tactile feedback for detecting interference fit and mismatching of parts. The assembly simulation can also provide feedback to the design-for-assembly approach, and incorporate ergonomic principles for reducing worker fatigue.

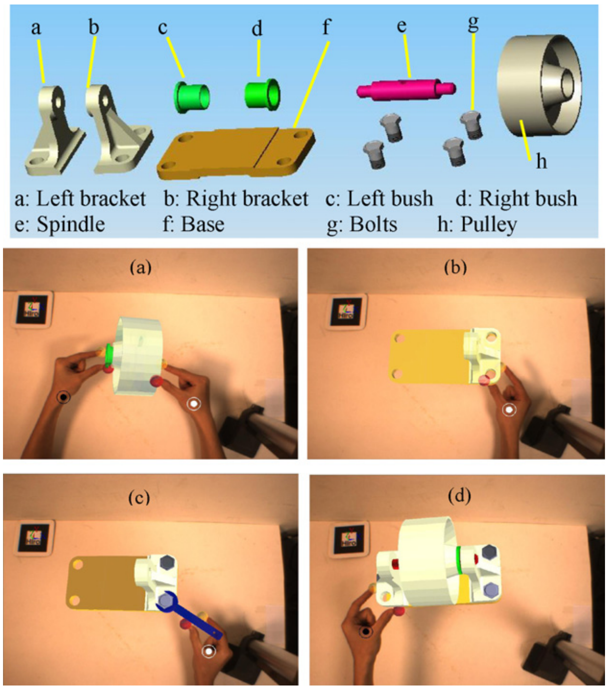

Fig. 28. The AA processes of a pulley bracket [110].

4. Technical challenges in AR

4.1. Accuracy

Unlike applications in advertising, gaming, fashion, etc., AR applications in manufacturing and design requires a high level of accuracy in tracking and superimposition of augmented information. Outdoor AR systems use GPS and inertial tracking techniques with a combination of gyroscopes, electronic compass, accelerometers, and other types of sensors, together with CV tracking techniques. Precision and accuracy are generally lacking in outdoor applications but very often, a high level of precision is not required. In design and manufacturing, such activities are usually indoors, and GPS will not be applicable. In addition, very accurate position and orientation tracking will be needed in operations such as CNC simulation and robot path planning. Computer-vision, inertial and hybrid tracking techniques will be required. CV-based tracking will not be able to handle high frequency motion as well as rapid camera movements. Hybrid systems using laser, RFID and other types of sensing devices will be required.

4.2. Registration

One of the basic issues in AR is the placing of virtual objects with the correct pose in an augmented space. This is also referred to as registration, which is a difficult and much researched topic. As different tracking methodologies possess their own inherent deficiencies and error sources, it is necessary to study the best tracking method for a particular application which could be subject to poor lighting condition, moving objects, etc.

The first type of errors is referred to as static error which arises from the inaccuracy present in the sensory devices, misalignments between sensors, and/or incorrect registration algorithms [38]. These types of errors can be eliminated quite easily as higher accuracy sensors are available and other sensor alignments can be set up accurately.

The second type of errors is the dynamic errors that are less predictable, which can be due to latency problems between data streams due to off-host delay, synchronization and computational delays [38]. Researchers have been working on methods to resolve the latency issues and some of the solutions are to adopt multi-threading programming or scheduling system latency [68], and predicting the camera motion using Kalman filter [83].

Dong and Kamat [38] described a solution which could eliminate these types of errors. They presented a mobile computing framework which provides an integrated hardware and software solution to achieve centimetre level accuracy for AR applications both spatially and temporally. They developed the Augmented Reality Mobile OpeRation platform (ARMOR) based on the ARVISCOPE hardware platform [11]. A Scalable and Modular Augmented Reality Template (SMART) was developed by Dong and Kamat [38] and it builds upon ARVISCOPE. The registration algorithm of SMART can ensure high accuracy static alignment between virtual and real objects, and reduces dynamic registration errors.

4.3. Latency issues

AR displays require an extremely low latency to maintain the virtual objects in a stable position [118]. An important source of alignment errors come from the difference in time between the moment an observer moves and the time when the image which corresponds to the new position of the observer is displayed. This time difference is called the end-to-end latency, which is important as head rotations can be very fast and this would cause significant changes to the scene being observed. It is suggested [112] that the displacement of objects between two frames should not exceed 0.25 of a degree. In terms of latency, this would translate to 5 ms when an observer rotates his head at a speed of 50° per second. Pasman et al. [118] described a method to meet this requirement. Their method used a combination of several levels of position and orientation tracking using varied relative and absolute accuracies, as well as different levels of rendering to reduce the 3D data to relatively simple scenes such that the 3D data can be rendered in a shorter period of time.

4.4. AR interfacing technology

Four essential elements are needed to set up an AR environment [72], namely, target places, AR contents, tracking module and the display system.

Kim and Dey [72] reported a comprehensive review of AR prototyping trends and methods. They addressed three features for creating an AR environment that are essential for end-user interaction, viz., intuitive observation, informative visualization and immersive interaction, and in the development of Interactive Augmented Prototyping (IAP). These three features are further used to integrate AR technology and develop custom-built 3D simulations.

3D interface and wearable computing devices are popular areas of AR research on interfacing technologies. Poupyrev [121] divided the AR interface design space along two orthogonal approaches, viz., 3D AR interfaces and tangible interfaces. In the 3D AR interface, users interact with virtual contents via HMDs and monitor-based displays and these are not the tools that they would interact with the real world. In tangible interfaces, users would use traditional tools in the same way as they manipulate the physical objects.

5. Industrial applications of AR

The majority of the AR research appears to have originated from the academia over the last two decades. Industrial AR applications are far less reported in comparison.

Regenbrecht et al. [125] reported a number of industrial applications of AR. The Boeing wire harnessing project in the early 1990s was amongst one of the earliest [96,97] case studies.

In servicing and maintenance of complex equipment, and even a car's electrical circuits would call for a database system and advanced computer equipment and electronic testing devices. It will be unwieldy to have printouts of such databases as they could

Fig. 29. Car engine maintenance [125].

be thicker than a telephone directory. It is necessary to decide the kind of information that is useful for a particular servicing operation, and the best way for the information to be represented. Multiple markers are placed at well-defined positions to provide the operator with precise tracking (Fig. 29). Several data types are presented. Maintenance and repair instructions are represented as texts; pre-recorded video instructions are displayed in the form of a virtual TV; 3D models with pre-determined animated sequences are displayed as overlays. A video and audio link can be provided to allow an expert mechanic to obtain remote technical assistance on the virtual TV.

Many major manufacturing enterprises are contemplating using AR technology in their maintenance and servicing applications. In fact, the more complex the product is, the greater can be the potential benefit from the use of AR technology.

Another application is the aircraft cabin design. Passengers' opinions are usually solicited in the design process in coming up with the final design. Both physical and digital mock-ups are used in the simulation. Seat placement, compartment shape, etc., can be simulated. In addition, other properties such as temperature, humidity, air flow direction and pressure can also be simulated using computational fluid dynamics (CFD) and other simulation tools (Fig. 30).

Wiring has become increasingly more complex as modern vehicles have more functions and high complexity. Wire bundles need to be measured at the beginning of a production line. The usual manual step of measuring the wires can be assisted by using an AR approach where virtual wire bundles are placed into the real area inside a vehicle compartment. The data is then sent to the station where wire bundles are being constructed. Fig. 31(a) shows the vehicle girder where the wire bundle is to be placed, and Fig. 31(b) shows the placement of the augmented bundle of wiring in place.

Fig. 30. Simulation of aircraft cabin using CFD and phantom model [125].

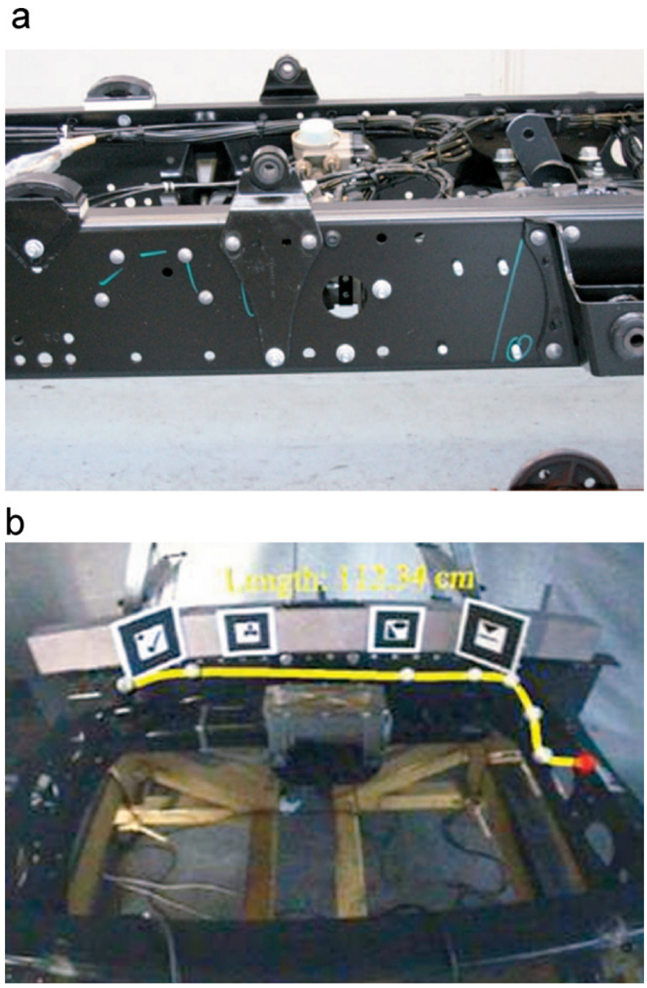

Fig. 31. (a) A vehicle girder without the wire bundles, (b) the vehicle girdle with augmented wire bundles [125].

In an edited volume by Ong and Nee [107], several industrial AR projects were reported. Baratoff and Regenbrecht [10] described the research at DaimlerChrysler in applying AR technology to a range of activities in design, production, service and training. Applications developed include interactive layout of wiring harnesses for truck assembly, visualization of airplane cabins in terms of volume and surface data, maintenance and repair of car engines using multimedia presentation, electrical fault diagnosis for tram service, AR-based training system; collaborative design review, etc. They concluded that there are many potential uses of AR in the manufacturing industry along the entire product lifecycle. The most crucial tasks in translating research prototype systems for real use lies in the integration of the system with the processes and data chains of the enterprise, and in the particular context. In particular, they pointed out that one has to consider several aspects, such as old and new working processes, old and new data flow systems, an objective measurement of the efficacy of the new system compared to the old processes, a clear requirement analysis before the final integration, as well as the usability tests after an integration has been made.

Weck et al. [168] described the use of AR to assist a service technician in complex maintenance and repair tasks. They mentioned that for an efficient use, it is necessary to integrate the developed AR system with the company's information infrastructure, which includes the retrieval and storage of the process data and information from the enterprise systems. At that time, authoring tools were still in the early stage of development and there was also a lack of interaction technologies. Context dependent information retrieval and effective filtering mechanisms would need to be in place as they can influence the applicability of AR in manufacturing environments.

In the automotive industry, an intelligent welding gun was developed by Echtler et al. [40] to help welders shoot studs with high precision into prototype vehicles. These prototypes are built to test new car concepts and do not warrant the usual set-up for mass production equipment. Hence, manual assembly provides the cheapest and simplest solution. AR has shown great potential for improving manual work processes [43,49,96].

An AR helmet was developed by Hillers et al. [61] for a welder to produce seams of higher quality and reduce inspection cost. The welding scene is captured using a stereoscopic high dynamic range CMOS camera system which allows a welder to observe the welding arc and the environment at the same time. The scene is enhanced and displayed on a video see-through HMD. Apart from a better view of the welding scene, the welder can operate the welding machine remotely and change the welding settings. Welding data and synchronized images acquired can be recorded on-line and used for off-line quality inspection and documentation.

6. Human factors and interaction in AR systems

Although AR has found a good number of applications in design and manufacturing, there are few in-depth studies that assess and evaluate human factors and interaction in AR systems. The limited understanding of human factor issues is likely to hinder widespread adaptation of AR systems beyond laboratory prototypes.

Trevisan et al. [163] mentioned that one of the central design aspects in HCI in AR is concerned with how real and virtual objects are combined into a real environment where a user can interact with both virtual and real objects simultaneously. As one needs to deal with both digital and physical spaces, inconsistency would inevitably arise, resulting in interaction discontinuities which could hamper natural workflow. This may force a user to abandon either of the operating modes. They proposed a methodology to analyse continuous interaction and ergonomic integrity in AR systems. Ishii et al. [66] defined continuity in interaction to be a seam which is a spatial, temporal or function constraint that forces the user to shift among a variety of spaces or modes of operations. Seams can be of two types:

- Functional seams, which are the discontinuities between different functional workspaces, forcing the user to change modes of operation.
- Cognitive seams, which are the discontinuities between existing and new work practices, forcing the user to learn new ways of working.

Continuity will be perceived as the capability of the AR system for promoting smooth interaction with the user during task accomplishment, taking into consideration perceptual, cognitive and functional aspects. For an AR system to be effective and user-friendly, at least three types of synchronization would need to be considered, namely, media, device and task. The integration aspects to be considered are namely physical, spatial, and insertion context of devices [66]. They conducted a series of usability studies to identify the potential combinations of input and output modalities that a user and accommodate and preserve a certain cognitive load.

Recently, there has been research towards understanding the effect of interfaces of AR tools on a designer's work efficiency and mind state, such as creativity and mental workload [12]. In a slightly different context from design, namely, human workers who supervise a dynamic plan, a general design framework by employing function–behaviour–structure (FBS) paradigm was proposed [85]. Based on the experimental comparison of the FBS interface design framework with a more popular one called the ecological interface design (EID) framework, the FBS framework has shown to be more superior to the EID framework in terms of the worker's performance [87]. Nevertheless, the current understanding of the interface effect on designer's work efficiency and mind state is still limited.

Livingston [90] has highlighted a number challenges and difficulties which need to be overcome when evaluating human factors in AR systems. The challenges come from hardware used in AR, such as display devices which have a number of limiting factors, e.g., insufficient resolution, FOV, poor brightness and contrast, ergonomics, etc., as well as software, such as tracking algorithms which lack accuracy, robustness, ease of calibration, etc. It is also well recognised that user performance depends on the hardware and software features. More importantly, the users must feel comfortable in using AR devices.

It is necessary to ensure that the field of application makes good use of the benefits of AR, and provides the design of well-constructed user interfaces. Livingston [90] has emphasised the following two questions:

- How do we determine the most important perceptual needs of the AR user and the best methods of meeting those needs with AR interfaces?
- For which cognitive tasks are AR methods better than conventional methods?

Nakanishi et al. [98] reported the results of a study on the use of an AR manual in a wiring task. They found that the wiring time was shortened by about 15% and at the same time, the error in wiring positions was reduced to almost zero. They also identified the basic human factors requirements in using an AR manual through a series of experiments. They noted that the performance of the user may be affected by the following six factors, namely, (a) effect of eyesight correction, (b) effect of eye dominance, (c) effect of surrounding Illumination, (d) workload, (e) attention to surrounding, and (f) difficulty in preparing AR manuals. Their tests showed that for users wearing see-through displays (STDs) and retinal-scanning displays (RSDs), the principal human factor requirements have been identified with respect to the above-mentioned six factors. It is also necessary to examine information design for presentation using STDs or RSDs. Livingston [90] also observed that HMDs in AR devices can reduce the user's effective visual acuity. This problem can reduce the capability of the user and it depends on his tolerance to perform a specific task. There could also be the long-term effect of prolonged wearing of HMDs, giving rise to giddiness, nausea, and even headache and loss of attention.

There is a need for mobile devices to be socially acceptable and natural to interact with. The devices should not cause distractions or even surprise or shock from the people who are not familiar with such technologies. Ideally, the application of mobile devices should be subtle and discrete, and in the most unobstructive manner. The users should also be able to interact with the devices in a most natural way, such as without awkward postures and gestures [22].

Privacy of displayed information is another concern as some information need to be protected and should not be seen by the public. It is often a trade-off between privacy and sharing of information as and when required. In the extreme scenario, contact lenses with the capability of displaying private information to the user have been reported [117].

7. Future trends and directions

Although much progress in AR has been made in the recent two decades, potential AR manufacturing applications are still in exploratory and prototyping stages. This is unlike in games, education and entertainment, where accuracy and robustness are of a lesser concern. With significant improvements in tracking algorithms and faster response time of hardware, many

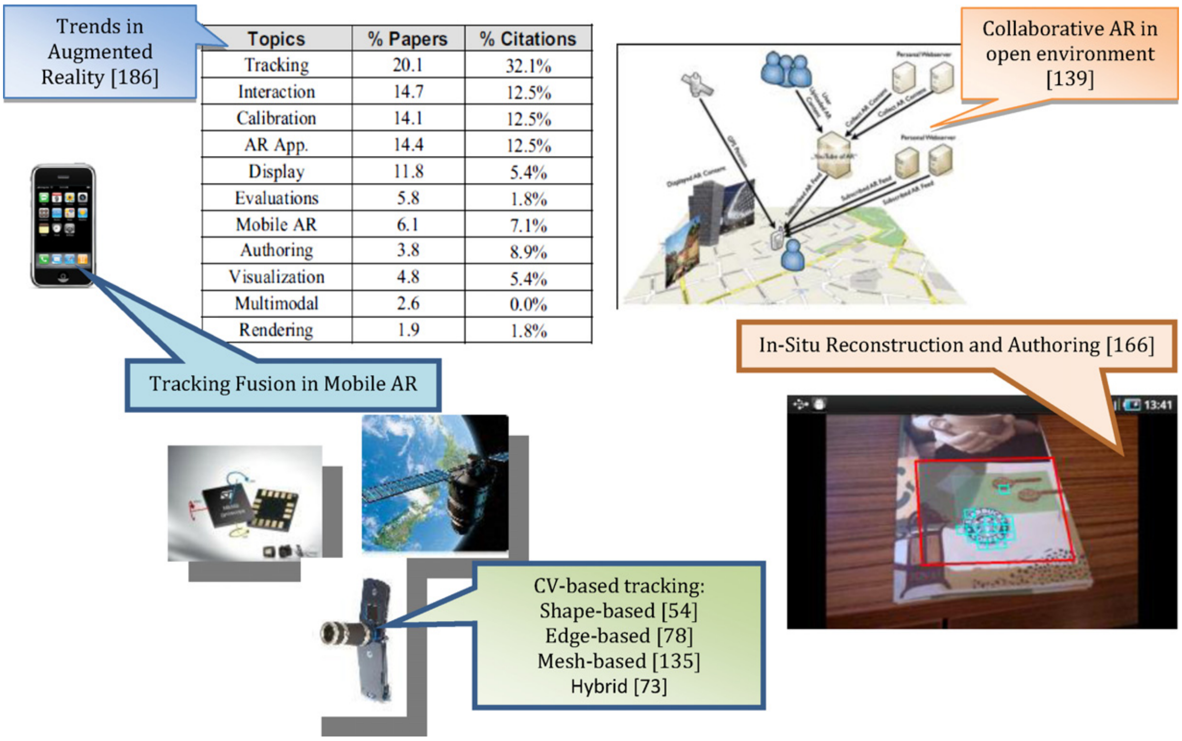

Fig. 32. AR research topics and ubiquitous AR applications.

manufacturing operations can be simulated effectively in near real-time where users will no longer perceive a time lapse, jittering of objects, and inaccurate registration issues. Hardware technologies have also advanced significantly in terms of lighter, smaller and more powerful wearable devices, providing much reduced obtrusion to the users.

As depicted in Fig. 32, the highest number of papers published around 2008 is in the areas of tracking, interaction and calibration, followed by AR applications, display and evaluations. Mobile and collaborative AR are increasingly receiving attention.

A much desired direction will be in the development of highly interactive and user-friendly interfaces. The interfaces would need to be customised according to a particular type of application a user is expected to perform. The need is not only in the development of novel AR devices, but to convince users that they will forego traditional methods and opt for AR-assisted solutions. However, it must be borne in mind that not all applications are well suited for AR implementation. The crucial factor is therefore to identify applications which will benefit users in terms of ease of learning new tasks, error-free job execution, reduced cognitive load, etc. Eventually, a user should be a happy worker, equipped with better skill and technology, and able to carry out his work much more efficiently. The goodness in the system lies very much in the interface between the user and the AR system. To some extent, this is still an open research issue since choosing a task suitable for AR application relies on a good user interface, but before this is developed, one is not sure if the task is suitable. Livingston [90] has aptly put it as: ‘‘How can we know which applications will benefit users until good interfaces exist?’’

Apart from improved hardware and software development, one of the future directions of AR applications in manufacturing is a systematic study on the viability and efficacy of the AR system with respect to a particular task. It is cautioned that not every task is well suited for AR. Every task would need to be studied carefully with a series of user studies in terms of both performance and cognitive tests, as well as monitoring the long-term effect of using/wearing AR devices, and user satisfaction.

Research directions can be generally classified into two streams, namely tool development and tool application. In the tool development stream, one of the promising areas is the interfaces of AR tools, including the ergonomics issues and aesthetic issues [86]. The effect of interfaces is mainly on a designer’s work efficiency and mental state. While the first element of the effect is more apparent, the effect on the mental state may have a profound effect on the designer’s creativity. For instance, if a tool with its interface may create a negative emotion in a designer’s mind, e.g., frustration, the designer’s creativity per se may degrade. In other areas such as HCI in learning, negative emotion has been shown to degrade a learner’s cognitive performance [145]. Visual attention can be another important factor to be considered in designing the interfaces for AR tools [88]. Further in this stream, adaptive AR tools are promising. The idea of adaptive AR tools is such that interfaces of AR tools are made adaptive to individual designers by tailoring to their individual design behaviours. Though there have been quite a few studies [46] on developing core technologies for adaptive interfaces in areas other than design, such as general human–machine interaction and HCI, similar developments in the area of design are worthwhile to pursue.

8. Conclusions

Augmented reality has taken the world by storm as it has found applications in every area from sports, gaming, sales, advertising, learning, touring, to medical and manufacturing applications. New applications are being developed almost daily. Its ability to provide high user intuition and the relative ease of implementation has outperformed VR, which was one of the most notable impacts of the late 1990s. AR on handheld devices has found a proliferation of applications with the advent of smart phones. Moving from marker-based to markerless registration and tracking, mobile and outdoor AR are now common place.

AR in design and manufacturing is a relatively new application compared to some of the entertainment type of applications. This is due largely to the accuracy required in tracking and registration in such applications, and a good alignment with traditional practices. Unlike playing an AR game where one can quit any time, the engineering users are likely to spend a considerable amount of time using the system in their jobs, and this is where ergonomics, human factors and cognitive strain on the users must be well recognised and catered to.

This paper presents some of the applications of AR which are relevant to the manufacturing community, although most of them are still in the laboratory stage. The paper emphasizes the importance of designing and providing intuitive and effective human interfaces, as well as suitable content development in order to make AR a powerful tool in the manufacturing engineering field. The future trends of AR have also been addressed. Has AR really arrived? Some say it is 80% of the way there, but the remaining 20% will be hard and may take a much longer time.

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