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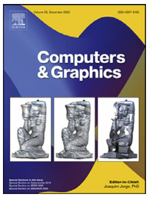

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A survey of immersive technologies and applications for industrial product development

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ABSTRACT

With the expanded digitalization of manufacturing and product development process, research into the use of immersive technology in smart manufacturing has increased. The use of immersive technology is theorized to increase the productivity of all steps in the product development process, from the start of the concept generation phase to assembling the final product. Many aspects of immersive technology are considered, including techniques for CAD model conversion and rendering, types of VR/AR displays, interaction modalities, as well as its integration with different areas of product development. The purpose of this survey paper is to investigate the potential applications of immersive technology and advantages and potential drawbacks that should be considered when integrating the technology into the workplace. The potential application is broad, and the possibilities are continuing to expand as the technology used becomes more advanced and more affordable for commercial business to implement on a large scale. The technology is currently being utilized in the concept generation and in the design or engineering of new products. Additionally, the immersive technology have great potential to increase the productivity of assembly line workers and of the factory layout/functionality, and could provide a more hands-on form of training, which leads to the conclusion that immersive technology is the step to the future in terms of smart product development strategies to implement for employers.

1. Introduction

As with all industries the increase in the digitization of product development and manufacturing processes has occurred since the development of the first computer. In factories, the switch to more autonomous processes using specialty designed robots is becoming more increasingly common in factories around the world. This widespread digitization in the industrial product industry is also referred to as Industry 4.0, Industrial Internet, or Digital Factory [1], which characterize the era of smart manufacturing. The idea behind the smart manufacturing is the convergence of digital and physical worlds, allowing for a flexible system to operate a stream of data and reduce mistakes, and decreasing the amount of time and resources when handling an intelligent network of manufacturing process.

Although there has been a steady switch to digitization and automation, humans still have an important role to play in the product development and manufacturing processes. Humans can change and adapt to new tasks and behaviors faster than the time it takes to reprogram a machine [2]. Additionally, machine breakages can result in wasted material or delays in production. Yet, the pool of available skilled workers to fill these essential roles in the manufacturing process are dwindling. The time to train unskilled or inexperienced workers is a time-consuming and a resource draining task. Especially, if the training requires them to practice their skills repeatedly in order to build up muscle memory, like welding [3,4] or machining [5]. Hence, the focus on tools to assist human workers to increase their productivity or reduce the cognitive workload are being investigated to combat these issues.

One promising solution to address these issues is using immersive technology, which can create a simulation of any training scene for learners to operate safely [4,6], open a digital portal for engineers to maintain the inventory and machines remotely [7], or create a digital workspace for product design [8]. Immersive technology has been investigated initially by Morton Heilig for cinematic experience in the late 1950s [9]. Since then it has occurred in the film and gaming industries and recently continues to advance the development of serious video games and interactive systems across diverse applications such as for operational training, education, healthcare, live broadcasts, etc. Immersive technology

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has been a focus of research since the end of the twentieth century, on how to integrate it into a product development setting and environment [10,11]. The technology has the potential for innovating many areas of the industrial product development, including reducing mental workload or physical demands of workers and as well as allowing for 3D visualization of designs interactively without need for physical resources [12,13]. The market for immersive technology is expected to grow 74% between 2018 and 2025, and the market value is expected to increase to $75 billion by 2025 [2].

While the term “Immersive Technology” has been commonly used in many different domains, there is not yet consensus on specific technical aspects. The most common use of immersive technology in recent years has focused on virtual reality (VR) and augmented reality (AR) applications due to their praised ability to provide 360-degree display [14]. However, it would be biased if defining the application of immersive technologies as visual experience only. A full sense of immersion should also leverage human interaction modalities such as hand or full-body gestures to make users feel in control of the virtual environment. Furthermore, immersive technologies are domain-specific; different domains produce different types of data or VR content with different interaction interfaces, such as examples in gaming [15], training [4,10], and learning [16]. In the context of immersive technologies for the domain of industrial product development, this survey paper looks into techniques for CAD model processing and acceleration, portable and stationary display devices that can provide immersive visual experiences, and intuitive interaction modalities. We review a collection of publications gathered from proceedings and journals in multiple disciplines in the past decade (2010–2020). For who are interested in other aspects of immersive techniques in the industrial product development, please refer to some existing review papers focusing on computational intelligence for AR [17], AR in engineering analysis and simulation [18], and AR assembly [19]. This paper adopts the narrative literature review method. Narrative reviews generally are comprehensive and cover a wide range of issues within a given topic, but they do not necessarily state hard rules about the search for evidence [20]. The narrative literature method has been successfully used for reviewing other similarly interdisciplinary research literature, such as deep learning and manufacturing [21], fabrication and HCI [22], and game and education [23]. The primary databases used for literature searching include Scopus, ACM Digital Library, Web of Science, Science Citation Index, and EBSCOhost Electronic Journals Service. A range of keywords associated with this paper’s topics, such as augmented reality, CAD, GPU rendering, HMD, Industry 4.0, and etc. are included. The research question of this paper is defined as follows: *how would CAD modeling, different types of display devices, and interaction modalities support immersive techniques in manufacturing applications?*

For the rest of this paper, we first present the history of immersive technology in Section 2, tracing from its origin to the latest development and application trends. The three key techniques, including CAD modeling and rendering methods, display technologies, and interaction modalities, are explained in Sections 3–5, respectively. In Section 6, we look into the areas of product development that the immersive technology has been integrated into, and discuss its value in human-involved product development processes. In Section 7, we discuss future research directions on immersive technology for smart product development, followed by the conclusion of the paper in Section 8.

2. History of immersive technology

Immersive technology, as defined in a variety of resources [26–29], refers to a system that mixes physical and virtual realities. It utilizes a combination of high-performance CAD model processing methods, engaging display technologies and human-centered interaction modalities, with both hardware and software development efforts, to create in-situated user experiences and be used for training, learning, and collaboration. The scientific experiment with immersive technology can be traced back to the “Put-That-There” system in the early 1980s [30], in which users utilize gestures and voices to control simple shapes on a large display. It mimicked for the first time an interaction with computer-generated shapes using a visual platform and natural user modality, as what can be used when people perform the same tasks without a computer. Since then, immersive technology has improved with the growth of VR and AR applications [31], such as the head-mounted VR display and DataGlove for identifying hand gestures developed by the VPL Company in the late 1980s [32] and the pioneering virtual fixture systems for AR training [33] and maintenance assistance [34] in the 1990s. Table 1 shows the development milestones in the history of immersive technology.

Table 1
Milestones in immersive technology history.

1962	Morton Heilig built a multi-sensory, mechanical multimodal theater simulator called Sensorama.
1968	Ivan Sutherland developed the first HMD system called the Sword of Damocles.
1972	General Electric developed a computerized flight simulator, featured with a 180-degree FOV.
1975	Kueger et al. developed the first interactive VR system called VIDEOPLACE [24], which allows a user to interact with other users’ silhouettes.
1979	McDonnell-Douglas Corporation integrated VR technology into a HMD with a head tracker for military use.
1980	StereoGraphics developed Stereo vision glasses.
1982	Sandin and Defanti created Sayre hand monitoring gloves.
1985	VPL Research was the first company to sell VR goggles and gloves.
1992	U.S. Air Force developed the first immersive AR system called Virtual Fixtures.
1997	Steve Feiner et al. developed the first mobile AR system called the Touring Machine, which uses a see-through head-worn display [25].
2001	The first PC-based cubic VR room called SAS Cube. It is a four-sided projection system receiving back-projected images through a multi-client network.
2012	Oculus Rift VR HMD was released. It is a goggle-shaped device integrated with three sets of lenses, a head tracker, and position trackers.
2014	Google Glass headset was released, which is known for its lightweight and transparent display.
2016	HTC Vive SteamVR HMD was released, with sensor-based motion tracking in a space. Microsoft HoloLens AR headset was released, which itself is a complete AR system, running the Windows 10 and containing various tracking sensors, a holographic processing unit, and optical lenses with a holographic projector.
2018	Magic Leap AR headset was released, which is a complete AR system featured with binocular FOV.
2019	Oculus Quest VR HMD was released, featured with freehand tracking. Varjo XR HMD was released, featured with video pass-through AR and wide FOV. Pimax 8K VR HMD was released which has high display resolution.
2020	Eye and hand tracking modules for Pimax VR HMD were released. Fove VR HMD was released capable of eye tracking.

With the latest development trend, the term of immersive technology is intertwined closely with applications of wearable VR and AR, or even with wearable mixed reality (MR) [35,36]. In computer graphics and virtual reality communities, the term VR is usually related to real-time, three dimensional, autonomous models of the real world combined with technology that allows the user to be immersed in the interactive environment. It is a viewer-centered, multi-sensory experience in which the user is presented with a stereoscopic head tracking display, hand and body tracking, as well as binaural sound [31]. The advantage of VR is the ability to create any environment without limits, even if it is impractical or impossible in the real world. However, this is also its drawback and special consideration must be used when creating the navigation and physics of the environment to ensure the user does not become disoriented or sick.

AR is a technology that does not replace the real world, but instead, enriches it. This is usually accomplished using a see-through head-mounted display (HMD) that imposes an overlay of computer-generated objects upon physical objects. The advantage of AR is accessibility, which has been enabled in almost all smartphones providing a convenient and comfortable experience for the user. However, AR does not recognize the physical objects in the real world or make virtual objects respond/interact with the physical objects [33]. With respect to the continuum, 2D filters imposed upon the environment are considered basic AR, while MR is one step further of advancement from AR. It enables the physical-virtual interaction with the feature of occlusion detection and awareness [37]. In other words, that means a virtual object imposed to the scene of the real world can be visibly obscured by physical objects, such as a virtual robot crawling under a physical table in the real environment.

Manufacturing industries are finding it increasingly difficult to meet the demands of their customers. They are facing the facts that the volume of computer-aided design (CAD) models and data for manufacturing continue to explode in both quantity and quality. Viewing, interacting, operating, and analyzing the data of manufacturing have been a challenging problem. To meet the development trend of artificial intelligence, robotics, internet of things and provide better services and experience for customers, immersive technology has been integrated in more and more engineering activities from manufacturers. For example, graphics algorithms have been proposed to accelerate the rendering of ever large-scale CAD models [38,39], and VR/AR/MR applications and natural modalities have been developed for product design [40], manufacturing training [41], [29]. The integration of immersive technology offers a more interactive model for designing and concept evaluation to be completed virtually before any physical construction or prototyping [42], which further improve the efficiency of entire manufacturing process.

3. CAD model conversion and acceleration for rendering

Manufacturers have found it beneficial to render CAD models of assembly parts and engineered products into immersive images and animations. Such rendering techniques and associated graphics algorithms are necessary tool kits for manufacturing industries to build complex production lines, machines, and training and maintenance systems, as well as to create a form of digital media for showing concepts or detailed manufacturing processes to customers, strategic partners, and other broader audiences.

Nowadays, engineers are producing more complex design which results in increasingly larger CAD models. Even for a small product, the model may incorporate multiple, complex assembly parts, material properties, and rich metadata. Simulation and design tools leverage data structures and algorithms to reinvent their data management features that allow an immersive system to manage and retrieve parts in the CAD model database while delivering performance increases.

In this section, we reviews CAD model representation and acceleration techniques for efficient rendering of large CAD models. The integration of model representation with acceleration techniques for rendering is shown in Fig. 1.

3.1. Model conversion

We focuses on techniques that convert CAD models into representations that can be efficiently rendered in VR and AR. Berta presented the characteristics of CAD tools and VR applications [43]. While CAD tools contain most of functionalities that VR and AR applications would require, there is a significant difference that the interactivity and rendering performance in VR and AR have priority over the model accuracy, while CAD tools weigh more on accuracy than interactivity. In regards to the difference between the CAD design and CAD visualization, the design often describes the model using non-uniform-rational-B-spline (NURBS) surfaces, which are mathematical definition of the geometry presenting the exact shape of the model, while the visualization normally needs to use polygonal surfaces which are discretized and optimized for hardware rendering [44]. To convert CAD models to polygonal mesh representations, *tessellation* techniques (e.g., [45–48]) have been applied to represent the NURBS surfaces as topological meshes composed of interconnected vertices and triangles. Triangulated meshes are the most popular form of tessellated CAD model representation because triangles are the most rendering-efficient geometric primitives to the hardware-accelerated rendering pipeline, and they are required by many efficient meshing procedures and rendering acceleration techniques in VR [49,50].

The conversion process actually needs to generate two types of data sets: polygonal meshes and kinematic information [51]. The polygonal meshes are used for rendering and the kinematic information contains the hierarchy of part assemblies. As the Industry 4.0 requires to incorporate kinematic animation sequences and production knowledge into CAD system or other software combinations, research efforts have been conducted to develop automatic conversion systems to generate these two data sets. For example, Lorenz et al. [47] presented a system with independent modeling workflows that can process models at different quality levels, which enabled flexibility to balance between the accuracy of converted meshes and the performance demands of visualization. The conversion module in that system focused on the cross-system automation of model complexity reduction, animation, and kinematic mechanism adoption. Braun et al. [44] discussed several challenges on converting kinematic CAD information for high-quality visualization. The assembly hierarchy and kinematic dependencies can converted in an automated manner to generate hierarchy structures and local coordinate systems and use in visualization and game development engines.

There are also inverse tools of that allow users to specify input parametric configurations to synthesize the desired mesh by interpolating CAD model samples in the parametric domain [52]. Then, the parametric values can be updated in real-time in accordance with the user's input and change physical properties for the output mesh. The input parametric configurations usually reflect the manufacturability that captures engineer's design intent [52], and improve reusability of the models [53] for applications such as automotive construction of immersive VR environments.

3.2. Acceleration techniques for rendering

All that people can see through a display device are pixels. Vertices and triangles must be converted into pixels before people can visually inspect shapes and color. *Rasterization* is the most commonly used rendering method for immersive technology. The execution of rasterization for rendering CAD models can be accelerated with graphics processing units (GPUs). Regardless the types of display, the standard rendering pipeline requires vertices and triangles to be transferred from CPU main memory to GPU memory before they can be rasterized. Many modern wearable VR and AR devices require the use of GPUs with the rasterization rendering

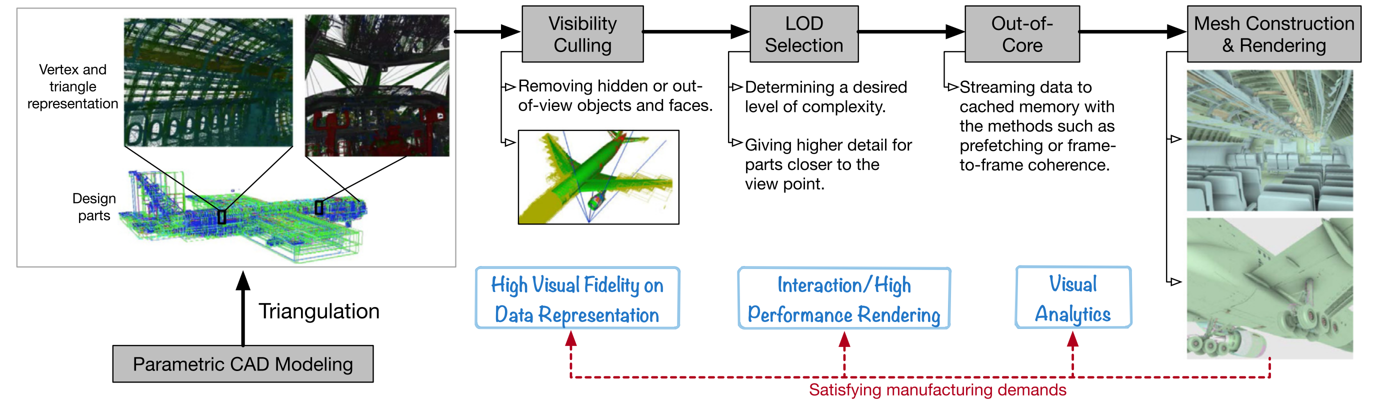


Fig. 1. The integration of triangulated CAD models with rendering acceleration techniques.

pipeline. For example, HTC Vive Pro-requires Nvidia GeForce GTX 1080 or better. The backbone of Magic Leap One is the Nvidia's new Tegra X2 GPU architecture. To maintain high rendering performance, it is crucial to utilize GPU-friendly methods to optimize the use of the models in real-time, avoiding the processing of redundant data (e.g., invisible triangles) and latency on host-to-device data transfer. In this subsection, we particularly describe three techniques: *mesh simplification*, *visibility culling*, *out-of-core*, to accelerate the rendering of complex CAD models on the GPU. As a result, these techniques have been adopted for real-time manufacturing visualization and the creation of *digital twins* for future remote-based manufacturing and production.

Mesh simplification for CAD models uses a series of geometric primitive operations to gradually reduce the mesh complexity and obtain smooth appearance transitions between different levels of detail (LODs) [38,54]. Both Tang and Gu [55] and Cui et al. [56] discussed the limited processing powers of VR devices. Large and complex CAD models may not be rendered in real-time in VR if they are not appropriately simplified. Kwon et al. [57] presented an adaptable method to simplify models with various semantics during the life cycle of the industrial plants. This was to satisfy the need of light-weighting 3D CAD models while supporting the metadata needed by assembling and fitting to the GPU-based rendering pipeline. The model can be simplified adaptively up to 99% in accordance with the device's rendering power and the desire on the rendering quality.

Visibility culling is a technique that rejects the rendering of objects that can not be seen by the camera. The popular trend of using visibility culling for CAD model rendering is to integrate the concept of occlusion culling into the framework of GPU computing, which can disable the rendering of objects that are occluded by other objects [58–60]. For example, when standing in an airplane interior, doors and seats will occlude many objects behind them. Rejecting the rendering of those occluded objects saves computational power. The visibility culling is critique to the performance of VR and AR applications as they mostly provide first-person perspectives.

Due to the increasing size of CAD models, GPU memory is not sufficient to hold the large amount of vertices and triangles. This is especially critical with wearable display devices such as HMDs. In such cases, data has to be transferred from CPU memory to GPU memory in multiple passes, and therefore the rendering performance will be suffered. *GPU out-of-core* combining with simplification and culling methods is able to select and transfer a portion of vertices and triangles from CPU memory to GPU memory [38,61–63]. Instead of transferring the entire set of data, GPU out-of-core identifies only frame-different data at each time a frame being rendered. In other words, whenever the view changes, the frame-different data is identified in correspondence with the new detail level from the simplification and culling modules.

In summary, acceleration techniques have been employed through the entire flow of CAD model processing that includes modeling, simplification, manipulation, and graphical rendering. Those methods have become the essential foundation preparing for real-time product development visualization and analysis [36]. To reach the goal of digital transformation of smart manufacturing and Industry 4.0, acceleration methods for CAD modeling and rendering are evolving towards suitability on embedded computing platforms and wireless automation through a 4G/5G network, where designed assembly parts could be stored and processed on a cloud server and then rendered remotely to the end-user platform [64–66]. Such remote graphics technology advances concepts like *digital twins* in the production lines, with a boost on visual monitoring of manufacturing operations through digital twins over the Internet [67,68]. In association with engaging display technologies, users are immersed with the digital replica of product development environments and gain an increased sense of presence in the virtual world.

4. Display technologies

This section reviews different types of displays that are being integrated into the product development industry, including handheld devices, projection-based displays, and head mounted displays. In smart product development, the choice on a display type is an important design factor that impacts the sense-of-presence in the virtual environment. An introduction into the technology of each display is given as well the comparison of benefits and drawbacks on those displays, which is also summarized in Table 2. This table is derived based on the literature reviews of the capabilities of these display devices about perception and usability in order to enable VR and AR immersive experiences [15,16,69,70].

4.1. Handheld displays

Handheld displays like smartphones and tablets are a type of augmented reality device that may be used during the manufacturing process in industry. The user uses a handheld device to scan over the desired area, and virtual objects and information are displayed on the screen held in the user's hand, allowing interaction by performing tangible actions on the screen surface [73] or performing trackable finger motions in 3D space [74], and even supporting for collaborative work [75]. While a handheld display is easy to carry with the user, it has many limitations, such as the limited filed of view and physical restrictions for operation. The user has to use one or both hands to support or use the device,

Table 2
Characteristics of different display types.

	Handheld display	Projection-based display	Head-mounted display
Example Devices	Smartphone, Tablet	Mounted projector, mobile projector	Google glass, HoloLens, Magic Leap, Oculus Quest, HTC Vive, Varjo XR
Support for AR	Yes, the composed image is displayed on the screen of the handheld device.	Yes, the projected image is displayed on a physical surface.	Yes, the mixed view is displayed in midair.
Support for VR	No	No	Yes
Portable	Yes	Yes if using a mobile projector	Yes
Support for collaboration	Yes, but each user has an individual view.	Yes, the view can be shared among multiple users.	Possible, but it is mainly for individual usage.
Sense-of-Presence	Limited, and hands are not free for operation.	Limited, and the FOV is restricted and the image has to be projected on a physical surface.	Immersive, varied FOV, and first-person perspective experiences
Support for prolonged operations	Yes, it is easy to carry for an extended period of use.	Yes, with SAR interfaces and freehand interaction.	Not suitable because of the device weight on head and possible motion sickness.

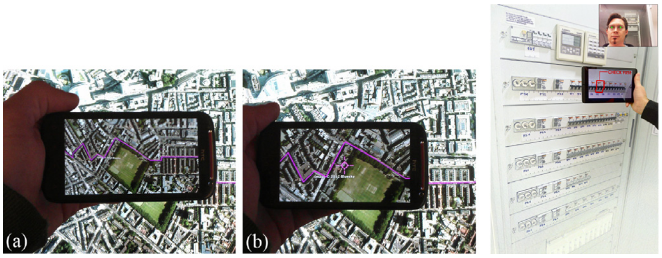


Fig. 2. (a) The dual-view problem caused by device- perspective magic-lens rendering. (b) User-perspective magic- lens rendering where such dual-view problem is not present. [71] (c) the users views AR instructions through the tablet [72].

and this limits the ability to operate the information [76]. There is also a concern on the viewing perspective. Any implementation with a handheld display shows the captured field from the device's perspective rather than a user's perspective [71]. Thus, the displayed image may not be scaled correctly to match the user's view of the surrounding real-world visuals, like the example in Fig. 2 excerpted from Pucihar et al.'s work [71]. This may distort user's spatial perception and weaken the sense-of-presence. User-perspective rendering solutions [72,77] have been proposed to solve the perceptual issue in a fixed point of view, they are not yet applied as a standard add-on to the front facing camera of handheld devices because of the user's dynamic point of view and the need of head tracking.

4.2. Projection-based displays

Projections are typically used in industry when interaction is needed between many users or for tasks like assembly where projection of the virtual environment onto a workspace is sufficient for guidance [13]. The projector works by using a camera, either fixed [78,79] or portable [80], to take in the required information from the environment, then the information is interpreted and then projected back as a textured image to the user(s) on the projection screen or workbench [10].

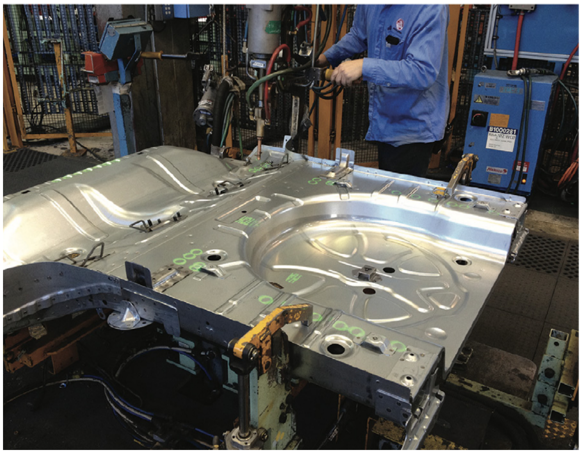


Fig. 3. SAR annotations indicating locations for spot welds in an industrial scenario. CAD models are loaded into the SAR system, making this approach fit within existing engineering processes [78].

The projection with a fixed projector has been commonly used to create spatial augmented reality (SAR) interfaces, like the example shown in Fig. 3. With a SAR interface, users do not have to hold or wear devices, such as a handheld display or an HMD. However, a major limitation is that a physical surface in the workspace is required in order to project the virtual information. The projection with a fixed projector cannot display the virtual information in the midair [78], but the user can “touch” the information at the physical position it projects onto. The projector usually suffers from the limited field of view that influences the effectiveness of user's inspection on the operating spots. Thus, in practice, users may need to employ multiple projectors to augment the information into a larger-scale physical environment or project the information on a moving surface along an assembly line [81].

For the projection with a portable projector, the projector is usually mounted on the user's head or held in the hands, so that the virtual information can be projected onto the physical surface or workstation in front of the user. This is also known as *mobile projection* [80,82]. One advantage over the fixed (stationary) projection is that it is no longer limited to the display at a single spot and can adapt to a flexible manufacturing environment [82], in which for example the floor layout may change regularly [80]. Comparing to the fixed projection, real-time object tracking is more challenging within the mobile projection. There is also a lack of generic platform for light-weight hardware requirement. Also, for both types of projection, latency problems can occur with projectors, as well as surface distortions which include brightness, contrast, or the clearness of the image [76].

4.3. Head mounted displays

HMDs for VR and AR systems tend to be the focus of current research. These categories included wearable devices such as Google Glass, HoloLens, Magic Leap, Oculus Quest, Pimax, HTC Vive, Fove VR, and Varjo XR. To get a fully immersive experience

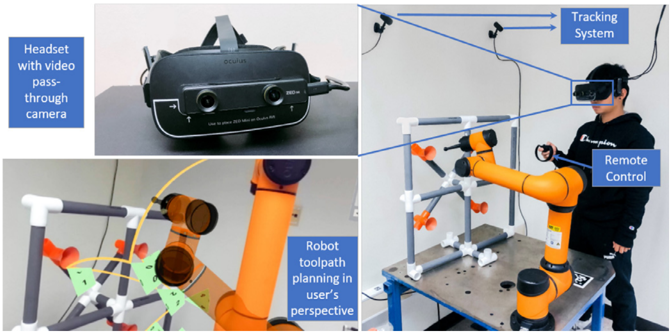


Fig. 4. An see-through AR HMD is utilized for a robot toolpath planning task in the AR environment.

using VR, HMDs are the only option that are wearable and allowed for this technology since the real-world visual need to be blocked to experience the virtual environment. However, for AR systems, HMDs are a large area of focus due to their *see-through* ability to take in data in real-time from the environment. The convergence of AR with see-through HMDs can help promote hands-free and heads-up work, allowing users to see and follow overlaid instructions from the first-person perspective without looking away from what they are working on. The see-through capability can be accomplished using optical see-through HMDs (e.g., HoloLens and Magic Leap) and video pass-through HMDs (e.g., HTC Vive Pro- and Varjo XR). Two example devices are shown in Fig. 4. Recently, there is a discussion about optical see-through versus video pass-through HMDs [83]. With an optical HMD, the physical world is seen directly through semi-transparent mirrors placed in front of the user's eyes, and the rendering of the virtual environment is reflected by those mirrors into the user's eyes. In a video pass-through HMD, real-world sceneries are captured by two miniature video cameras mounted in the front of HMD.

Modern AR HMDs are powered with multi-processor computing architectures. Many of them require high-end GPUs. For example, HTC Vive Pro-requires Nvidia GeForce GTX 1080 or better. The backbone of Magic Leap One is the Nvidia's new Tegra X2 parallel computing architecture. To maintain high rendering performance and reduce energy consumption, as discussed in Section 3.2, it is crucial to develop GPU-friendly parallel methods to render digital models in real-time within the GPU memory limit, avoiding the high power consumption and latency on host-to-device data transfer.

One important property of the human visual system, field-of-view (FOV), is addressed differently in the two types of AR HMDs. A FOV is the angle through which the user sees the observable area. The FOV of optical see-through HMDs is narrow (e.g., 50 degrees on the diagonal axis in Magic Leap One). In contrast, the FOV of a video pass-through HMD is usually wider (e.g., 135 degrees on the diagonal axis in HTC Vive Pro). For the use of an optical see-through HMD, a visualization technique with abstract contour lines may be used to assist the interaction with out-of-FOV information [84], within the context of training users to follow picking and assembly instructions in an assembly application. For a VR or video pass-through AR application, a wide FOV accommodates to the human visual system and requires a less amount of head movements when scanning an active field, but the rendered image of the virtual environment may be distorted because of binocular overlap and the limitation of projection methods [85,86].

HMDs are typically used in industry when only one user is needed to observe the virtual information [13]. Many VR and AR applications for assembly training and product design are still in the experimental stage [87,88], and future efforts are needed to develop suitable contents aligned with industrial training and practice standards. HMD technology is still under development for better integration of these devices into a product development environment. For example, the devices are often heavy and sometimes lagging on display due to overburdened computation, which may make the user experience strain or hindrance [10,11]. After an extended period of use, the user may begin to feel the effects of motion sickness, which include the symptoms of headaches, dizziness, or nausea. Additionally, latency or lagging on display can cause confusion for users if they are not able to spot the difference between what is being displayed in the virtual and real worlds [76]. Some newer models of HMD technology feature eye tracking ability, such as Fove VR and Varjo XR. Eye tracking is a beneficial tool since it can be used to calibrate the device to the user [89,90]. By using eye tracking the device can register if the individual is looking at the correct object or focus area, and can detect when the user is looking away and if so, the device can direct the user's attention back. Furthermore, in future applications, eye tracking could be used to interact with the device itself.

5. Interaction modalities

With the marriage of cognitive learning, computer vision, high performance visualization, and human-computer interaction (HCI), and associated computational modeling and simulation, new natural user interface (NUI) to support the industrial product development have been developed in a multi-representative and multi-modal manner. These modalities including the sketch-based interface, the mid-air interface, and tangible-based interface, are being actively explored with immersive techniques for applications of industrial product development. The sketch-based interface has been adopted in design and manufacturing applications for long time since the adoption of touch screens. As the hand-held AR techniques also adopt a touch screen as the input device, the sketch-based interface is inherited naturally. For HMD based VR/AR, the mid-air interfaces is more utilized, as the more immersive experience with the HMD requires more intuitive interactions with the 3D objects and less restrictions brought by using the touch screen. The tangible interface provides the physical feedback, which is particular favorable in applications requiring hands-on experiences. On the other hand, the sketch-based interface outperforms on the precious control of the interactions. The mid-air interface, and tangible-based interface can hardly achieve the same level of precision as the touch-based interface does. Another problem for the mid-air and tangible interface is more fatigues of the users for long time usages.

5.1. Sketch-based interface

In spite of traditional WIMP (Window, Icon, Menu, Pointer) interfaces, over the last decade, sketch-based interfaces in smart product development, especially in the design stage, are becoming ubiquitous using natural and expeditious interaction of sketching to create and edit the digital models. Strokes and touch-based gestures are utilized to serve as input for searching and template models retrieval [91,92], and sketches can also be used to reconstruct and deform the obtained objects directly [93–95]. In these systems pen-based, nimanual, and multi touch-based interactions evolve from their counterparts in other systems to support the requirement of designers and manufacturers.

Some of recent works take the curves from sketch as the main embodiment of the design and manufacturing. These curves, namely "styling curves", can be used in different fabrication processes, including cutting and sewing lines for fabricating wetsuit [97] (Fig. 5. (a)), metal wires for wire bending [98] (Fig. 5. (b)), and thin-frames for 3D printing [96] (Fig. 5. (c)).

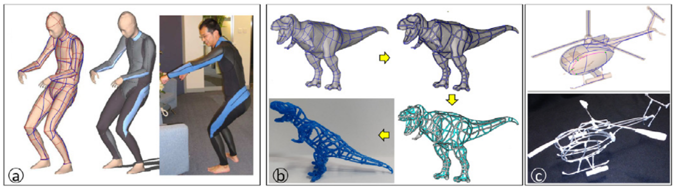


Fig. 5. The sketched styling curves can be utilized as cutting and sewing lines for wetsuit fabrication (a), thin frames for 3D printing (b), and metal wires for wire bending (c) [96].

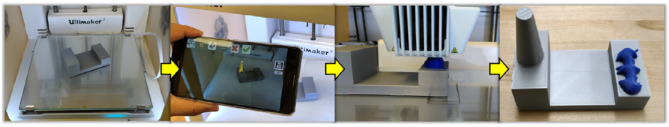


Fig. 6. An hand-held AR interface [101] for design 3D shapes with respect to an existing physical and then the 3D design is sent to 3D printer for fabrication.

Another interesting application is to utilize sketches to control fabrication systems interactively. LaserOrigami [99] presents an interactive interface which allows defines sketches on the planner materials in the laser cut using a laser pen, and then laser cutter follows the defined sketches and cuts the materials. Sketch&Stitch [100] supports users to draw curves on textiles using colored pens, and then a computer vision program converts the curves into embroidery patterns, which is ready for the sewing machine to sew electronics components on the textile following the embroidery patterns. An hand-held AR-based interface is presented [101] (Fig. 6.) enables users to define sketches on an existing object, converts the sketches into 3D shapes, and directly send the 3D design to the 3D printer for the fabrication. RoMA [102] system leverage AR display and hand-held controller allowing users to define thin-frames as the input for a robot-based 3D printing process.

5.2. Mid-air interfaces

The recent advancement of low cost 3D data acquisition divides such as Kinect [103], Leap Motion [104,105], and sensor-based motion capturing devices [106–108], has substantially lowered the barrier of mid-air interaction in design and manufacturing. With the capacity of real-time 3D human data sensing, the natural human hand gestures are adopted as basis of interactions to create 3D model and control the manufacturing facilities. In a recent work [109], voxel representation and data mining, combined with hand gestures for shape modeling. Another recent work [110] proposed a gesture-based 3D shape creation system to create 3D shapes categorized under general cylinders. The remaining challenge in gesture based mid-air interfaces exists in the recognition and interpretation of the gestures accurately and robustly. Mid-air gestures are also used to control CNC machines [111,112] and industrial robots [113,114].

5.3. Tangible-based interfaces

Latest literature shows holding, manipulating and modifying real-world objects, with hands and hand-held tools, are natural ways in which humans learn to design and operate machines. Therefore, in recent decades, engineers and scientists have adopted tangible and haptic devices in design and manufacturing. The haptics interfaces with force rendering are adopted in product design, manufacturing, and simulation applications [116]. Krishnamurthy et al. [117] proposed a method to model 3D pottery using bare hands and physical objects. The physical objects are utilized to create virtual contents by copy and paste [118], and remixing [115] (Fig. 7.). Zoran et al. [119,120] demonstrate tangible interaction approach to carve or scupture complex 3D objects, and perform the editing and interpretation of the virtual model accordingly. A simple 3D scanning method is proposed by Oe et al. [121] to scan the cross-section of physical objects and reconstruct the 3D models based on the cross-section shapes.

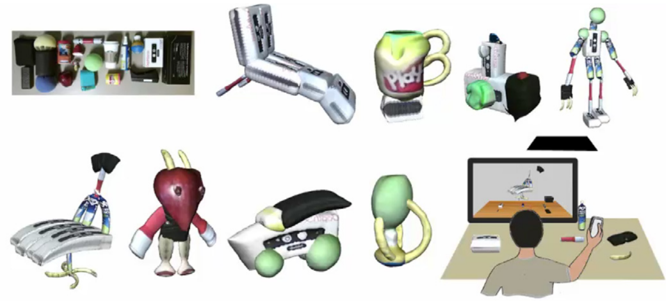


Fig. 7. RealFusion [115] enables the a quick and intuitive design ideation by scanning and remixing physical objects.

6. Product development applications

In the era of Industry 4.0, immersive display technologies have been integrated in various components of new product development. According to the keyword search through multiple academic databases, including Web of Science, Science Citation Index, and EBSCOhost Electronic Journals Service, the importance of different display technologies in various product development processes increased in the past decade, which has been reflected by the number of relevant publications summarized in Fig. 8. At the same time, and interaction modalities have also been gradually integrated in entire product development system with following aspects.

Off-the-shelf software tools for developing immersive experiences could be truly demanded by engineers and manufacturing industries, and possibly as important as hardware devices. We have seen developer tool kits such as Vuforia [122] by PTC, ARCore [123] by Google, ARKit [124] by Apple, which have been used to develop successful immersive experiences for instructional and training applications. However, the process of an actual manufacturing and production always requires the software tools with high precision and high reliability, which would usually overburden the VR/AR capability that the state-of-the-art software algorithms could provide with. The key challenges in supporting the development of immersive experiences still heavily rely on further improvement of hardware, for example, the needs of larger GPU memory capability and less data transferring latency (Section 3.2), higher display resolution and wider FOV (Section 4.3), and more reliable sensing devices for creating natural and intuitive interactions (Sections 5.2 and 5.3). Software tools so far appear to be more suitable for offline data processing and modeling like the model conversion in Section 3.1. In the future, software tools should be adaptive in connecting different hardware platforms including other smart devices and manufacturing systems, and become robust in 3D localization, efficient in high performance rendering, and intelligent in supporting the development of immersive experiences.

6.1. Product design and prototyping

The immersive techniques have been extensively adopted in multiple design and prototyping applications including, design

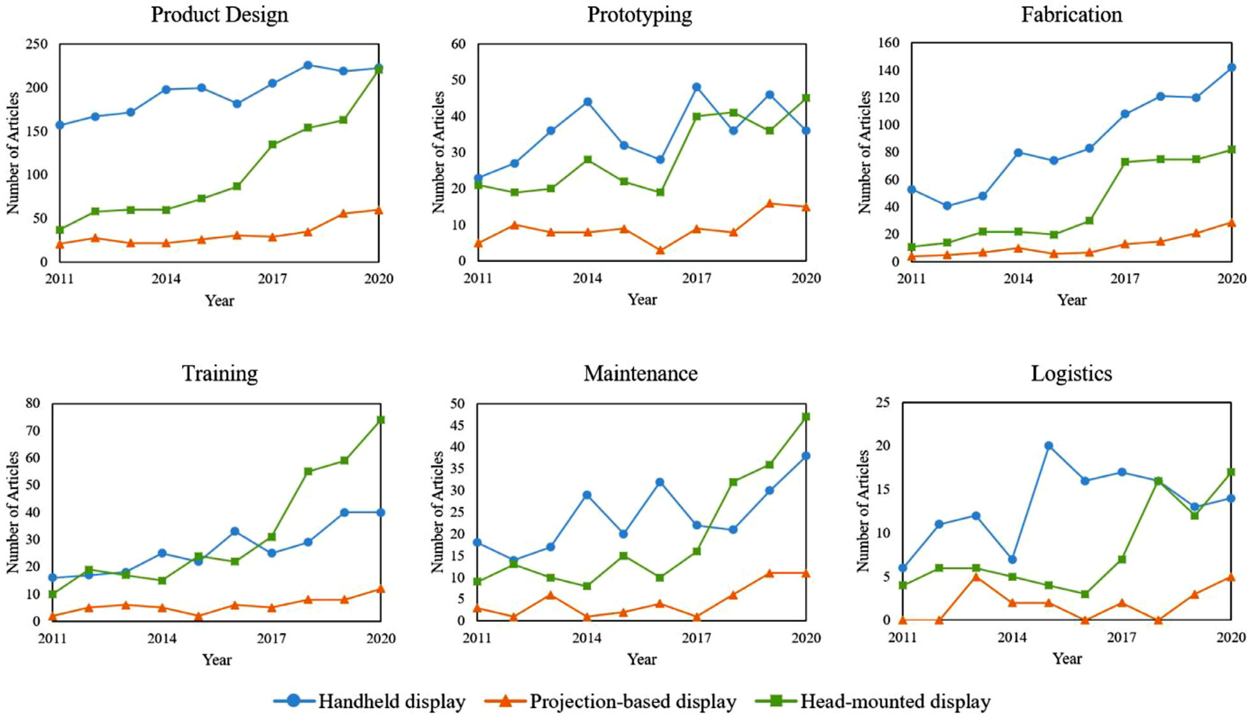


Fig. 8. Distribution of relevant papers about the applications of different display technologies in various product development processes.

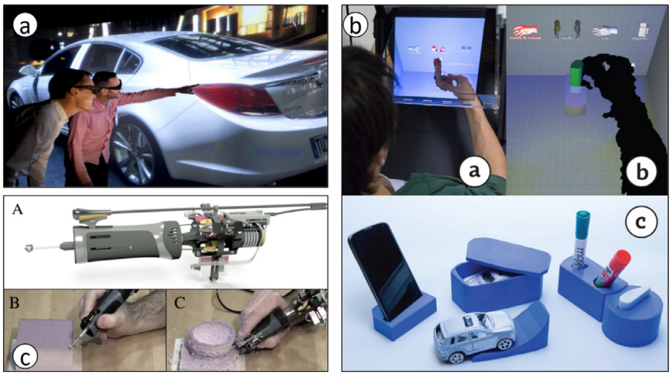


Fig. 9. The immersive techniques are adopted in applications such as (a) design ideation [126], (b) 3D CAD design [135], and the (c) integration of virtual design and physical fabrication [120].

ideation, 3D CAD modeling, and the integration of virtual design and physical fabrication.

Design ideation The instant visualization and versatile interaction of immersive techniques provides new affordance of design ideation and conceptual design. The adoption of these techniques will reduce the cost and time of prototyping in a new product development [10], and therefore speed up the cycle of design iteration [125]. OPTIS's software enables designers to interactively change the paint color and lighting for car appearance design [126] (Fig. 9 (a)). Window-Shaping [127] allows a fast 3D ideation by design 3D objects considering world's information in an AR environment. Physical tools are also involved in virtual contents creation, by providing context of physical world including dimension [128], geometry [129], and tangible information [130]. Another recent work RealFusion [115] provides the functions to compose shapes acquired from physical environment to form a new design. The immersive techniques also provides the capacity for collaborative design. Co-3Deator [131] is a sketch-based design system allowing multiple designers to create, reuse, and explore new design concepts collaboratively.

3D CAD modeling There has been numerous effort dedicated on introducing immersive techniques to CAD modeling. Martin et. al [132] discuss the CAD model data representation to support a VR-based modeling system. Feeman et. al [133] evaluate the modelling ability of a VR-based CAD system compared with s conventional CAD system. A study claims the new interaction capacity of VR improves design understanding and decision making [134]. For AR based CAD modeling systems, the dimensionality, spaciality, and geometry information of physical environment play a important role. MixFab [135] (Fig. 9 (b)), Holo Tabletop [136], and Situated Modeling [137] utilize the information from physical environment to support users' 3D design. The tangible and haptic feedback complement the touch sensation of users about a 3D model besides the visual feedback. CADLens [138] renders the haptic feedback for navigating CAD models, while other tangible feedback such as pressure-based tactile, and vibrotactile feedbacks [139] are utilized to support the interactions.

Integration of virtual design and physical fabrication In many applications, the immersive techniques, integrated with CPS-equipped fabrication systems, merge the gap between virtual design and the physical fabrication. A recent work [101] connect a hand-held AR device with an internet accessible 3D printer, and realize an end-to-end design to fabrication pipe line for customized design and fabrication. RoMA [102] synchronizes an AR design interface and a robot-based 3D printing system for real time design and fabrication. MiragePrinter [140] overlays the product image onto the 3D printer platform and allows an interactive editing the prints during the printing process. The laser pointer is adopted to realize the interactive fabrication [141] in a laser cutter system. Besides virtual feedback, the tangible feedback is also utilized to enable the interactive fabrication. FreeD [120] (Fig. 9 (c)) provides the tangible feedback in a sculpturing process and meanwhile keeps an update of intermediate geometries of the sculpturing progress on the virtual objects.

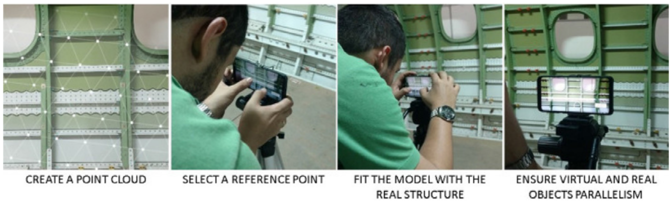
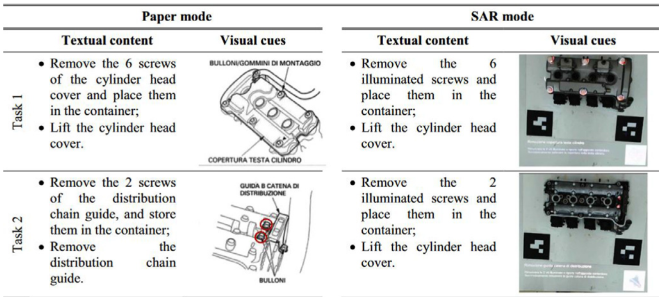


Fig. 10. Mobile augmented reality to support fuselage assembly [143].



	Paper mode		SAR mode	
	Textual content	Visual cues	Textual content	Visual cues
Task 1	• Remove the 6 screws of the cylinder head cover and place them in the container; • Lift the cylinder head cover.	BULLONI/GOMMINI DI MONTAGGIO COPERTURA TESTA CILINDRO	• Remove the 6 illuminated screws and place them in the container; • Lift the cylinder head cover.	
Task 2	• Remove the 2 screws of the distribution chain guide, and store them in the container; • Remove the distribution chain guide.	GUIDA B CATENA DI DISTRIBUZIONE BULLONI	• Remove the 2 illuminated screws and place them in the container; • Lift the cylinder head cover.	

Fig. 11. Two similar sequential procedures for engine maintenance with paper and SAR instructions. The instructions about the identification of a component, in the SAR mode, are given red “coloring” the interested area [76]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6.2. Applications in fabrication

One of the major applications of immersive display technologies and interaction modalities is the fabrication process of products, and the applications of these technologies, such as AR lenses or AR projections onto the workbenches, have shown their advantages in improving the fabrication efficiency and reducing the number of operational errors [10].

Assembly In typical metal fabrication processes, assembling, one of the major fabricating steps, utilizes immersive technologies extensively to improve worker's performance. As mobile devices (PDAs, smart phones, miniature PCs) develop since late 1990s, handheld augmented reality (HAR) has attracted more and more attention in assembling operations as shown in Fig. 10, due to its good portability and ease of implementation [10]. Elia et al.'s study highlights that handheld devices are ranked as the most reliable system by comparing with projectors and HMDs [142].

As another display technique, the digital projectors have also been implemented into actual assembly operations [2,144,145] with a display solution for visualizing both physical parts and instructions simultaneously, as shown in Fig. 11. The advantages of projection based augmented reality have been comprehensively investigated by Funk et al. [146] through a comparison of the performance of a in-situ projected system with pictorial instructions, video instructions, and contour instructions in a manual assembly environment.

As the third display option, HMDs have been used in fabrication processes since the beginning of AR, as shown in Fig. 12, due to the advantage in directing their attention to the tasks at hand [89] and decrease the mental processing required to complete the tasks which resulted in the reduction of errors [76]. The AR systems with the Google Glass and the Microsoft HoloLens have been tested in a device assembly setting [2,89]. However, by comparing with the other two options, AR HMDs may cause discomfort to the worker, such as headache or dizziness, after prolonged use [11], which is the major reason to mainly apply this technique in the assembly training rather than the actual assembly process.

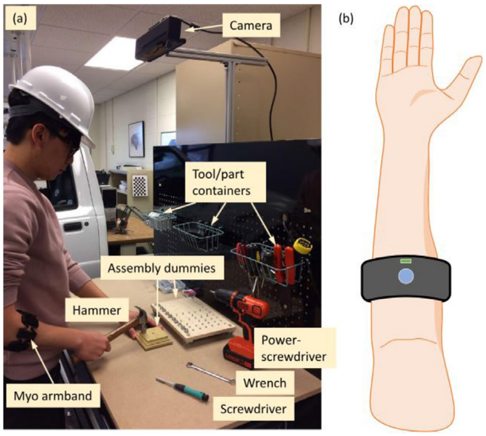


Fig. 12. (a) Data collection setup; (b) Wearing orientation of a right-hand [149].

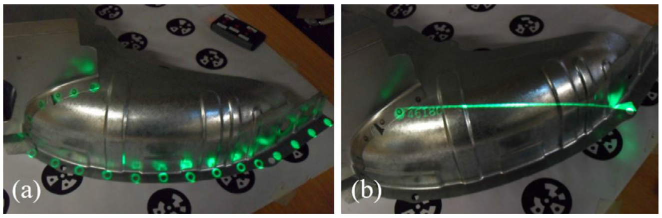


Fig. 13. (a) Multiple welding spots are displayed on an unpainted metal car part at the same time, (b) an arrow line from previous spot to the current spot helps operators to locate the spot [152].

In the era of Industry 4.0, human-robot collaboration (HRC) plays an increasingly important role in the assembly environment, and advances in display technologies enable interaction modalities in operator support systems between human and robot. Human activity recognition (HAR) based on motion capture and wearable sensors has been extensively investigated in assembly applications [147–149]. In addition, safety in HRC is another important research topic which has been well studies by recent studies [150,151].

Welding Besides assembly-related applications, the projection based augmented reality has also been used in typical applications in the automobile industry, such as spot welding. General Motors (GM) also conducted A series of studies in which they used SAR in their spot-welding operations for vehicle panels [79,152] as shown in Fig. 13, and it has been proved that the use of visual markers on the panels led to a significant increase in the precision and a decrease in the standard deviation of the operational errors for the welds. By comparison, the applications using HAR and HMD devices are relatively rare in welding applications due to the special working environment.

Considering over 50% of industrial robots are used for various welding operations in the US and globally [153], the interaction between operators and robots has been primarily studied to enable human welders to implement welding task off-site as shown in Fig. 14. To effectively realize this working mode, how to accurately track operator's motion and minimize the time delay become major research topics by recent studies [154,155].

6.3. Training

Since there is a shortage of skilled workers throughout the manufacturing industry, immersive technologies can additionally serve as a training device for unskilled workers entering the manufacturing industry. Many of the skilled laborer tasks involve repetition to learn the proper technique, positioning, etc., but by hav-

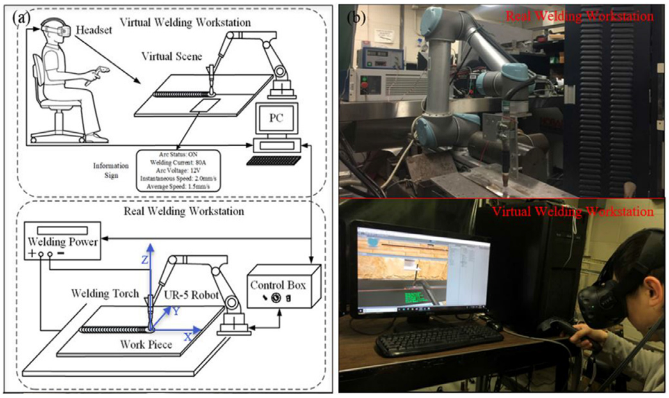
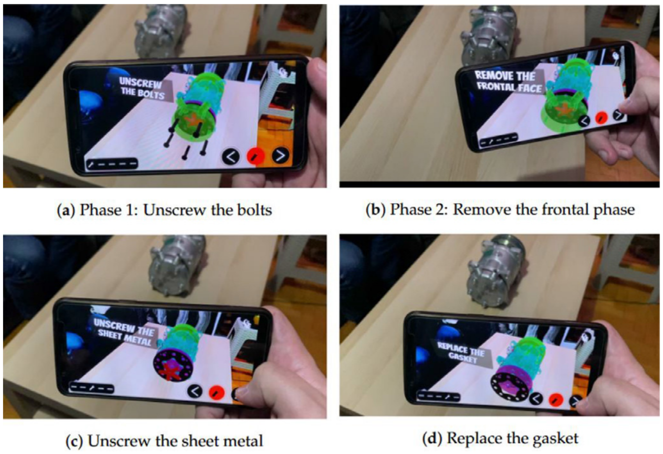


Fig. 14. Diagram for system configuration (a) schematic, (b) practical [154].

ing the trainee instead train and learn to use the setup in the immersive environment, it would reduce the time needed for other workers to spend training the new hire and would reduce the resources that the trainee would be using before they are able to perfect their technique. The immersive environment for a training simulation would feature a room with the device they are going to be training on. Within the simulation the user can interact with the device as they normally would and teaching scripts can be utilized within the simulation, for the immersive device to assess the quality of their virtual machining. Upon the completion of the training module the device could allow for a report to be viewed by the trainer to determine the progress of the trainee and from that report determine when they are ready to move onto the physical machine. The immersive environment enables repetitive training for muscle memory to generate high quality operations, such as welding [4]. Augmented reality has also been designed for use in CNC machining to simulate the cutting process in the virtual workspace to cut down the training time and make the training more efficient [10]. In addition, training in a virtual environment prevents the risks associated with machine damage or individual injury involved in real-world training [156]. While, hands on training will still be needed after the completion of the virtual training, this technique for training could save a company on time and resources it will need to invest in a new hire, if unskilled or only entry level [4,156].

6.4. Maintenance

Another major industrial application of immersive display technologies and interaction modalities applied is maintenance. As machine tools becomes even more sophisticated in modern manufacturing factories, the maintenance activities require more complex procedures and expertise in various areas, and any delay due to maintenance can slow down the entire manufacturing process. The AR-assisted maintenance systems offer a solution to support the maintenance engineers. The mobile HAR devices have been utilized in maintenance activities to help locate potential failures and generate AR-based maintenance instructions [157] as shown in Fig. 15. The process of conducting the repaired maintenance through a digital media has been referred to as "Tele-maintenance". This process usually involves a virtual team that can work with the onsite maintenance staff to guide them through the unfamiliar repair works [158]. To realize this intelligent service, as shown in Fig. 16, AR HMDs have been extensively studied to improve maintenance staff's working performance with better spatial awareness and higher usability [158]. However, it has also been found that, by comparing with other handheld device or paper manual methods, the use of AR HMDs yielded longer completion times for those specific steps with ambiguous instructions [159], and such research result has been proved by Pringle el al.'s study [160].



(a) Phase 1: Unscrew the bolts
(b) Phase 2: Remove the frontal phase
(c) Unscrew the sheet metal
(d) Replace the gasket

Fig. 15. Demonstration of the maintenance steps of an A/C compressor in amobile device [157].

Fig. 16. Application of industry-ready AR HMD on real Maintenance Tasks [160].

Fig. 17. A virtual factory model was created based on the planned layout [164].

Due to the new challenges of maintenance industry in safety and availability at minimum cost, new maintenance forms, e.g. remote maintenance and collaborative tele-maintenance, have been proposed and tested in various maintenance applications, and the integration of immersive display technologies and interaction modalities provides a solution to effectively operate various maintenance processes, including diagnosis, repair, and analysis [161]. If a manufacturing robot is being reprogrammed at a remote site, there is the ability to use augmentation features to take in the spatial information from around the device and to be used by technicians while completing the repair of the device to understand the current working conditions of the machine [10].

6.5. Logistics

One the most persistent uses of VR technology in the manufacturing environment is the use of VR simulated environments to model factory and shop floors to organize and plan out assembly spaces [42], as shown in Fig. 17. By using a virtual environment, designers and engineers can get a better sense of layouts for assembly processes that make the most sense based on the floor plan of the plant, and the scene can be interacted with by multiple users and testing of the proposed design can be conducted before implementation of the system [10]. A lot of machines which have been modeled in CAD software can be directly implemented into a VR setting [12], but the accuracy and availability of those models restrict the wide application of VR in logistics. By comparing with VR environment, if the up-to-date virtual environment is required, AR allows more flexible planning activities and reacts more efficiently to the changing market demands [162]. A factor that is leading to this extensive use in factory layout planning is the low cost of the RGBD 3D sensors to acquire real time data from the shop floor, including the flow of workers, materials, and equipment around the facility floor. To create the virtual environment a basic model is required first in CAD and then the sensor can overlay the area with more detailed information that it is taking in from the environment [163]. However, a large downside to this technology is the need for the virtual simulation to exactly mirror the environment in real life, if the simulation is not exact, this can cause a solution designed in the virtual environment to no longer be effective [11].

7. Discussions and future trends

7.1. Interfaces for personal fabrication

Recently, “personal fabrication” [165] (PF) has become an emerging research field in Human Computer Interaction (HCI) and related disciplines. In personal design and fabrication, ordinary people turning from “consumer” into “maker”, tend to express their creativity by designing and fabricating personalized products. Personal design and fabrication are mainly driven by the development of the Do-It-Yourself (DIY) culture and the maker movement [166], as well as public access to digital fabrication tools [167] (3D printer, laser cutter, and milling machines, etc.). On one hand, PF democratizes the fabrication, substantially increases the flexibility, creativity, complexity, and degree of customization of the product fabrication. On the other hand, this new paradigm brings up new challenges and requires new techniques to support it. Different from the conventionally paradigm of fabrication, which is centered by the centralized fabrication facilities, PF is more distributed, and centered by each individual maker. To support the maker, who is even a novice in product design and fabrication, the immersive techniques are expected to play an important role in different aspects of PF.

In the design stage, the VR techniques, incorporated with versatile interaction, can transfer the conventional modeling tools with WIMP interfaces and 2D display to a full 3D environment with more intuitive interactions for navigating, manipulating, and editing 3D design. The AR techniques provides the context of the physical environment with the physical appearance, dimensionality, spaciality, and geometry information, which allows the users to design products according to the requirement and constraint from the physical environment. Another important support for novice users is the assistance to enforce the functionality constraints, and fabricability constraints to the designs. The immersive techniques can be utilized to display the simulation and process preview to make sure these constraints are properly enforced.

In fabrication stage, the novice users usually require more information and assistance to operate the fabrication machines, assemble parts, and testify the final product. The immersive techniques will be the best fit to display these necessary information, and work together with the different interaction techniques to enable a more intuitive operation of the complex fabrication systems. Ultimately, the immersive techniques will be combined with computer vision, AI, process planning and simulation, and geometry model together, to provide a more intelligent work environment to support users in PF.

7.2. In-situ assistance

The current uses of immersive technologies have the potential to improve workers’ performance by guiding them to the interested item or placement location, responding to their actions, or signaling to them if the completed action of the task was correct [2,89]. This will be a new method with a bright future to outperform the traditional paper manual method or the static screen assembly process. The reduction in cognitive workload with immersive technologies has shown a sign to open more product development opportunities to those who may be cognitively impaired [12]. Engagement for workers may be increased to keep them focus on task during the workday, by providing feedback and a gamification of the tasks.

However, a guidance system developed with immersive technologies may be a hindrance to some skilled/longtime workers [2]. The user may be able to operate at a faster pace than the guidance system, but the user would need to stay on pace with the system. So in this regard, the system may be only used for training purposes, while the user familiarizes themselves with performing unaccustomed tasks. Moreover, latency issues could severely affect the performance of the worker when using a HMD device. The rendering rate needs to remain below the level of human realization which is 5ms. Anything above this, a human will register the discontinuity and may begin to feel the effects of motion sickness [10]. Thus, this presents a critical requirement for advanced methods for rendering. For HMDs, visual fatigue could slow the productivity of the worker down if the worker is wearing it to perform a task for an extended period of time. Another important aspect when considering if HMDs should be implemented into a facility is the level of the acceptance the workers have regarding this technology.

Moreover, in the logistics department, the use of remote technicians to guide the on-site maintenance staff would allow for a reduction in the time it takes to repair a broken-down machine. If the company is able to remotely monitor/maintain the machine through a combination of AR and real world monitoring systems, periodic assessments of the machine can be and cause of potential problems can be identified without sending a technician to site.

7.3. Collaborative manufacturing and training

The use of immersive technology from a design and product development standpoint helps increase the collaboration by allowing interaction in a 3D space using projections or networked HMDs to alter aspects of the design. The ability to view the design virtually or through a mix with the real environment can help speed up the process of product design since the amount of prototyping to see the effect of simple design changes can be minimized with the use of immersive display devices [11].

In the recent development trend of immersive technology, the use of AR provides a great ability to reduce the cognitive workload of an individual, and allows for more individuals who are cognitively impair to take on new jobs and tasks. The ability for the user to train virtually, can be expanded to many other industries not just manufacturing. While the devices like HMDs, could theoretically be in use all day, the majority of workers may eventually find them distracting and a hindrance, but HMDs may be a good fit for the initial training stages. Furthermore, the technology and sensors need to continue to improve. The current state provides some benefits, but the current plant wide design, and advanced monitoring of the flow of workers, materials, and equipment across the plant is still a few years out, since it is only available in a limited capacity currently.

7.4. Tracking-enabled support and analysis

As the eye tracking ability of the devices continues to improve, users could begin to interact with the device through eye movements, which can be useful in an assembly line setting to bring up more instructions if needed, or hide them if not needed, to minimize the visual strain and/or distraction to the user [89]. Furthermore, eye tracking measures the gaze and the motion of eyes to indicate how human perceptually processes information when interacting with a device while performing a task [168]. Analysis of eye gaze exposes cognitive processing at the level of visual perception, which is relevant to domain expertise of skilled workers. There have been an increasing amount of effort to develop advanced AI/machine learning models to analyze human eye movement sequences [169], especially when performing domain specific tasks in knowledge-rich domains, such as medical diagnosis [170]. Useful patterns have been extracted that contribute to the understanding of experts' tacit knowledge related to their decision-making process [171,172]. The results also show a clear distinction between the eye movement patterns learned from experts and novices.

With the increasing support of the state-of-the-art immersive technologies, large-scale high-quality eye movement data could be conveniently collected from skilled workers during the manufacturing and product development process. A promising future direction is to develop novel AI/machine learning models to extract useful eye movement patterns from skilled workers. It is also interesting to study the relationship between eye movement and human behavior data in other modalities, such as language and motion, assuming that a multimodal data set can be collected and jointly analyzed. Multimodal data fusion can better capture the underlying human cognition, which is an inherently multimodal process [171]. The learned multimodal patterns will provide a valuable resource to train next-generation skilled workers.

8. Conclusions

This paper reports the use of immersive technology for industrial product development. We have focused on reviewing three aspects of immersive technology including CAD modeling and rendering methods, display technologies, and interaction modalities. We also discussed their applications in product design, prototyping, fabrication, training, maintenance, and logistics. The methods, technologies, and applications reviewed in this paper were retrieved from the publications in the past ten years, which is the time that the manufacturing industry increasingly takes the advantage of immersive technology. As the 5G technology begins to roll out, the problems with lag and other visual discrepancies may be minimized. Additionally, as the degree of FOV of HMDs, reliability of intuitive interaction modalities, and rendering speed are improving, more companies may begin to see a use in the technology and begin implementing it into their own company.

There is room to improve CAD modeling and rendering methods to meet the demand on high-performance simulations and in-situ real-time applications, as well as on the capability to work with a variety of display devices. HMDs tend to be used for guiding users, through series of tasks, for either assembly or maintenance purpose, or for simulation of a VR environment to plan out the logistics of a plant or factory. The integration of HMDs with eye trackers can help improve users' cognitive process at a visual perception level. Handheld devices are commonly used in maintenance tasks, while projectors have been used in new product development, assembly, and fabrications or when collaboration is needed between users. With the improvement of computer vision algorithms and motion tracking devices, we were aware that the NUIs for interacting with devices have been tailored for supporting intuitive, multinodal interactivity, which are adopted in the product development process to facilitate human ability on product design, machine operations, robotic controls, and simulations.

Use cases and results from the literature indicate that immersive technology has started flourishing in the product development, and its popularity continues to grow in the era of Industry 4.0. New research challenges are outlined in this paper for the community, in regards to the fields of computing, interaction, devices, and applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rui Liu: Methodology, Data curation, Writing – original draft, Writing – review & editing. **Chao Peng:** Methodology, Writing – original draft, Writing – review & editing. **Yunbo Zhang:** Methodology, Writing – original draft, Writing – review & editing. **Hannah Husarek:** Data curation, Writing – original draft. **Qi Yu:** Writing – original draft, Writing – review & editing.

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