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Review

Augmented Reality and Artificial Intelligence in industry: Trends, tools, and future challenges

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ABSTRACT

Augmented Reality (AR) is an augmented depiction of reality formed by overlaying digital information on an image of objects being seen through a device. Artificial Intelligence (AI) techniques have experienced unprecedented growth and are being applied in various industries. The combination of AR and AI is the next prominent direction in upcoming years with many industries and academia recognizing the importance of their adoption. With the advancements in the silicone industry that push the boundaries of Moore's law, processors will be less expensive, more efficient, and power-optimized in the forthcoming years. This is a tremendous support and necessity for an AR boom, and with the help of AI, there is an excellent potential for smart industries to increase the production speed and workforce training along with improved manufacturing, error handling, assembly, and packaging. In this work, we provide a systematic review of recent advances, tools, techniques, and platforms of AI-empowered AR along with the challenges of using AI in AR applications. This paper will serve as a guideline for future research in the domain of AI-assisted AR in industrial applications.

1. Introduction

Industry requirements change every year as the global competition drives continual technological advancement. Augmented Reality (AR) is among the leading technological applications in various domains (Carmigniani, Furht, Anisetti, Ceravolo, Damiani, & Ivkovic, 2011). AR is computer-generated virtual information superimposed onto the actual scene called rendering, which is the process of displaying digital information in a realistic manner (Dubois & Nigay, 2000) such that it appears to be a part of the actual environment (Display) (Zhou, Duh, & Billinghurst, 2008). While there are many other forms of superimposition of computer-generated objects to "enhance", i.e., deepen or broaden one's understanding of the "reality", AR is the most widely used (Cheng, Zhang, Fan, & Harris, 2018; Craig, 2013). Recently, there has been groundbreaking development in the field of AR, and it has been widely adopted in many industries, including gaming (Kumar, Kumar, Yadav, & Johri, 2021), education (Ali, 2020), and entertainment (Mahmood, Ali, Muhammad, Bibi, Shahzad, & Azmat, 2017). Developers create inputs in the digital world that adapt to the changes in the user's environment in real time, such as motion, graphics, and GPS overlays. It has enormous potential when integrated with machine learning (ML) techniques since the recent ML algorithms have achieved great success to process and extract information from images. AR applications have been considered significantly helpful to improve efficiency and efficacy in industrial operations (Fraga-Lamas, Fernández-Caramés, Blanco-Novoa, & Vilar-Montesinos, 2018b). Fig. 1 depicts four layers design of AR, ranging from object detection to display associated with AR applications.

Mixed reality (MR) hybridizes physical reality with virtual reality in which the physical and virtual worlds can interact, whereas AR occurs in the physical environment but with information added virtually. MR experiences can be achieved through MR glasses such as Holographic devices (Kozek, 2020). AR, on the other hand, can be experienced through a variety of devices, including AR glasses and smart phones/tablets. AR is emerging as part of the Industry 4.0 revolution due to the popularity of the devices (De Pace, Manuri, & Sanna, 2018).

Industry 4.0 describes the present state of the manufacturing industry. Mechanization, mass production, and automation were key ideas for Industry 1.0, 2.0, and 3.0 revolutions, respectively (Ababsa, 2020). Industry 3.0 has seen many robots and sensors on the plant

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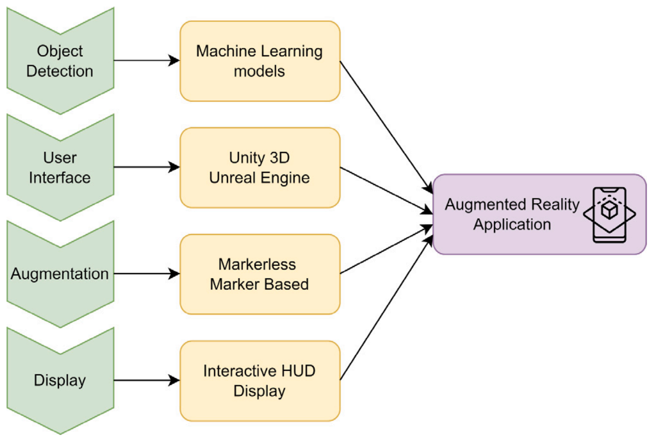

Fig. 1. AR's four layers design ranging from object detection to display.

floor, automating all potential production tasks. Industry 4.0, also known as smart manufacturing, is based on technologies that aim to (1) accelerate the remaining work that requires human expertise and skills; (2) combine intelligence with automated infrastructure to make robotic systems autonomous and capable of making decisions based on data (Rüßmann et al., 2015). Artificial Intelligence (AI) and ML techniques are promising to improve flexibility and effectiveness of AR systems. The tremendous success of AI/ML in object detection and related tasks demonstrates their applications in the AR domain. AI has the potential to revolutionize AR applications in the same way that AR has revolutionized manufacturing. AI has already made significant improvements in manufacturing industries (Liu, Rai, Purwar, He, & Mani, 2020), and more implementations can be introduced into applications, such as inspection (Zhang, Jaiswal, Rai, Guerrier, & Baggs, 2019) and information management for materials (Furini, Rai, Smith, Colombo, & Krovi, 2016).

In this study, we provide a detailed literature review for AR and AI applications in the industry. We keep our survey limited to the articles published between 2010 and 2021. Given that articles are published in multiple sources, we focused our search on three prominent publishers: IEEE, Springer, and Elsevier. In order to limit ourselves to the review topic, we used keywords such as 'Augmented Reality (AR)', 'Artificial Intelligence (AI)', 'Industry', and their combinations. The purpose of including these keywords in our study was to cover various AR platforms and frameworks and AI/ML approaches such as regression (Maulud & Abdulazeez, 2020), classification (Schapire, 2015), neural networks, deep learning (Nielsen, 2015), and reinforcement learning (Sutton & Barto, 2018) along with their contribution to AR in the industry applications. We searched on Google Scholar with keywords used in Table 1 and looked for papers that mentioned AR and AI. We reviewed the first ten pages of the search result in Google Scholar as we observed that keywords started diluting into just words in papers appeared in later pages without much relation left between AR and AI. As shown in Fig. 2, the number of articles published in the field of AR is gradually increasing overall, except some reduction in the last few years. The pace at which the technology is catching up is remarkable. There is a growing trend in the publications from 2015 as many industries have started recognizing and utilizing AR.

Recently, a number of survey articles related to AR and AI are published, and most of them are focused on a specific field or an industrial sector. Kaviyaraj and Uma (2021) summarized the status of AR applications in the education domain and briefly mentioned the benefits of using AI in AR applications. The article highlighted applications of AR in existing learning scenarios, which aim to motivate interactive learning environments. Another work by Gandedkar, Wong, and Darendeliler (2021) provided an insight into the role of AR and

Table 1
The keywords used for the literature search for AI and AR articles in the context of industry that were published between 2010 and 2021.

No.	Keywords Used
1	Artificial Intelligence and Augmented Reality in industry
2	AI and AR in industry
3	Deep learning and augmented reality
4	Deep learning and AR

AI applications in the field of orthodontic teaching and research. It outlined the limitations of traditional teaching in the field and illustrated the potential of AR and AI in effective learning and conducting research. Sahu, Young, and Rai (2021) reviewed current AR strategies and identified the limitations of current approaches utilized in AR systems. Corresponding AI solutions to the AR computational pipeline were also discussed. In a recent work by Szajna and Kostrzewski (2022), the need for AR and AI tools in sustainable working environments is emphasized. The authors discussed the benefits associated with AR-AI applications including job simplification and work efficiency. Our work fills the gap in the existing literature by providing a more comprehensive review of AR and AI applications related to various industries in a systematic way. Specifically, we discuss fundamental AR frameworks that are utilized in the industry as well as platforms that are used to create these AR apps. In addition, we explain how AI can be utilized in conjunction with AR to benefit various industry sectors. Lastly, the challenges in AI approaches for AR-assisted manufacturing applications are also outlined. The primary contributions of this work are listed as follows:

- Provide a detailed review of AR and AI research related to various industries.
- Perform a comprehensive analysis of current tactics used for AR computational component.
- Investigate platforms and frameworks that are being used to build different types of AR applications.
- Summarize the challenges and identify a number of potential areas in the AR ecosystem for future research.

The remainder of this paper is organized as follows. Sections 2 and 3 provide a thorough discussion of the various techniques, platforms, and frameworks used in the industry. Section 4 gives a review of the application of AR and AI in different industry sectors. Section 5 covers the most critical and promising areas for future research developed from or influenced by the findings of previous sections. Finally, the work is summarized and concluded in Section 6.

2. Machine learning methods

Recently, AR and ML techniques are gaining huge popularity in the industry. Object detection techniques powered by AR and ML can integrate the current world with the industry sector to provide an enhanced experience. Deep learning (DL) – a sub-field of ML consists of state-of-art algorithms – aims to develop unique solutions for many real-world challenging applications. DL techniques consist multiple processing layers to learn hierarchical representations of data with multiple levels of abstraction (LeCun, Bengio, & Hinton, 2015). They are applicable to a wide range of domains since they provide a plethora of valuable and novel applications, solutions, and services. They will become even more popular in the near future as more complex algorithms and architectures are developed (LeCun et al., 2015). Some of the most significant areas of DL applications include computer vision, natural language processing (NLP), sentiment analysis, social computing, and speech recognition.

Cheng et al. (2018) demonstrated that combining Convolutional Neural Networks (CNN), a popular DL algorithm, with AR and AI is highly promising. In the realm of computer vision, CNN-based DL

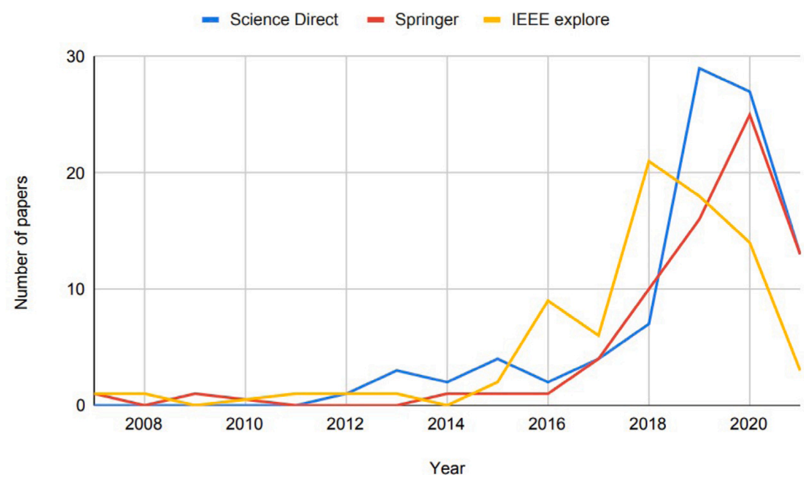

Fig. 2. AR articles in the context of industry published between 2010 and 2021.

Table 2
Pros and cons of three deep learning methods.

Methods	Pros	Cons
YOLO v3	Faster than SSD	Performance drops significantly as IoU (Intersection over Union) threshold increases
MobileNet	Reduced computational cost and model size	Relatively less accurate
SSD	Simple and faster than YOLO	Not skilled for detecting small objects

models have become essential tools for dynamic image identification problems. There is an abundance of DL-based object detection techniques by which AR can be accomplished efficiently and instantly, including YOLOv3 (Redmon & Farhadi, 2018), MobileNet v2 (Sandler, Howard, Zhu, Zhmoginov, & Chen, 2018), and SSD model (Liu et al., 2016). Table 2 summarizes pros and cons of these three models (Huang et al., 2017; Zhao, Zheng, Xu, & Wu, 2019).

2.1. YOLOv3

YOLO (You Only Look Once) (Redmon, Divvala, Girshick, & Farhadi, 2016) enables end-to-end training and performs incredibly fast compared to other DL-based object detection techniques. The merit of YOLO method is that it unifies the separate components of object detection framework into a single neural network and reasons objects globally, which enables its real-time object detection capability while maintaining high average precision. An improved version of YOLO method called YOLOv2 (Redmon & Farhadi, 2017) uses anchor boxes to predict bounding boxes and introduces a new classification model named Darknet-19. A faster version of YOLOv2, called Fast YOLO (Shafiee, Chywl, Li, & Wong, 2017), enables real-time object detection in videos displaying on resource-constraint embedded devices. Fast YOLO creates an optimized architecture through evolutionary deep intelligence framework, which is then used within a motion-adaptive inference framework to accelerate object detection while reducing energy consumption of the embedded device.

YOLOv3 (Redmon & Farhadi, 2018) is a newer version that operates in 22 ms at 28.2 mAP (mean average precision) on a 320×320 input image, which is three times quicker than SSD (Liu et al., 2016). When compared with YOLOv2, YOLOv3 is a bigger network but with better accuracy.

2.2. MobileNet

The MobileNet model is built on depthwise separable convolutions, a type of factorized convolution that divides a regular convolution into depthwise and pointwise convolutions (Howard et al., 2017). The depthwise convolution used by MobileNets assigns a unique filter to each input channel.

MobileNetV2 includes a fully convolutional layer with 32 filters followed by 19 residual bottleneck layers (Sandler et al., 2018). A consistent expansion rate is employed throughout the network except the initial layer. The experiments conducted by Sandler et al. (2018) discovered that the expansion rates between 5 and 10 produce almost identical performance curves, and lower expansion rates are suitable for smaller networks while higher expansion rates are good for bigger networks. MobileNet has achieved significant performance in object detection, image classification and segmentation tasks, along with highly memory-efficient inference. A more detailed architecture can be found in the work by Sandler et al. (2018).

2.3. Single shot multi-box detector (SSD)

SSD splits the output space of bounding boxes into a collection of default boxes spanning several aspect ratios and sizes for each feature map position, allowing for object detection in images or videos using a deep neural network (Liu et al., 2016). SSD is straightforward compared to approaches that rely on object proposals since it removes proposal development and subsequent pixel or feature resampling steps, encapsulating all processing in a single network (Endres & Hoiem, 2010). SSD is simple to train and integrate into systems that require a detecting component. In addition, it uses a feed-forward convolutional network to generate a fixed-size array of bounding boxes and score for the occurrence of object class instances in those boxes, accompanied by a non-maximum suppression step to provide final detection. Besides, it adds auxiliary structures to provide detection with properties: multi-scale feature maps and convolutional predictors for detection along with default boxes and aspect ratios.

3. Augmented reality frameworks and platforms

Incorporating cognitive technologies into AR (Shelton & Hedley, 2004), photographs become immersive and engaging in this digital era, providing a better and comprehensive knowledge of a subject. It is a widely used technology that allows organizations to graphically depict products, services, techniques, processes, and other items to users. Many companies utilize AR (Fraga-Lamas, Fernandez-Carames, Blanco-Novoa, & Vilar-Montesinos, 2018a) applications to increase user engagement and efficiently and convincingly depict their subjects. Industries that create AR apps continually improve user experiences by providing brands and SMEs with visually rich and novel ways to

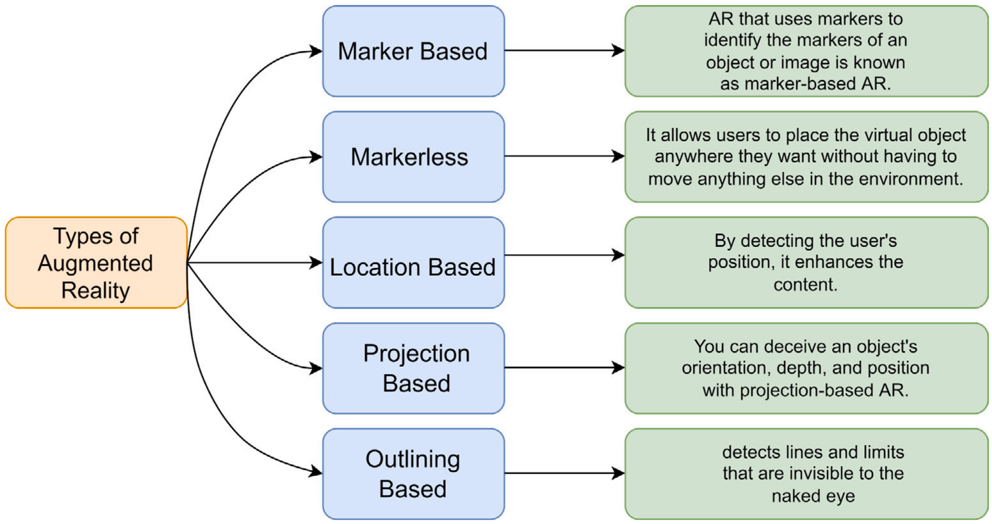

Fig. 3. Different types of Augmented Reality applications.

portray digital material. Moreover, they are doing it using a variety of AR approaches, some of them are described in Fig. 3.

Augmented Reality SDK (Software Development Kit) provides APIs for different tasks within the AR application including object recognition, object tracking (Azuma, 1993), and content rendering (Lee, Moon, Ko, Lee, & Yoo, 2020). The module for recognition works as the brain of the app. The tracking module serves as eyes for the AR experience, while the content rendering component creates imaginative virtual objects and scenes on the real-time information. The APIs are provided to developers through SDK for recognizing, tracking, and rendering in AR applications efficiently (Amin & Govilkar, 2015).

Several broad categories may be used to organize AR SDKs: Natural Feature Tracking (Neumann & You, 1999), Geo-located AR Browsers (Khan & Andy, 2011), Marker-based AR (Katiyar, Kalra, & Garg, 2015), and Browser SDKs (Amin & Govilkar, 2015). A few of them allow users to construct geo-located AR apps utilizing the GPS and IMU on today's smartphones and wearables. Marker-based SDKs build AR experiences by using specific pictures called markers (Gherghina, Olteanu, & Tapus, 2013). By monitoring planar pictures or using a SLAM (Simultaneous Location and Mapping) technique (Durrant-Whyte & Bailey, 2006), Natural Feature Tracking SDKs depend on the characteristics that really exist in the environment to accomplish the augmentation.

Building an AR system from the ground up is challenging and time-consuming. Many AR frameworks and platforms are created to assist developers focusing on higher-level applications rather than low-level implementations. Next, we will explore a sample subset of the existing platforms and frameworks. A summary is provided in Table 3.

3.1. ARBlocks

ARBlocks (Roberto & Teichrieb, 2012) is a dynamic block-based platform aimed towards early childhood educational activities, based on projected augmented reality and physical user interfaces. The apps and the platform itself were created to help educators teach general subjects to children, such as arithmetic and language skills, as well as help them build crucial skills like motor coordination and collaboration.

3.2. ARCore

ARCore is Google's AR platform (GoogleARCore, 2018; Lanham, 2018) that allows a user's phone to perceive its surroundings, interpret the real world, and interact with information through various APIs. ARCore is mainly designed to work on various Android phones running Android 7.0 and later. To allow shared AR experiences, several APIs are available across Android and iOS as listed below (GoogleARCore, 2018):

- Motion tracking: ARCore employs feature points to compute its change in position by detecting visually distinguishable features in the acquired camera picture.
- Environmental understanding: ARCore is able to detect key points that present similar horizontal or vertical interfaces, such as tables or walls, and makes these surfaces available as geometric surfaces to customers' app. ARCore can also detect the border of geometric plane.
- Depth understanding: ARCore can use the primary RGB camera to build depth maps that contain information about distances of surfaces from a specific position.
- Light estimation: ARCore can recognize information about its environment illumination and present the typical camera image's intensity and color correction.
- Oriented points: ARCore employs hit testing to project a beam into the phone camera's view of the world.

3.3. ARKit

The AR application development kit (ARKit) was launched by Apple around June 2017 (AppleARKit, 2017; Wang, 2018). This iOS specific kit allows the user to develop AR apps for iPhones and iPads running iOS 11 or above. All iOS developers with an Apple developer account may use ARKit SDK. Apple ARKit 5 is the most recent version, which was unveiled at Apple Worldwide Developers Conference (WWDC) in 2021 and provides new features for AR (AppleARKit, 2017):

- Expanded Face Tracking support: The ultra wide camera in the iPad Pro (5th generation) now supports face tracking as well. The TrueDepth camera can track up to three faces at once.
- Location Anchors: AR projects may be anchored at a certain latitude, longitude, and altitude using Location Anchors.
- Depth API: This API may leverage per-pixel depth information about the surrounding environment due to the LiDAR Scanner. This depth information when paired with the 3D model data created by Scene Geometry makes virtual object occlusion even more realistic by allowing for fast placement of virtual objects.
- Scene Geometry: It makes a topological map of rooms, labeling objects such as floors, doors, etc.
- Instant AR: The LiDAR Scanner offers exceptionally fast plane identification, allowing AR items to be placed in the actual environment without having to scan them.

Table 3
Characteristics of various AR platforms and frameworks.

Platforms	Characteristics	
ARBlocks	• Good visualization and Tracking	• Relatively slow
ARCore	• Good understanding of the environment.	• Good for gaming. • AR Tracking is not consistent • Not stable on older generation devices
ARKit	• Instant AR (Using Lidar) • Good AR rendering devices • supports old devices	• Only for iOS and iPad OS • Free for Xcode features • Charges for app distribution
AR-media	• Offers Cloud based services for AR	• Easy AR project development without coding skills. • Free registration. • Depth mapping is not available yet
ARToolKit	• Processing happens in real time • fast AR placing is possible	• Can be used only with image markers. • Free and open source
ARWin	• Can be categorized based geometry • Interact in the virtual environment	• Camera resolution constrains more accurate tracking, • Careful calibration of markers is required
Bright	• Comfortable AR HMDs (HoloLense) • Text to speech • Local Processing	• Slow processing as it is done locally • Improper control over functionality
CoVAR	• Eye-Gaze based interaction • Head-Gaze based interaction • Hand Gestures based interaction	• Simulator Sickness • Only head tracking is visible
DUIRA	• Create a realistic virtual digital environment • that reflects real-world experiences	• Requires multiple AR markers • Angle changes in AR markers leads to create different effects
KITE	• Quickly assembled from existing hardware • Initialization is simple	• Only available on a desktop system • Algorithm for mesh reconstruction is not accurate and stable
Nexus	• Spatial-aware applications • Easy and common infrastructure.	• Needs to stores and manages the location information globally • Harder location-aware communication concepts
Vuforia	• Most widely used (Documentations available) • tracking is flicker-less	• Paid license is required for advance AR features
WARP	• A well defined Layered Structure architecture	• Relatively slower processing
Wikitude	• Geo-based tracking available	• License needed for the app development

- People Occlusion: Enable immersive AR experience by passing front and back of people in the real world.
- Motion Capture: Taking motion and poses as arguments to the AR experience and it performs in real-time with single camera.

3.4. AR-media

AR-media SDK (InglobeTechnologies, 2022) is built on a 3D model tracking technique that detects flat photos and complex 3D objects. A renderer for generating 3D objects, a tracker for identifying the target, a capture for recording frames from the device camera, and native Android and iOS user interfaces are all part of the SDK architecture. AR-media is a cross-platform foundation written in C/C++. This SDK can be used to construct an AR application by capturing images of the object where the user wants the target audience to interact with as well as creating a 3D model that will be overlaid on the tracker established on the online SDK server. OpenCV, natural feature trackers; OpenNI (Falahati, 2013), which allows motion capture with depth cameras; and Inglobe Tracker, a sophisticated 3D tracker, are all included in the framework. Following are the key features of AR-media (InglobeTechnologies, 2022):

- Cloud-based services are available for creating and managing 3D targets.
- Fine-tuning of the findings is easy as several tracker settings are available for tweaking.
- To interface with any other AR platform, the frame is only needed to convert to an OpenCV.Mat object and pass it to the tracker.
- Real-time 3D tracking of real-world objects in various lighting conditions is possible.

3.5. ARToolKit

ARToolKit is an open-source software marker-based AR toolbox (Kato, 2007). It is a programming package for creating an AR software that layers an interactive 3D item on an AR marker captured by a smartphone camera. Detecting the coordinates of the AR marker using computer vision techniques defines the virtual object's location and direction. ARToolKit works on various systems and uses OpenGL (Shreiner, Group, et al., 2009) for rendering; ARToolKit API is written in C language. It is multi-platform as it can be used on Windows, Mac OS X, Linux, iOS, and Android operating systems. Marker tracking techniques, calibration, and parameter collection are all included in the AR package of the ARToolKit library. The camera module has procedures for capturing video input data, while the sub-module contains graphic procedures based on the OpenGL and GLUT libraries. Additionally, a variety of ARToolKit extensions for mobile devices are available. Following are the important features of ARToolKit:

- Perform real-time AR applications.
- Code for camera calibration is easy to use.
- Position/orientation tracking with a single or stereo camera is possible.

3.6. ARWin

ARWin (Di Verdi, Nurmi, & Hollerer, 2003) is a single-user AR desktop in a 3D environment that allows both classic 2D and innovative 3D programs to populate the physical space above the user's desk, with some of them improve operations of physical objects on the desk.

The event and display manager are the two main components of the ARWin architecture as shown in Fig. 4. When used together, they substitute the functionalities of a conventional Windows X environment with a window manager. It is the role of the event manager to process

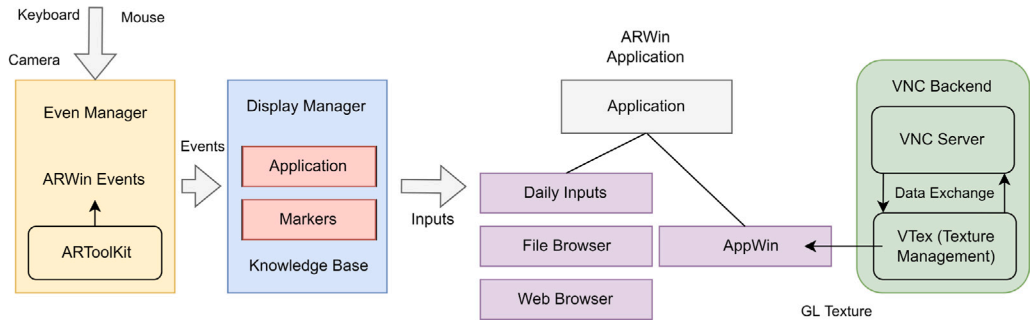

Fig. 4. ARWin workflow. Inputs (keyboard/mouse/camera) data is processed, and then communicated in the form of events, which will be displayed on the display, after which the data is processed and provided as an output by the application. This figure is modified from the work by Di Verdi et al. (2003).

input and produce ARWin-specific events. The event manager, for example, is prompted by the camera input to execute marker detection and tracking. The ARToolkit detects markers mounted to the user's workstation and walls in their office. The space above the user's desk creates a global vector space. Other input, like keyboard and mouse events, can either be passed through unchanged to the display manager or initiate more complex actions, such as window movement or menu engagement. An ARWin application is created by inheriting the App3d super class, which includes callback methods for event processing and window management services. AppWin is a particular type of program that lets users run old X programs (xterm, emacs) within ARWin. AppWin uses a virtual VNC-enabled X server to run the X program. VNC client connects to an OpenGL texture map and draws the image data to a polygon in the workspace. The targeted application is constantly oriented to face the user directly to optimize application exposure.

3.7. Bright

Bright (Bakshi, Simson, de Castro, Yu, & Dias, 2019) is a software solution for those with significant vision impairment. It uses a modern optical see-through AR HMD (head-mounted display) transparent front lenses with a projected display overlay (Kiyokawa, 2012), which contains rich features, greater ease-of-use and cheaper price.

While most AR solutions strive to enhance the user's view of the world by graphically adding objects to the actual world, their approach aimed to address the problem that persons with vision impairments may be missing out on the numerous layers of relevant information that come with vision. A third type of AR is restoring some of these contextual layers by using a speech interface to transmit the results of computational vision processing (e.g. facial recognition). Bright has to be completely self-contained and movable (i.e., not reliant on a local computer), in order to maximize ease of use and comfort. Furthermore, given the wide range of remaining visual acuity among possible users, the system has to be built to be usable even by individuals with no vision at all. As a result, all parts of the user interface have to be voice-controllable.

3.8. CoVAR

CoVAR (Piumsomboon, Dey, Ens, Lee, & Billinghurst, 2017) is a new VR and AR remote collaboration technology, which allows users to share a 3D model of AR visual interaction. Natural inputs such as eye-gaze, hand movement, and gaze cues are provided to facilitate this mixed platform cooperation.

CoVAR is a cross-collaboration solution with a server architecture in which the host server is either an AR or VR server. The Microsoft HoloLens helmet-mounted display is used for AR, whereas the HTC Vive is used for VR. The CoVAR application was created in Unity 5.6. The HoloLens is linked to CoVAR via a Wi-Fi connection on the AR side. The Vive's rendering engine connects directly to the second machine. The two devices are linked by an Ethernet with TCP/IP connection, and Unity Networking handles data sync.

3.9. DUIRA

DUIRA (Chang, Chen, Lin, & Yu, 2010) is an interactive multimedia learning platform which combines AR and Arduino capabilities for ecology education. Learners can take AR marker data using a webcam and create 3D objects on-screen, so that they can learn about plant growth through change AR platform marker.

This interactive learning platform was created by utilizing FLARToolKit, Adobe Flash, and an analog clock. Various AR Markers are taken as input signals and filtered by FLARToolKit module and Flash to able to recognize the image content of the AR Markers, and finally, 3D animation and effects are rendered.

3.10. KITE

Kite (Piumsomboon, Clark, & Billinghurst, 2013) is mobile AR platform with a magnetic tracker and a depth sensor that is generally available on a desktop system for games and interaction creation. The main goal of this platform was to show four different modalities based on hand input to provide a platform for game designers experimenting with new gaming possibilities in AR.

3.11. Nexus

Nexus (Hohl, Kubach, Leonhardi, Rothermel, & Schwehm, 1999) is a platform for mobile position-aware apps developed by the University of Stuttgart. Fig. 5 shows the architecture of Nexus platform. It supports spatial modeling, network connectivity, and virtual information representation. The architecture is divided into three layers: abstraction of client devices, uniform presentation of information, and fundamental function wrapper. To exhibit distinct data objects, a hierarchical class schema is created. To provide universal access to actual and virtual objects, it allows both local and distributed data management. To enable scalability in various application circumstances, an adaptable module is created. In terms of stability and portability, Nexus outperformed other platforms.

3.12. Vuforia

The Vuforia platform offers a robust and effective computer vision-based image recognition technology and includes a number of features that facilitates mobile applications and alleviates technical barriers for developers (Simonetti Ibañez & Paredes Figueras, 2013). Vuforia platform includes the target management system (Target manager), cloud target database, device target database, and Vuforia engine. The target that a developer wants to track is uploaded as an input picture. The mobile app then uses a cloud connection or local storage to access the desired resources. A Vuforia SDK-based AR application contains a camera that captures frames and passes them to the tracker, an image converter that converts the image sensor data to a format suitable for OpenGL ES rendering, and internal monitoring that tracks the contents

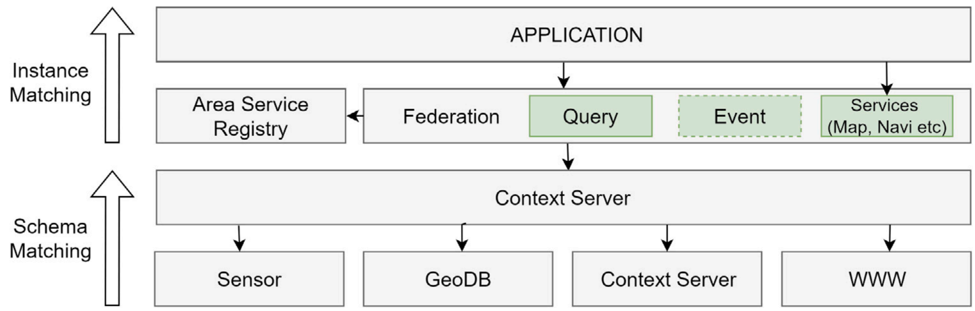

Fig. 5. Nexus (Hohl et al., 1999): The architecture depicts the application's workflow, in which data is delivered from the application to different needs, then to a server for processing, and finally to the sensor.

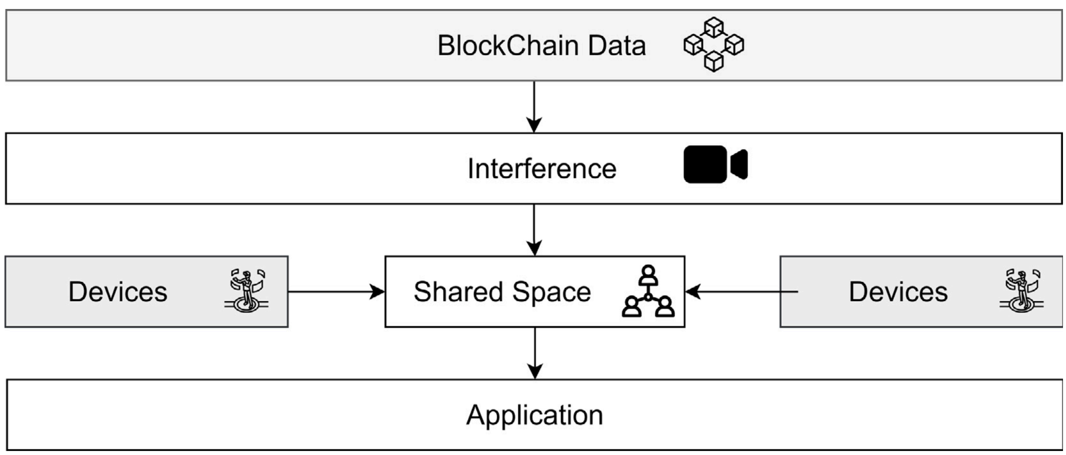

Fig. 6. WARP : Worldwide Augmented Reality Platform. This figure is modified from the work by Sosin and Itoh (2019).

of the tracker. A tracker that can import and activate many datasets simultaneously contains computer vision algorithms for detecting and tracking real-world objects in video captured frames. The SDK allows both native iOS and Android development, as well as the creation of AR apps in Unity that are readily transferable across multiple platforms. The Vuforia SDK supports multi-target setups, markerless picture targets, frame markers, and cloud recognition targets for monitoring one million targets at once. The SDK includes capabilities such as virtual buttons for localized occlusion identification, real-time picture target selection, and the ability to reconfigure and create target sets based on the circumstance. Following are the important features of Vuforia:

- Tracking is effective even when the object is partially obscured in low light circumstances.
- It provides quick local target recognition with the ability to simultaneously monitor up to five targets.
- Provides VuMarks, which are a new type of bar code for creating a unique and brand-conscious design and encode data that serves a AR target.

3.13. *WARP: Worldwide Augmented Reality Platform*

WARP (Sosin & Itoh, 2019) is an architecture that allows enthusiast organizations to contribute equally to build a sensor network. Sosin and Itoh (2019) proposed a distributed Blockchain-based architecture for storing entity pose tracking data. Users can submit tracking entities to the blockchain and distribute them via peer-to-peer network as shown in Fig. 6.

The underlying facts and foundations used by the other levels are defined by the context layer. It should have tools for quickly adjusting and expanding the scope of the monitoring area by adding or changing tracking entities and communicating these changes to all users. Inference layer receives the input from the previous layer and generates a spatial relationship graphs (SRG) around the user. SRGs, unlike scene graphs, represent connections between real-world and virtual items. Application layer required to allow for the integration of WARP-based apps. To enable the creation of a creative collaborative community, an API for this layer must be established and made available in order to nurture and build AR apps and interactions. When there is a large number of publicly accessible AR applications, widespread acceptance of such a platform will be seen.

3.14. *Wikitude*

Wikitude features picture monitoring and classification, 3D model generation with video overlay, and location-based augmented reality (Madden, 2011). The Wikitude SDK integrates geo-based and image recognition abilities that can provide hybrid tracking. It is heavily based on web technologies (HTML, JavaScript, and CSS) that allows developers to create cross-platform AR experiences known as ARchitect worlds, which are simple HTML pages that can use the ARchitect API to create AR objects. The system view component called ARchitectView may be added to the app user interface to integrate Wikitude SDK into apps. The Wikitude SDK is presently available for both Android and iOS. Following are the important features of Wikitude:

- The JavaScript API is used to enable animation.

- 2D and 3D transformations are both available.
- It has a direction indication as well as a position tracker.

4. Augmented reality and artificial intelligence in industry

4.1. Importance

AR offers a useful interactive tool for reducing cognitive load by creating a connection between the physical task and supporting documentation by displaying the information without interfering with the user's ability to concentrate (Kim & Dey, 2016). It is highly valuable in the manufacturing industry, where a variety of jobs such as assembling and maintenance must be accomplished as inexpensively and efficiently as possible.

AR applications initially started to show up in interfaces for mobile devices (Larasser & Conradt, 1992), and then began appearing in the healthcare and automotive industries in 2004 and 2005, respectively (Fischer, Bartz, & Straßer, 2004; Regenbrecht, Baratoff, & Wilke, 2005). It eventually made its way into robotics (Green, Billinghurst, Chen, & Chase, 2008), defense (Livingston et al., 2011), education (Patel, Virparia, & Patel, 2012), and construction and building management (Chi, Kang, & Wang, 2013). In 2017, it gained popularity in the retail and fashion industries (e-commerce) (Dacko, 2017), and we began to see the trend of AR and AI in tourism (tom Dieck & Jung, 2018) in 2018.

4.2. AR in manufacturing

AR can speed up industrial processes since it allows continuous information sharing without diverting the operator's attention. As a result, it has become one of the Industry 4.0's nine essential disruptive technologies (Rüßmann et al., 2015) along with big data analytic (Morabito et al., 2015), autonomous robots (Fahimi, 2009), simulation (Ingalls, 2011), horizontal and vertical system integration (Pérez-Lara, Saucedo-Martínez, Marmolejo-Saucedo, Salais-Fierro, & Vasant, 2018), Industrial IoT (Butun, 2020), cybersecurity (Kemmerer, 2003), cloud computing (Dillon, Wu, & Chang, 2010), and additive manufacturing (Gebhardt, 2011).

In the manufacturing industry, the majority of AR applications are in three areas: assembly, maintenance, and training. In order to conduct assembly sequences and processes, technicians must follow specified tasks and procedures within these three areas. Operators or staffs who take benefits of AR for installation and service can work with components or tools they have never worked with before. AR reduces the requirement for operational instructions to be memorized. Assembly operations using AR have witnessed 82% reduction in mistakes (Uijlings, Van De Sande, Gevers, & Smeulders, 2013). Several experiments have been launched to introduce AR into assembly processes. To forecast the user's assembly intent and handle virtual objects, AR was used to construct an interactive manual assembly design technique, e.g. (Chen, Hong, & Wang, 2015; Wang, Ong, & Nee, 2013) applied AR for assembling a gearbox. AR also supports remote assembly processes to meet customization expectations of customers (Mourtzis, Zogopoulos, & Xanthi, 2019). As a result, personalization can be easily incorporated to items.

AR has been identified as a useful technique for disseminating information and enhancing training methods. BMW (Werrlich, Nitsche, & Notni, 2017) used a head-mounted display to instruct employees at BMW who assemble engines. Users were taught how to assemble a milling machine as well as how to weld (Peniche, Diaz, Trefftz, & Paramo, 2012; Quandt, Knoke, Gorldt, Freitag, & Thoben, 2018). After conducting a usability research, it has been found that adopting AR must be promoted for training in industrial assembling and servicing occupations as AR is much more productive than VR (Gavish et al., 2015). In addition, AR has aided in design process by analyzing design variations (Bruno, Barbieri, Marino, Muzzupappa, D'Oriano, & Colacino, 2019); assembly and disassembly planning (Chang, Nee, & Ong, 2020; Wang, Ng, Ong, & Nee, 2013); robot orientation planning (Fang, Ong, & Nee, 2013); users' hand movement (Motoyama, Iwamoto, Tokunaga, & Okane, 2020). AR can aid in the analysis and enhancement of manufacturing processes and products prior to their implementation. This will assist in completing the activities correctly on the first attempt. Furthermore, collaborative AR apps can allow us to tap into the expertise of several people in different parts of the world at the same time.

4.3. Manufacturing aided by AI

The widespread usage of sensors and robotics was ushered in by the introduction of automation (Industry 3.0) in manufacturing. As a result of the deployment of sensors, a vast amount of data from the manufacturing process is now available, referred to as big data. The primary goals of Industry 4.0 include deriving inference from large data and making robots autonomous so that they can make their own decisions (Motoyama et al., 2020). AI has become widely used as a result of autonomous robots and massive data analytics. AI technologies offer a mechanism to manage and utilize this massive amount of data (Aggour et al., 2019). This information can help production systems adjust with the real time changing requirements in the industry supply chain and customers needs across product life cycle (Zhang & Kwok, 2018).

4.4. Use of AI and AR in the education and industry

AR-assisted industrial applications and AI-driven production have evolved independently and have advanced manufacturing in their own ways. The majority of previous works have attempted to use AR to enhance manufacturing tasks. Many of those attempts are marred by a number of flaws, which can be addressed by incorporating AI into the AR computational framework.

Many business verticals, including healthcare, retail, automotive, and transportation, are ready to be transformed by Industrial Internet of Things (IIoT) technologies. The IIoT will increase dependability, output, and customer happiness in numerous industries. While IIoT with Additive Manufacturing (Gebhardt, 2011) improve existing processes and infrastructure, the ultimate goal is to create completely new and much-improved products and services (Radziwon, Bilberg, Bogers, & Madsen, 2014). Industries that understand how and where IoT based solutions can create operational gains, new (or upgraded) products, services, and business models, will have a better chance of success. The IIoT will be integrated with specific essential technologies, devices, software, and applications focusing on enhancing existing processes and augmenting present infrastructure. IIoT encompasses a wide range of technologies, many of which necessitate careful integration and orchestration (Dagnaw, 2020).

4.4.1. Education

Rossano, Lanzilotti, Cazzolla, and Roselli (2020) created an AR application called Geo+, developed using a human-centered design method, to teach primary school students solid geometry in a modern paradigm. Students from third and fourth grades were separated into small groups and application guidelines were based on the Italian Education Department. Geometric shapes were displayed on student's devices, and if they selected one, an augmented item was displayed in a video replay. The authors performed assessments through a pilot study with 4–5 individuals in each group receiving a smart tablet running an AR application. The information was compiled using pre-test and post-test technique's with 10 sets of AR-based questions and activities, and the results were calculated using the t-test method. One limitation found in the AR program was that when students tried to pinch the images on a video to view details, but they were not responsive to zoom in or zoom out. Song, Zhong, Li, Du, and Nie (2014) recommended using a multi-agent system technique for developing an AR supported smart classroom, which is a student-centered approach that involves different types of learning processes.

4.4.2. Construction industry

With the induction of industry 4.0, the construction industry has driven a large portion of the development in integrating AR with AI. In the field of construction, highway work zones are considered as one of the most dangerous places to work. In the year 2018, critical incidents resulted in 124 worker deaths. A major limitation in the highway maintenance and operation is the lack of predictive safety measures that could warn the workers about dangers in advance. Sabeti, Shoghli, Baharani, and Tabkhi (2021) provide an integrated design approach for using current breakthroughs in AR and AI to improve highway worker safety by providing real-time multi modal notifications. Sabeti et al. (2021) achieved end-to-end operation latency of 24.83 FPS with 48.7% mAP for BDD100K dataset on the Xavier AGX Jetson board. They also reported real-time communication over 120 m with a latency of 5.1 ms for the maximum distance. Their mixed-method user research demonstrated that the proposed technology along with the user interface elicit an adequate level of interest and involvement from highway personnel.

4.4.3. Manufacturing industry

AR and AI is widely used in a variety of sectors of the manufacturing industry. The current innovation pace for the AR development in this industry is astonishing, especially when we consider Industry 4.0 and the adoption of AI systems as discussed in Subakti and Jiang (2018). The authors also proposed a concept aligned with an Industry 4.0 vision in which they build and execute a rapid and marker-less mobile AR system for machine registration, visualization, and interaction in smart factories. To detect distinct machines and parts of machinery, a lightweight MobileNets based detection module operating on mobile devices is employed (Howard et al., 2017). Following are the processes in the manufacturing industry where AR is currently being utilized.

(a) **Testing**

Fiorentino, de Amicis, Monno, and Stork (2002) debuted the SpaceDesign MR workspace, based on the StudierStube architecture that enables visualization and change of car body curvature and engine arrangement among other things. Volkswagen visioned to employ AR to compare computed and real-world crash test pictures (Friedrich, Jahn, & Schmidt, 2002). Clear and Present Car, a simulation where one can open the door of a virtual car and experience the inside, dashboard layout, and interface design for usability testing, was created by the MR Lab using data from Daimler-cars (Tonnis, Sandor, Klinker, Lange, & Bubb, 2005). Olwal and Feiner (2004) categorized application areas in construction where AR can be used to improve performance.

(b) **Assembly**

AR can be used to plan and evaluate assembly sequences successfully. In an AR-based hybrid prototyping technique for assembly assessment, a multimedia augmentation was used to assist a person in building an industrial device (Molineros, 2002; Raghavan, Molineros, & Sharma, 1999). A modular AR system was created by Reinhart and Patron (2003) to assist with manual assembly and assembly planning. For verifying and analyzing assembly sequence and interactive validation, AR may be used in conjunction with CAD software as well as a wearable computing device (Liverani, Amati, & Caligiana, 2004). An AR-based interface may be established in the early phases of product design to aid manufacturers with assembly design. Pang, Nee, Ong, Yuan, and Youcef-Toumi (2006) suggested an AR-based proof-of-concept system to assist users in designing assembly features on a real-world assembly platform.

(c) **Maintenance**

In the AR maintenance system, users are supplied with data relevant to a particular task at hand at the appropriate moment (Feiner, MacIntyre, & Seligmann, 1993). As a result, AR has the potential to be used in sophisticated machinery maintenance, servicing, inspection, and repair. Instructions will be simpler to comprehend if they are provided in the form of computer-generated material overlaid on the production line, displaying the important tasks that must be completed step-by-step and how to do so.

(d) **Product Design**

During the developed design process, or even during production, products or components are modified or adjusted several times. As a simple and quick tool, the AR simulation environment is great for design evaluation and ergonomic validation. Mixed prototyping, which mixes actual mock-ups of non-reconfigurable elements with 3D visual prototypes, is made possible by AR. Mixed prototyping implies showing virtual prototypes overlaid on actual prototypes in an upgraded environment, obviating the need for actual prototypes to be built (Balcisoy, Kallmann, Fua, & Thalmann, 2000). It enables users to evaluate synthetic prototypes in real-time in a physical setting. It also enables users to conduct in-depth product evaluations, ergonomic validation, assembly sequence validation, and, on occasion, functional verification. Engineers can use high-fidelity simulations to evaluate novel materials, components, and systems before spending time and money building physical prototypes using a hybrid prototyping technique like this.

4.4.4. Health care

Medical care is emerging as one of the most potential application areas for virtual system and AR interactive interface advancements. The development of real-time AR implementation, the clinical use of AR improvements, and the design and evaluation of medical training systems are all required (Shoaib & Jaffry, 2015; Van Krevelen & Poelman, 2010).

Doctors employ AR devices as a visualization help during surgery. MRI and CT scan acquire 3D data from patients in real-time, then display and integrate with the patient's real-time perspective. This is beneficial in minimally invasive operations since the difficulty with them is that they limit the surgeon's ability to see into the patient, making the procedure much more difficult. Here, AR aids doctors by providing interior images of the body (Nilsson & Johansson, 2008). Auloge et al. (2020) investigated the feasibility, consistency, safety, and patient radiation exposure of an innovative navigational tool that combined AR and AI during percutaneous vertebroplasty in patients with vertebral compression fractures (VCFs). In laparoscopic liver resection surgeries, recognizing the three-dimensional (3D) spatial position and orientation of arteries and tumor(s) is critical. In combination of laparoscopic video footage, AR technology can enable surgeons visualize the patient's inside anatomy, which can save lives (Luo et al., 2020).

4.4.5. Gaming

Researchers indicate the possible AR settings given for integrated animated agents, and illustrate numerous sophisticated comprehensive materials and scenario methodologies in AR through entertainment applications (Barakonyi & Schmalstieg, 2005; Shoaib & Jaffry, 2015). The use of video simulation in the real world elevates the gaming experience to new heights. By rotating a flat-screen display (Maeda, Hirose, Yamashita, Hirota, & Hirose, 2003) with a narrow viewing angle and modifying the picture on the display panel according to its orientation, (Maeda et al., 2003)'s framework allows users to reconstruct a featured avatar that they can look at from all sides. Simulating reality as closely as possible, combined with the incorporation of artificial items into the actual environment, can foster interactive empathy amongst participants and their characters. The future will become more dynamically hybrid, with advanced digital artifacts blending into real ones, allowing us to communicate throughout a wide range of spectrum like 5G/6G. Simultaneously, game-based visualization and interaction approaches may be used in real-world AR applications (Luz, Bila, & Dinis, 2008).

It is now being looked at whether AAA title (Consalvo, 2012) games can be employed successfully in the actual world of gaming using AR. AAA games are high-quality video games produced by huge firms with enormous budgets. The utility of AR applications in games can change how we think about training and multi sensory learning. Recreational games will provide a wide range of new applications in AR growth in the gaming industry (Liarokapis & De Freitas, 2010).

Pokemon Go (LeBlanc & Chaput, 2017) was the first AR game to make it to the top of the app store's download charts. This new generation of mobile internet AR games, on the other hand, is mostly new. Existing ideas are only partially applicable to user comprehension. Customer reactions are driven by hedonic, emotional, and social rewards and social norms, whereas physical hazards inhibit consumer reactions. The value of these drivers, on the other hand, varies depending on the type of user activity (Rauschnabel, Rossmann, & tom Dieck, 2017).

5. Challenges

When it comes to applying AI approaches to AR-assisted manufacturing applications, there are numerous technological obstacles listed as follows.

- Production environments have insufficient object variation to facilitate identification and tracking. As a result, developing generic AI is challenging. Collecting data to capture abnormalities is time and resource-intensive, which makes training of AI systems to recognize anomalies an expensive endeavor. Another problem is gathering and exchanging massive data from industrial processes with the AR system. AR systems must be updated and have context awareness in order to be helpful, relevant data must be transmitted to them. If the data is not properly secured, it is possible to gain control of the physical equipment (Khan, Wu, Xu, & Dou, 2017).
- Time-varying uncertainties are common in manufacturing processes (Ginsberg, Mohebbi, Patel, Brammer, Smolinski, & Brilliant, 2009). In order for statistical or AI methods to work precisely for AR-assisted manufacturing technologies, these uncertainties must be taken into account; numerous problems arise from the management perspective.
- Implementing AI on a broad scale, as on a production floor, is a challenge in itself as most previous implementations have been designed and evaluated in lab environments (Arinez, Chang, Gao, Xu, & Zhang, 2020). It may be required to acquire data from actual machine processes while constructing training datasets for AI systems. Data from machine failures or malfunctions would need to be collected in the event of predictive maintenance, diagnostics, or prognostics. This data collection procedure could be hazardous to the developer and expensive to the manufacturer. The most effective component of supervised learning necessitates the use of data labels. Labeling is time-consuming and can necessitate expert labor in production applications.
- AI models are usually black-box in nature and difficult to interpret, which cast doubt on their credibility. Users' faith in AI-powered AR systems is eroded by a lack of explainability of models' predictions, which must be interpretable or understood by human operators.
- Human operators and decision-makers must be in the loop and take over anytime the AI or ML system fails unless operations can be totally automated.
- The fast growth and implementation of AI systems have overtaken the legal framework that governs how and where these systems should be used effectively and securely in applications. To ensure that AI policy is up to date and appropriate for the technology, the government will require new technological knowledge (Dagnaw, 2020). Access to a computer and human resources as well as legal and regulatory constraints are critical at the organizational level when it comes to implement AI in manufacturing.

While the above-mentioned technical and management hurdles might impede AI's incorporation into AR-assisted production, the benefits of AI-driven AR significantly exceed these challenges. AR systems will evolve into sentient machines, similar to autonomous robots and sensors. AI-powered AR systems will be able to work independently in the production environment with minimum human interaction. AI enables AR systems to interact with the manufacturing environment and human operators to be unified as a whole, facilitating Industry 4.0.

6. Conclusion

The extent of AI in AR-assisted industry applications is identified in this review work. We investigated various industries including manufacturing landscape where AR and AI fit into industrial operations. The study summarized some popular deep learning algorithms employed in the advent of AR, such as YOLO, MobileNets, and SSD models. Then, a brief review of AR platforms and frameworks used to build the AR applications was provided. Furthermore, we discussed the most recent research in both AR-assisted production and AI-driven manufacturing.

Next, the primary technical and management challenges for incorporating AI into AR operations were discussed in detail. Challenges with processing of enormous information for AI in AR systems and organizational issues such as safety, legislation, and trust in AI technology are the key obstacles. However, AI-driven AR-assisted industrial applications' practical advantages much outweigh these drawbacks. Despite the obstacles of applying AI techniques into AR-assisted manufacturing applications, the effect of progress and innovation will be significant improvements in AR systems' efficiency, dependability, and utility. Although widespread adoption of AR applications in production is not yet done, the notion of ubiquitous AR is quickly gaining attraction.

CRediT authorship contribution statement

Jeevan S. Devagiri: Writing – original draft, Formal analysis, Methodology, Software, Visualization, Data curation. **Sidike Paheding:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Quamar Niyaz:** Writing – review & editing, Conceptualization, Funding acquisition. **Xiaoli Yang:** Writing – review & editing, Conceptualization, Funding acquisition. **Samantha Smith:** Writing – review & editing, Conceptualization, Funding acquisition.

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.

Data availability

No data was used for the research described in the article.

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