Augmented-Reality Survey: from Concept to Application

Soo Kyun Kim[1], Shin-Jin Kang[2], Yoo-Joo Choi[3], Min-Hyung Choi[4] and Min Hong[5*]
[1]Department of Game Engineering, Paichai University, Daejeon, 35345 - South Korea
[e-mail: kimsk@pcu.ac.kr]
[2]School of Games, Hongik University, Sejong 30016 - South Korea
[e-mail: directx@hongik.ac.kr]
[3]Department of New Media Content, Seoul Media Institute of Technology, Seoul 07590 - South Korea
[e-mail: yjchoi@smit.ac.kr]
[4]Department of Computer Science and Engineering, University of Colorado Denver, CO 80217 - USA
[e-mail: min.choi@ucdenver.edu]
[5]Department of Computer Software Engineering, Soonchunhyang University, Asan-si 31538 - South Korea
[e-mail: mhong@sch.ac.kr]
*Corresponding author: Min Hong

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Abstract

The recent advances in the field of augmented reality (AR) have shown that the technology is a fundamental part of modern immersive interactive systems for the achievement of user engagement and a dynamic user experience. This survey paper presents the descriptions of a variety of the new AR explorations, and the issues that are relevant to the contemporary development of the fundamental technologies and applications are discussed. Most of the literature regarding the pertinent topics—taxonomy, the core tracking and sensing technologies, the hardware and software platforms, and the domain-specific applications—are then chronologically surveyed, and in varying detail, this is supplemented with the cited papers. This paper portrays the diversity of the research regarding the AR field together with an overview of the benefits and the limitations of the competing and complementary technologies.

Keywords: Realistic display, Tracking, AR-hardware platforms, AR applications, Augmented Reality

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1. Introduction

Augmented reality (AR) enhances real-world environments with additional virtual information. The presence of AR is spread across our lives in areas such as gaming, study, work, and travel. Especially, the worldwide popularity of “Pokémon Go” has increased the AR presence in the lives of its users, as the AR game provides a new type of gaming experience for smartphone users throughout the world.

The aim of this paper is the summarization of the state-of-the-art AR technologies and the corresponding applications. The AR categorization that is presented in this paper is based on the types of virtual information, the tracking types, and the display devices. Also, to understand the way that the AR-research trends have changed over time, a review of the categories of the core AR technologies, which is based on the major survey papers and the papers that were presented at the ISMAR (International Symposium on Mixed and Augmented Reality)conference, was conducted.

The next focus of the paper is the tracking technology that is a mature AR-research area, and the kinds of technical detail that are required are explained. The recent AR-hardware (HW) platforms are then introduced including webcam-equipped computers, smartphones, smartglasses, head-mounted displays (HMDs), and haptic devices; accordingly, a variety of the corresponding software (SW) platforms are also described including those for computers, smartphones, and Web-based systems. It is the combination of the SW and HW platforms that enables the AR in many applications. Although the prototype of the AR system was introduced in 1968 by Sutherland [1], recent HW devices such as the small high-resolution camera, Google Glasses [2], Gear VR [3], and the smartphone help in the implementation of the various AR applications. Real-world and virtual objects are therefore seamlessly blended in the AR applications, and the applications have been widely used for the real-world interactions in the everyday lives of humans such as those for work, study, training, relaxation, and travel, among many others. In this paper, the AR applications are roughly classified into the following four categories: “Training & Education,” “Entertainment & Commerce,” “Navigation & Tourism,” and “Medical Health Care & Construction.”

Section 1 is a description of the introduction of AR and the corresponding motivations. Section 2 is a discussion of the core AR technologies and the issues that have been presented in the previous survey papers. Section 3 presents a key issue of the AR systems that is regarding the efficiency of the integration of the SW and HW platforms with the real world. Section 4 shows the AR applications that have been widely used in a variety of fields for the real-world interactions. Lastly, the conclusion is provided in Section 5.

2. The Taxonomy of Augmented Reality

2.1. Core technologies and Issues of AR

The major survey papers [4-10] regarding AR that have been published since 1997 have presented the classifications of the core AR technologies and challenges. Table 1 shows a comparison of the core AR technologies that are presented in seven of the major survey papers. In 1997, Azuma pointed out that the registration and the sensing errors were two major problems regarding the development of AR systems [6]. Registration means that the objects in the real and virtual environments are properly aligned with respect to each other. Azuma divided the registration errors into the following two types: static and dynamic. Static errors are the ones that are caused by tracking-system errors, optical distortion, or incorrect viewing parameters, even when the user's viewpoint and the target objects are completely fixed. Alternatively, the dynamic errors occur due to systemic delays. Azuma presumed that the tracking-system delay results from the difference between the moment that the tracking system estimates the position and orientation of the viewpoint and the moment that the image corresponding to that position and orientation is displayed. The communication delays, tracking delays, and scene-generation time all contribute to the end-to-end systemic delay. The end-to-end systemic delay causes the dynamic registration errors only when motion occurs. In [6], Azuma mentioned that the registration problem was far from solved even though a few systems had achieved sound results [11-16]. An accurate registration of virtual objects in the real world requires an accurate tracking of the viewpoint and a sensing of the locations of the target objects.

In 2008, Zhou et al. reviewed the previously published conference papers from the ISMAR '02 to the ISMAR '07, as well as those of its forerunner events, the IWAR (International Workshop on Augmented Reality) '98, IWAR '99, ISMR (International Symposium on Mixed Reality) '99, ISMR '01, ISAR (International Symposium on Augmented Reality) '00, and ISAR '01 [5]. Based on the results of the review of the previous proceedings, the published papers were divided into two groups. The first group contains the five main research areas, and the second group consists of the emergent research interests; that is, the five main research areas of the first group are "tracking," "interaction," "calibration and registration," "AR applications," and "display," while the topics of the second group are "evaluation/testing," "mobile/wearable AR," "AR authoring," "visualization," "multimodal AR," and "rendering," as shown in the second column of **Table 1.**

In 2010, Krevelen et al. introduced various types of user interface and interaction through their survey paper including biosensing, gaze tracking, and the haptic interface. Moreover, they explained three further requirements for the mobile AR system that had been proposed by Höllerer and Feiner [17], as follows: computational framework, wireless networking, and the technology for data storage and access. An easy development of the AR system can be achieved with a computational framework like the ARToolkit. Also, Krevelen et al. emphasized that the specialization of content and the creation of dynamic content through the use of AR-authoring tools are very important for the commercial success of AR systems. Other survey papers that have been presented since 2011 have introduced new tracking and natural-interaction approaches for which a variety of sensors are used. The interest in mobile portability, natural interfaces, dynamic scene generation, and information management in terms of the content has rapidly increased due to the widespread use of mobile devices.

In the authors' research process, the conference sessions from the ISMAR '13 through to the ISMAR '16, as shown in **Table 2**, were reviewed to investigate the way that the AR-research areas have been changed in comparison with the pre-2008 research areas. A comparison of **Table 1** with **Table 2** revealed that the main areas including "tracking," "interaction," "calibration," and "display" have been steadily researched; furthermore, visual SLAM (simultaneous localization and mapping) tracking, realistic rendering with a 3D effect, real-time mobile AR, outdoor AR, and collaboration in AR have become increasingly important topics for the advanced AR-research field.

2.2 AR categorization based on the type of virtual information

Changes to the scope of mobile AR have created new types of the information-application service. As shown in **Table 3**, the information service regarding AR forms a new application category; also, the differences between the "Visualization" and "Informative" approaches are shown in this table. For the recent smartphone-based mobile AR systems, a variety of the sensing information regarding the location information and the angle are utilized; this sensing information combines a variety of Internet services, and it has evolved the enhancement of the information service.

The classification of AR into categories is achieved through the application of the provided information that has been divided into the "Visualization" and "Informative" approaches. Aleksy [18] presented an overview of the different visualization categories such as object information, navigation, user interface, and user attention in terms of the AR applications.

Table 1. Core technologies and issues of AR that are presented in the survey papers.

1997 **Azuma [6]**	**2008** **Zhou et al. [5]**	**2010** **Krevelen et al. [7]**	**2011** **Carmigniani et al. [8]**
Registration . static error . dynamic error Sensing . greater input variety . higher Accuracy . longer range	Tracking .sensor-based .vision-based .hybrid Interaction .tangible AR .collaborative AR .hybrid interface Calibration AR Application Display .see-through .projection-based .handheld Evaluations Mobile AR Authoring Visualization Multimodal AR Rendering	Tracking . modeling environment . user movement tracking User interface and interaction . tangible UI / 3D pointing . haptic UI /gesture recognition . visual UI / gesture recognition . gaze tracking . aural UI / speech recognition . text input . hybrid UI . context awareness . biosensing Display . aural display . visual display video see-through optical see-through projective . display positioning head-worn hand-held spatial Frameworks Networks and Database Content	Tracking . object tracking - feature-based - model-based . camera pose estimation Reconstructing/recognizing AR Devices . displays - HMD - handheld - spatial display . input devices . trackings devices - optical-based - sensor-based GPS/WiFi/ Accelerometer/ Magnetic/ Ultrasound/ Inertial/Hybrid/ UWB /RFID . computers AR Interfaces . tangible AR interfaces . multimodal AR interfaces . collaborative AR interfaces . hybrid AR interfaces
2013 **Rabbi et al.[4]**	**2016** **Wang et al.[9]**	**2016** **Manuri et al.[10]**	
Tracking .vision-based marker-based / markerless . sensor-based magnetic / acoustic / inertical / hybird . hybrid Interaction . acoustic . haptic . tangible . gaze . text-based Performance Alignment Mobility/Porability	*Typical components on AR-based assembly systems* Tracking . sensor-based . vision-based marker-based / markerless Camera . CMOS/CCD . stereo . depth Display . HMD . hand held display . spatial display Rendering . visual rendering . haptic rendering Interaction	Tracking . optical marker-based / markerless . inertial . mechnical . magnetic Asset/scene generation Combiner . see-through Monocular glasses/ Binocular glasses . hand-held . monitor-based UI and Interaction . contrast . resolution	

. small & light Visualization . HMD/monitor . contrast . resolution . brightness . field of view	. glove-based . desktop haptic . hand-based Bare-hand UI / Tangible UI Information Management	. brightness . field of view	

Table 2. Conference sessions from ISMAR '13 to ISMAR '16

2013		2014		2015		2016		Category
Session	#	Session	#	Session	#	Session	#	
Viewing and Rendering	5	Rendering	5			Lighting and Rendering	4	Rendering
Photometric AR	3			Perception	3			Realistic Rendering & 3D Effects
Initialization and Calibration	5							Calibration / Tracking / Registration
				Closed-loop Visual Computing	3			
Tracking and Registration	4	Tracking	5	Tracking	4	Calibration and Tracking	4	
						SLAM Tracking	3	SLAM Tracking
Interactive Modeling	5					Education and Modeling	4	Modeling
		Reconstruction and Fusion	4					
				Depth Cameras	3			
New places, New Views	3					AR Everywhere	3	Realtime Mobile System
Augmented Interfaces	3	User Interface	4					User Interface
User Study and Performance	5	Theory and Evaluation	4					Evaluation
		AR Interaction and Creativity	4			Collaboration and Interaction	3	Collaboration and Interaction
		Head-Worn Displays – Optical See-Through	4	Head Mount Display	3	Head-Mounted Displays	3	Head-Mounted Display
		Applications	4	Applications	3			Applications
		Medical AR	3	Medical AR	3			

#: The quantities of the short and full papers that were presented in the sessions.

Table 3. Visualization Approach vs. Informative Approach [19]

Differences	Visualization Approach	Informative Approach
Main focus	Virtual Reality	Information Provide
UI	3D object overlay (rendering and registration) and interaction	AR browsing or navigation
Requirement	Graphical performance or computing power	Mash-up possible
Devices	Desktop	Smartphone, Tablet PC
System Category	Isolated System	System through network
AR Target	3D virtual object	Information of location and real object
Application Type	AR 3D game, AR advertising, AR based e-learning, Medical AR, AR-based Technical Support System	AR information browsing, AR based Navigation, location overlays, geoinformation services

2.3 AR categorization based on the tracking type

Tracking is an important technology that plays a central role in AR experiences. This technology is repeatedly used for the localization of the position and the orientation of one or several real objects. In AR, the tracking technology is needed for the integration of virtual objects into the real world. Zhou et al. [5], Rabbi et al. [4], and Wang et al. [9] classified the AR-tracking technologies into sensor-based, vision-based, and hybrid approaches. **Fig. 1** shows a diagram of the mobile AR process from the technologies to the applications; here, sensor-based tracking is used for the recent LBS (location-based service)-based mobile AR application.

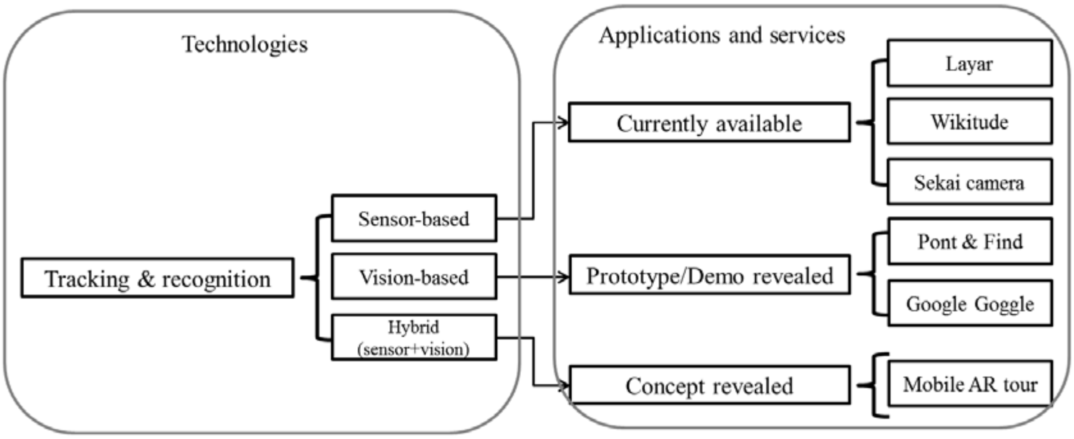

Fig. 1. Diagram of the mobile-AR process from the technologies to the applications [20].

2.3.1 Sensor-based approaches

The sensor-based approaches are divided into acoustic tracking, magnetic tracking, optical tracking, and inertial tracking. Similarly, the vision-based approaches are divided into marker-based tracking and markerless tracking [4]. Both the limitations and the advantages are applicable for each approach. Rabbi et al. [4] summarized the characteristics of the different sensors, as shown in **Table 4**.

- Optical tracking: Optical tracking is a 3D-localization technology that is based on the monitoring of a defined measurement space that is achieved with the use of two or more cameras. One of the advantages of optical tracking is that it allows for a simultaneous tracking of many objects [21].
- Magnetic tracking: When it is used for AR, the magnetic-tracker transmitter acts as the origin of the virtual coordinate system, and by mounting a receiver to the viewer, the position and orientation can be determined [22].
- Acoustic tracking: Acoustic tracking measures the length of time that is taken for an acoustic signal to reach a variety of receivers [23].
- Inertial tracking: Inertial tracking is performed using an accelerometer and a gyroscope. The accelerometer measures the linear acceleration while the gyroscope measures the angular velocity [23].

Table 4. Summary of sensor-based-tracking characteristics (Rabbi et al. [4])

Sensor-Based Tracking	Accuracy	Sensitivity	Cost	DOF	Advantages	Disadvantages
Optical Sensors	Accurate	Light	Cheaper	3/6 DOF	High update rate, better resolution	Effect with optical noise, occlusion
Magnetic Sensors	Less Accurate	Electronic devices, Electro-magnetic noise	Cheaper	6 DOF	No occlusion problem, high update rate	Small working volume, distance affects the accuracy
Acoustic Sensors	Less Accurate	Temperature, Humidity, Pressure	Cheaper	3/6 DOF	Slow, small, light, no distortion	Occlusion and ultrasonic noise
Inertial Sensors	Accurate	Friction	Cheaper	1/3 DOF	No reference needed, No prepared environment needed	Due to small friction-conservation error
Hybrid Techniques	Accurate	Depends on sensor that is used	Costly	6 DOF	Compact, accurate, stable	Depends on sensor that is used

2.3.2 Vision-based approaches

This type of approach determines the camera position through the use of optical-sensor data. These optical sensors can be divided into the following three categories: infrared sensor, visible-light sensor, and 3D-structure sensor. Also, vision-based tracking is a popular method because a camera is the only requisite special device [24].

For the vision-based tracking techniques, image-analysis methods are used to estimate the camera pose relative to the real-world objects [5, 25]. Fiducial markers were employed for the early vision-based approaches [26], but most of the recent approaches are based on the markerless approach [27]. In the first processing step of the markerless tracking, the feature points and/or edges are detected to interpret the camera images. The popular feature-detection methods include Harris [28], SUSAN [29], FAST [30], and DoG (Difference of Gaussian) [31]. The extracted features or edges must be represented as a multi-dimensional vector value; that is, in terms of the use of these vectors, the feature descriptors are required to represent the extracted features and for the estimation of the camera pose. The representative feature descriptors include SIFT [32], SURF [33], BRIEF [34], ORB [35], and FERNs[36]. The inter-frame features are matched by tree-based searching, hashing, or the full-search method. Likewise, for the feature-based methods, the matching relation between the 2D-image features is first discovered, followed by an estimation of the features' 3D world-frame coordinates [37]. For the estimation of the camera pose, the model-based methods can be applied. The model-based methods use models of the tracked-object features or templates [5]. If a matching relation is defined between the 3D world frame and the 2D image, it is possible to estimate the camera pose by projecting the 3D features into the observed 2D image plane, and by minimizing the distance between these 3D features and the corresponding 2D-feature coordinates [8].

SLAM is a principal technique that is used to progressively construct a map within an unprepared environment, while its current locaton is tracked based on the extracted scene features [38]. This approach has been applied for the robust tracking of the AR in a small space. The updating of the 3D structure in correspondence with the dynamic objects, however, is not considered for the SLAM system, so the target working scene must be kept stationary. Petit et al. [39] presented a tracking method for which the classical geometrical and color-edge-based features are integrated in the pose-estimation phase. See [40] for a comprehensive reference regarding the AR camera-pose estimation.

2.3.3 Hybrid-based approaches

For the hybrid-based methods, the data from multiple sensors are used, and the accuracy and weaknesses of the individual sensors are enhanced. Since the vision-based tracking methods include the jitter and drift problems, one of the objectives of the hybrid system is a reduction of the drawbacks of the vision-based approaches [5]. Although the hybrid-based methods provide a robust tracking, the development of its system remains difficult. The hybrid-tracking systems, however, provide relatively sound solutions despite the increasing of the tracking complexity by these systems that is owing to the respective limitations of each sensor-tracking system. For the hybrid tracking, both the sensor-based tracking and the vision-based tracking are combined, or multiple sensors are used to compensate for the limitations of each technique. The hybrid-tracking approaches represent the most-promising method for both the indoor and the outdoor mobile AR applications [41].

Schall et al. presented a hybrid-tracking system for which the vision-based tracking is combined with the inertial and magnetic sensors [42]. Their approach considerably improved the absolute-orientation estimation on mobile devices. Bleser et al. also presented a hybrid system for which the egocentric-vision approach is combined with the inertial sensors to track the upper-body motion [43]. Carmigniani et al. [8] compared the common tracking technologies, as shown in **Table 5**.

Table 5. Comparison of the common tracking technologies (Carmigniani et al. [8])

Technology	Range(m)c	Setup time(hr)	Precision(mm)	Time(s)	Environment
Optical: marker-based	10	0	10	∞	in/out
Optical: markerless	50	0-1	10	∞	in/out
Optical: outside-in	10	10	10	∞	in
Optical: inside-out	50	0-1	10	∞	in/out
GPS	∞	0	5000	∞	out
WiFi	100	10	1000	∞	in/out
Accelermeter	1000	0	100	1000	in/out
Magnetic	1	1	1	∞	in/out
Ultrasound	10	1	10	∞	in
Inertial	1	0	1	10	in/out
Hybrid	30	10	1	∞	in/out
UWB	10-300	10	500	∞	in
RFID: active	20-100	When needed	500	∞	in/out
RFID: passive	0.05-5	When needed	500	∞	in/out

2.4 AR categorization based on the display device

For AR rendering, a variety of technologies are employed including monitors, hand-held devices, optical-projection systems, and display devices that are mounted on the human body [44]. **Table 6** shows a comparison of the display types that are used for AR, wherein it is evident that people use HMDs and small displays during the current time period because they require the movement and convenience regarding their display devices that are gradually being developed for the hand-held type.

Table 6. Comparision of Display Type for AR[45]

	HMD	Large Display	Small Display	Hand-Held
Panel	LCD Eyepiece	LCD, CRT, DLP, SCREEN,PROJECTION	LCD, CRT, DLP, PDP	LCD
Immersiveness	High	Middle	Low	Low
Fit	Very uncomfortable	-	-	Good
Portability	Very uncomfortable	Impossible	Uncomfortable	Good
Optical Mixing	Possible	Possible	Impossible	Impossible
Advantage	Immersiveness	Real-object projection	Easy development	Excellent portability
Disadvantage	Poor fit	Partially shaded	Mismatch between gaze and screen	Small, Low quality

3. Hardware and Software platforms for AR

3.1 Hardware Platforms

A key issue of the AR systems is the extent of the efficiency regarding the integration of the SW and HW platforms with the real world. The recent HW platforms for AR include the following devices: 1) computers with a webcam, 2) smartphones, 3) HMDs, 4) glasses, and 5) haptic devices.

The personal computer with a webcam is the most widely used platform for AR. Because of the fixed nature of the computer, a marker is placed within the view of the webcam, which shows a live feed. The touch-sensitive screen of the Shiseido Makeup Mirror [46], which is a proper example of the PC-based AR platform, means that the users can choose from selections of eye colors, lip colors, and blushers. The kiosk, another PC-based AR platform, is simply a physical station at which customers can use AR information to find out more about the items they have brought with them. One example of the kiosk platform is the Lego Store kiosk [47] that displays completed Lego sets depending on the Lego box of the customer. The kiosk type is also used at trade shows and conventions to provide the attendees with a richer experience. The digital signs and window displays that are also used are basically large static markers that users interact with via the PC platform. The AR SandBox [48] project involved the development of a real-time integrated-AR system for the physical creation of topography models that are then scanned into a computer in real time; with the use of a projector, the scans of the models are then used as the background for a variety of graphical effects and simulations.

The use of smartphones or tablets to access AR content is arguably the most-common method of today. The two usage categories for the smartphone are as follows: *ubiquitous* and *constantly-held*. The Wikitude World Browser [49], one of the AR tools that is the easiest to use, is a representative case of the ubiquitous category; here, the information is displayed continuously with real-world images based on the Web plug-in. The Microsoft omniTouch [50], a representative constantly-held example, consists of a wearable computer, a depth-sensing camera, and a projection system for interactions on everyday surfaces.

The HMD comprises a display that is paired with a headset, and the information/images are placed on top of the user's view with six degrees of freedom (6 DOF), and the view is augmented according to the user's head movement in any direction/angle. The SKULLY Helmet [51] is the first helmet to feature a built-in 180° Blindspot Camera and a Heads-Up Display for an unparalleled situational awareness and safety. The Microsoft HoloLens [52] that allows users to seamlessly visualize 3D models in real life is a self-contained, holographic computer, whereby users can engage and interact with digital content and holograms, respectively, in the real world. The HoloLens consists of multiple sensors, advanced optics, and a custom holographic-processing unit. The DAQRI smart helmet [51] enhances the human abilities across industries by seamlessly connecting its user to the work environment.

While the AR-glasses technology is still uncommon, it represents another rising AR platform. It is likely that AR-enabled glasses will become as common as iPads and smartphones, giving the wearer the option of a continuous AR feed that is based on individual needs and preferences. The Google Glass [53] display is the most-famous AR-glasses product, while similar products like those made by Vuzix [54] do exist and are available for purchase. Over time, the technology will be improved and the prices will be reduced. The focus of Meta [55] is that which is absent from the focus of Google Glass. For Meta, the AR is overlain on top of the user's reality. The user gestures are identified by Meta so that the users can freely manipulate 3D objects that assume clay-like qualities. Meta users are also provided with an unlimited number of screens, as video content can be played on a piece of paper. Icis [56] looks like a set of normal glasses as a visibly large component such as a camera is absent. The Atheer One [57] smart glasses promote natural interaction, as the users can use hand gestures to control it; it consists of two displays for each eye, which are almost the equivalent of the placement of a 26-inch landscape-oriented tablet immediately in front of the user's face. The contact lenses [58] that provide images directly onto the human eye, for which near-to-eye pictures are combined with distant objects in the same view and an antenna is included for wireless communication, are in-development/military use. And lastly, for the in-development virtual retina display [59], objects are projected directly onto the retina of the viewer so that the UI/AR appears to be floating in front of the eye.

The haptic AR enables the user to experience a real environment that is augmented with synthetic haptic interactions. The AR of the game pads of the Nintendo Wii U/PS4/Xbox [60] provide the user with tactile feedback in real time. When an HMD is combined with the PHANTOM Stylus [61], the user can touch and feel the objects that are visualized in front him/her. When the VHB (virtual haptic back) system [62] is combined with the PHANTOM Stylus, a surgeon can see the human organs and whole body parts during surgery, while tactile feedback is provided to the surgeon's fingers during the cutting, removal, and device-moving processes regarding the body/organs. Lastly, Maestro AR [63] is a robotic-surgery simulation technology that provides 3D virtual instruments for the anatomical interactions in a 3D-video environment.

3.2 Software framework

A variety of SW platforms are also described for the AR-HW platforms, including the computer, smartphone, and Web-based systems. Because most of the recent SW frameworks support multiple platforms, a few HW dependencies are relevant in the selection of the AR-SW framework Among the SW platforms, the most-famous commercial SW-development kits (SDKs) are Metaio, Vuforia, and ARToolkit.

Metaio SDK [64] is an SW framework that consists of Mobile SDK, PC SDK, Web SDK, Design, Creator, Engineer, and the Junaio [49] browser plugin. The vision of the Metaio framework is the easy integration of the virtual into the real world. The Metaio Creator [65], for example, is a drag-and-drop AR-SW product that allows the user to create a complete AR scenario. The Vuforia SDK [64] is for the creation of the AR applications for mobile devices. Vuforia supports the recognition of complex objects, user-defined images, cylinders, text, boxes, and frame markers with cloud data. The features of Vuforia comprise an extremely varied range of marker types including the support for the Microsoft HoloLens. ARToolKit [64] is another SDK for the building of AR applications for which square marker patterns, which are traced by a single-camera position/orientation, are used. ARToolkit provides support for three general tracker categories for which natural-feature tracking, traditional-template square markers, and 2D-barcode markers are included. This SDK supports multi-camera support, the Windows Phone, and robust marker tracking over a range of distances.

The Wikitude SDK [64] includes image recognition and tracking, support for 3D-model rendering with video overlaying, and the provision of location-based AR. For this SDK, the geo-based and image-recognition capabilities are combined to provide a hybrid-tracking function, and because it is built heavily on Web technologies, it can be used to write cross-platform AR experiences. The Kudan [66] is a unique AR SDK that comprises an over every other AR SDK. It can support very robust single-camera SLAM which enable flexible tracking behavior for targets.

A variety of application-level or special-purpose AR libraries have been suggested. In general, these libraries use open-source libraries including those of ARToolKit and OPEN-CV, which are compatible at an application-level environment or the Web level. For the NyARToolKit [67] project, a vision-based AR library that is based on that of ARToolKit is being developed. An ARToolKit-compatible library that runs on a managed environment such as Java/C#. OSGART [68] is a library that simplifies the development of AR applications by combining the ARToolKit tracking library with OpenSceneGraph. But rather than acting just as a simple form of the “node-webkit” app runtime, it offers a high-level integration of the video-input, spatial-registration, and photometric-registration functionalities. OpenCV-AR [69] is an SW library that is used for AR development; its target is Linux, but it can also work on the Windows platform. ArUco [70], a minimal C++ library for AR-marker detection that is exclusively based on OpenCV, was developed at the University of Cordoba. The ATOMIC Authoring Tool [71] is an authoring tool for the creation of AR applications. It supports an authoring-tool SW for AR applications that can be used as a front end for the ARToolKit library. JavaCV [72] is a Java/Android interface for OpenCV licenses. ARSights [73] is a project of Inglobe Technologies, which specializes in the development of AR applications, and is based on Inglobe's AR platform that facilitates a simple method for the integration of digital content in the real world; its AR functionalities are also extendable to Google Earth (GE). CCV [74] is another cross-platform blob-tracking solution for which computer vision is used; here, a video-input stream is used, and tracking data and events that can be used in the building of multi-touch applications are generated. The Designers Augmented Reality Toolkit (DART) [73] is an authoring tool that can support the rapid design and implementation of AR experiences and applications. Designed to facilitate the overall development process, DART is built on top of Macromedia Director, thereby providing AR authoring to a wide range of designers. Goblin XNA [75] is 3D-interaction research platform that is specialized for the gaming field; written in C# and based on the Microsoft XNA platform, the platform’s focus is the core 3D user-interface functionality for which the existing functionalities of the DirectX 3D-game engines and 3D-development environments are used.

The DWARF [76] framework is based on the concept of distributed-service collaboration; here, the services are interdependent and expose the user's requirements. Layar [73] is a another popular application-level AR SDK for which the Layar Reality Browser that enhances real-world objects in the Web environment has been created. The Layar functionalities include postcards with interactive content such as video messages, Web and social links, and photo shows. mixare, the mix Augmented Reality Engine [77], is an open-source (GPLv3) AR engine for mobile devices that works as an autonomous application for the development of mobile applications. Catchoom [78] is an iOS and Android SDK that renders AR experiences with plugins for the Cordova and Unity 3D engines. Gravity Jack [79] specializes in the development of AR applications for customer products or services, enabling the creation of AR mobile and social games and the writing of custom AR applications for multi-platforms; it can also create facial-recognition apps and allow AR overlays. DroidAR [70] is an open-source AR framework for Android that has the location-based and marker-based AR functionalities. BeyondAR [80] is an geo-localization-based open-source AR framework for Android. FLARToolKit [70], which is free to use for non-commercial applications under the GPL license, can recognize the marker from an input image and calculate its orientation and position in the 3D world. SLARToolkit [70] is a flexible AR library for Silverlight and the Windows Phone, the aim of which is the construction of real-time AR applications with Silverlight. Argon [81], an AR browser developed by Georgia Tech, supports a mix of KML and HTML/JavaScript/CSS in its facilitation of the development of AR applications, whereby any Web content can be converted into AR content. GeoAR [82] is an open-source browser for Android that is specialized for location-based AR and a flexible data-source framework.

4. Applications

AR has been widely used in a variety of fields for the achievement of smooth blends between the virtual and real worlds. Examples can be seen in the military, where AR is used for the repairing or training of the field equipment for the soldiers, the game industry is moving into the outside realm with AR and additional wearable devices for the acceptance of real actions, and AR is also utilized in the medical field for the training of medical students or to help doctors during surgeries. In this paper, the AR applications are roughly classified into the following four significant areas: Training & Education, Entertainment & Commerce, Navigation & Tourism, and Medical & Construction.

4.1 Training & Education

AR technology has been applied to assist soldiers in the repairing of their weapons or their machines on the battlefield, or for training purposes with wearable-device accompaniments. An AR system can warn soldiers about the potential dangers around them, and it can support virtual maps to help the moving direction of a soldier. The system can also project realistic training scenarios, including virtual tanks or helicopters, into their field of vision regardless of their physical location. Surgical training, for which exercises of routine or complex operation procedures are undertaken, is essential for the enhancement of the surgical operation skills of trainee surgeons. Because AR surgical training is both time and cost intensive, it has been applied in the form of a superimposition of computer generated virtual organs in the trainee-surgeon vision field with the use of an optical HMD such as Google Glass or the STAR 1200 XL from Vuzix [83]. The holographic displays such as the Microsoft Hololens [84] or the Google Magic Leap [85] can localize tumors in the trainee-surgeon view and highlight specific anatomical features to help the instructors in their guidance of the trainees. For new manufacturing workers, the work-preparation process is difficult without a familiarity regarding the corresponding tools. AR training provides a direct or indirect view of a physical real-world environment like a factory, and the elements are augmented by computer-generated objects. A number of AR-based manufacturing applications have been developed such as a laser-printer maintenance [86], an object calibration [87], and automotive and aerospace maintenances. The Hyundai motor group introduced a virtual guide [88] that is an interactive owner's manual for which AR is used to show the components of the dashboard and the engine area, whereby the user can be intuitively guided to fix minor car-repair issues.

The AR-teaching and AR-learning approaches have been intensively studied by educational and computer-science researchers. Textbooks, flashcards, and other educational materials can contain AR-technology-based supplementary information, whereby students can readily understand the detailed concepts of physics, anatomy, astronomy, mathematics, and geometry through the corresponding interactive play [89]. The AR Flashcards [90] can be used to help students learn and understand the core concepts of the alphabet, color and shapes, and space with AR technology. For Anatomy 4D [91], AR is used to present the human body, and students can learn about the different systems and the human anatomy. The Elements 4D [92] inspires students to explore chemistry, from the elements to life, in an immersive and interactive manner. For the Arloon Geometry [93], AR is used to present 3D models of most of the geometric shapes that students can directly interact with them. SkyView [94] is an intuitive stargazing application for which the user's smartphone camera is used for the identification of the stars, constellations, and satellites in the sky. **Fig. 2** shows snapshots of these AR-based training and education applications.

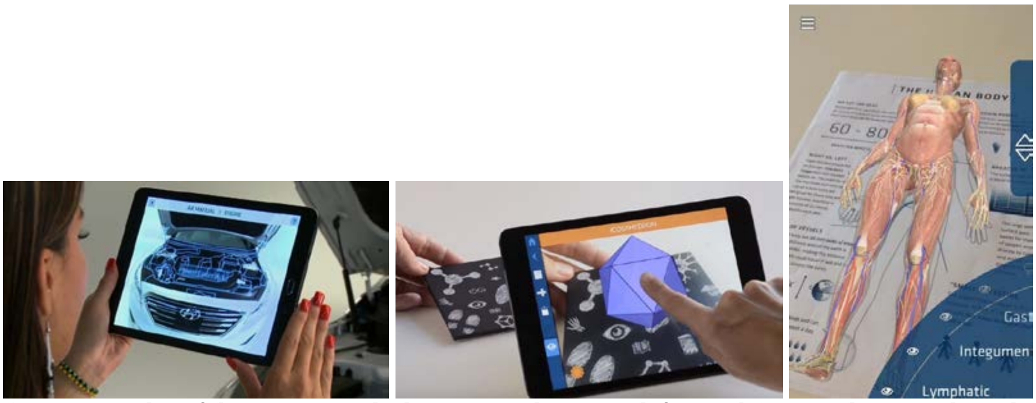

Fig. 2. Examples of the training and education applications (left to right): Hyundai Virtual Guide, Arloon Geometry, and Anatomy 4D

4.2 Entertainment & Commerce

AR was first introduced in the TV industry through the weather forecast for which 3D graphical symbols and weather charts were used. Since then, the FoxTrax system [95] is applied to highlight the location of the hockey puck, which is difficult to see because it moves extremely fast, while the ball trajectory for golf and the first-down line for football [96] are now highlighted in the playing-field view. AR systems are applied to concerts and cinema to provide an AR effect for which 3D virtual objects are convincingly mixed with the real-world view [97].

AR technology also expands gaming environments into the real world. Recently, AR-based games have been implemented with smartphones, with the "Pokémon GO" [98] game, which is developed by Niantic in collaboration with Nintendo, serving as a prime example due to its enormous success around the world. The functionality of "Pokémon GO" is reliant on GPS technology for the tracking of the user location, and the user is required catch Pokémon characters in real-world locations in competition with the other players. "Real Strike" is a 3D, AR-based, first-person shooting-gun game that is developed by Yii International, wherein a military base with a variety of sensitive support weapons is represented in the player's real-world surroundings.

AR has become one of the significant advertising trends in terms of commerce. AR is applied to the 2D or 3D TV-commercial advertisements during sports games such as football, baseball, or soccer with the incorporation of the playing field. AR is used enhance the previews of virtually-created 3D products, whereby an interactive manipulation of the view points is allowed for unopened products; that is, AR technology allows consumers to trial real-life products like furniture and clothing, thereby bridging the gap between the virtual and real worlds. To overcome the problem of the furniture returns that are due to the purchase of a piece that is incorrectly sized for the intended location, IKEA introduced an AR-based smartphone-catalog application whereby the users can try out the selected products in their homes first with the use of 3D virtual furniture. EZface Inc. [99] introduced a virtual-testing platform so that the users can try on a variety of its makeup products, to check what they would look like, without having to actually use the products. To promote the film release of Into the Storm, AR technology was used to bring the storm to the streets of the city of Sydney; here, a panel that looks like a window was used so that pedestrians could watch a virtual storm that was filled with the striking of lightning on the local buildings and realistic street furniture. Starbucks also released the AR-based smartphone application Starbucks Cup Magic [100] for the Christmas-holiday season whereby its customers could animate the coffee cup for an advertisement. For the operation of the Cup Magic application, the user points his/her phone camera at the red Starbucks holiday-season coffee cups to produce interactive animations that feature a number of characters. **Fig. 3** shows snapshots of Pokémon GO, Starbucks Cup Magic, and the Into the Storm promotional film.

Fig. 3. Examples of entertainment and commerce applications (left to right): Pokémon GO, Starbucks Cup Magic, and Into the Storm

4.3 Navigation & Tourism

For drivers and those who are navigating in a new area, modern smartphones are highly useful devices, as the users can utilize the GPS and networks to detect a location and determine the optimal routes. AR is exceedingly suitable for both indoor and outdoor navigation-based services, as the related information regarding the user's surroundings can be inserted into a camera image based on the user's position. Many vehicle manufacturers have applied the heads-up displays that project the speed or the turn-by-turn directions on the windshield in the designs of their automobiles.

Field Trip [101] provides a wide variety of information regarding the user's surrounding environment through the display of a card that contains the details of the user's location for which the user does not need to click anything to obtain; additionally, it supports voice announcements via the Bluetooth connection. Numerous interesting places and experiences such as those regarding architecture, historical places and events, lifestyle, offers and deals, food and drink, movie locations, outdoor art, and obscure places of interest are supported in Field Trip. Garmin introduced the Varia Vision [102] device as an accessory of interest for cyclists. This device is an AR display that is mounted onto the cyclist's sunglasses for the display of key information such as turn-by-turn directions and smartphone notifications; furthermore, through the addition of a rearview radar, the user can receive alerts about cars that are approaching from behind.

AR is a simple and interactive technology that can be of assistance in not only the planning of trips and the booking of hotels, but also in the accessing of the information that will be relevant during the traveling process that is undertaken to reach the destination. Travel applications provide quick and easy access to trip-related information, such as the reviews of nearby locations, real-time weather forecasts, and the translations of foreign signs or menus. The Metro AR Pro [103] application automatically detects the city that the user is in and shows a list of the nearest subway and metro stations with the camera view. Wikitude is a location-based AR SDK for mobile applications that supports image recognition, tracking, 3D-model rendering, video overlay, and geo-location-related functions for application-development purposes. Yelp Monocle [104] allows the user to view nearby businesses with the use of his/her smartphone camera; that is, the business names and reviews that are displayed by the application are based on the direction that the user points the smartphone in Google Translate [105] supports the automatic translation of the foreign-language text that is framed with the use of a smartphone camera into the user's native language; this intuitive and useful AR technology becomes an essential application for travelers, as they do not need to type anything into the smartphone. **Fig. 4** shows some examples of the AR-based navigation and tourism applications.

Fig. 4. Examples of the navigation and tourism applications (left to right): Varia Vision, Field Trip, and Yelp Monocle

4.4 Medical & Construction

The surgical AR can allow doctors to provide guidance, help, and support with valuable information during a surgical operation, or it can support the rehearsal or discussion of the operation, for which a realistic virtual version of the patient's organ is used, before the actual surgical operation [106, 107]. Shafi Ahmed [108] used Google Glass to perform the first-ever live-stream surgical operation. The AR-based surgical training can improve the live-procedure operation experience of surgeons due to the function whereby information such as the patient diagnostics, radiological images, and physiological data is displayed. Through the advancement of the technology in the field of computer modeling and simulation, the quality and value of the 3D virtual patient, which is created from head to toe using MRI and CT images, have been increased, and doctors can now inspect the patient's body from any angle without having to undertake a surgical procedure. For the doctor, this approach supports the formulation of a more-accurate diagnosis while the physical impact regarding the patient is minimized. The operation of the AR technology of the AV400 Vein Viewing System [109] involves the use of a handheld scanner that projects onto the skin to show the location of the patient's veins. With the use of the AV400 device, the medical practitioner is 3.5 times more likely to precisely find a vein during the first injection attempt. Smart Specs [110] enhance the vision of legally blind or partially sighted people. The product is designed to enhance the visual appearance for the detection of large obstacles, such as walls, tables, doorways, and so on, in the absence of light; for this purpose, a 3D camera and Android are used with AR and computer-vision technologies to hide the background, and the edges and features are highlighted to provide a clear visibility. For Saagara AR [111], an innovative smartphone technology is applied to improve the user's health and raise the user's consciousness. The live view, which is generated by the user's smartphone camera, is augmented with audio and 3D graphics to deliver explanations of health and wellness concepts. The 3D graphics include deep breathing, meditation, and a 3D city that shows the benefits of healthy and active lifestyles.

With the advancements of the GPS and AR technologies, it has become possible to use smartphones for the visualization of the geo-referenced models of construction sites, underground structures, cables, and pipelines. AR can play a key role in the support of the construction teams in the construction field in terms of the attainment of their understanding of those construction processes that comprise varieties of systems and components. The architecture and construction industries will therefore be able to realistically visualize a project, and architects and designers will be abe to show their new building designs to clients as they would appear on the proposed sites. CityViewAR [112] is an AR-based smartphone application that allows the user to see the pre-earthquake city of Christchurch. The user can walk around the current city and see full-scaled 3D virtual models of on-site buildings before they were demolished, and pictures and written information are also included.

Bentley Systems [113] has developed a prototype application for the visualization of underground infrastructure that supports a slice-tool measurement of the inter-pipe distances. In addition, the user can add 3D pipeline data by using a ground-penetrating radar. For Smart Reality [114], the user aims his/her smartphone camera at a printed target to overlay 3D virtual objects, thereby facilitating an interactive projection, and it can be used with Oculus Rift and the Epson Moverio BT-200 smartglasses. BIMevoke has introduced the 3D Guided Maintenance application [115] that supports the integration of the user's existing information into 3D information. The application supports engineers in the repairing of pumps with superimposed 3D imagery, it provides the necessary tool information, and the AR technology illustrates the exact motion that is needed for the engineering performance. **Fig. 5** depicts examples of the AR-based medical health-care and construction applications.

Fig. 5. Examples of the medical health-care and construction applications (left to right): Vein Viewing System, enhanced virtual excavation, and 3D Guided Maintenance

5. Conclusion

Augmented reality (AR) has evolved from an exploratory experiment for the supplementation of sensory channels in a well-controlled lab environment to a widespread enabling technology for a variety of interactive applications, and this progression is partly due to the advances in tracking, registration, and the display-device and associated-software fields. Its expansion, both in terms of technological maturity and the broader acceptance from the applications and user bases, indicates the further accelerated proliferation that has been expected. This paper contains a summary of the recent development of the core-AR and associated techniques with respect to the pertinent applications. Further, this paper provides a comprehensive review of the recent breakthroughs, and a comparative analysis of the tracking, sensing, display devices, SDKs, and the variety of emergent platforms is presented with key examples of the relevant applications.

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Soo Kyun Kim received Ph.D. in Computer Science & Engineering Department from Korea University, Seoul, Korea, in 2006. He joined Telecommunication R&D center at Samsung Electronics Co., Ltd., from 2006 and 2008. He is now a professor at Department of Game Engineering at Paichai University, Korea. He has published many research papers in international journals and conferences. His research interests include multimedia, pattern recognition, image processing, mobile graphics, geometric modeling, interactive computer graphics, and virtual realtity. E-mail : kimsk@pcu.ac.kr

Shin-Jin Kang received an MS degree from the Department of Computer Science and Engineering from Korea University in 2003. He has worked at Computer Entertainment Korea (SCEK) and NCsoft Korea as a lead game designer in AAA title level projects. He received PhD degree in Computer Science & Engineering at Korea University in 2011. And he is now a professor at the School of Games in Hongik University and a technical advisor in research and development division of NCsoft Korea.

Yoo-Joo Choi http://orcid.org/0000-0001-7520-097X
She is a professor in Department of Newmedia at Seoul Media Institute of Technology(SMIT), Korea. She received her M.S. and Ph.D. degrees in Computer Science from Ewha Womans University in 1991 and 2005, respectively. She was a researcher at R&D Department of KCI Co. and POSDATA Co. in Korea between 1991 and 1999. Her research interests include image processing, computer vision, computer graphics, augmented reality and human-computer interaction. E-mail : yjchoi@smit.ac.kr

Min-Hyung Choi received his M.S. and Ph.D. from University of Iowa in 1996 and 1999 respectively. He joined the Computer Science and Engineering Department at the University of Colorado at Denver in 1999. Currently he is the Director of Computer Graphics and Virtual Environments Laboratory. His research interests are in Computer Graphics, Scientific Visualization and Human Computer Interaction with an emphasis on physically-based modeling and simulation. E-mail: min.choi@ucdenver.edu

Min Hong received his B.S. from Soonchunhyang University. He received his M.S. from University of Colorado at Boulder, and Ph.D. received from University of Colorado at Denver and Health Sciences Center in 1995, 2001, and 2005 respectively. Currently he is the Department Chair of Computer Software Engineering and Director of Computer Graphics Laboratory in Soonchunhyang University. His research interests are in computer graphics, physically-based modeling and simulation, bioinformatics, and image processing related applications. E-mail: mhong@sch.ac.kr