Leveraging Augmented Reality for Highway Construction

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FOREWORD

Augmented reality (AR) is an immersive technology that combines computer-generated information with real-world imagery in real time. AR enhances the user's perception of reality and enriches information content. In the context of highway construction, enriched content can help project managers and engineers deliver projects faster, safer, and with greater accuracy and efficiency. Navigating through the phases of a construction project allows managers to catch errors before construction and potentially improve design and construction details. Managers can also use AR tools for training, inspection, and stakeholder outreach.

This study focused on documenting current AR technologies and applications, with an emphasis on the state of the practice for using AR technologies in design, construction, and inspection applications for highways. This study included a literature review and interviews with researchers and vendors. This report is intended for State departments of transportation, the Federal Highway Administration, highway contractors and designers, and academic institutions involved in highway construction research.

Cheryl Allen Richter, P.E., Ph.D.
Director, Office of Infrastructure
Research and Development

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Challenges in highway construction management and field operations include the lack of real-time and integrated information, gaps between planned solutions and practical implementations, quality assurance, and effective project communications. Three-dimensional (3D) model-based design and construction workflows are becoming more common on highway projects, and the Federal Highway Administration (FHWA) is promoting these and other innovations through its Every Day Counts program and Building Information Modeling efforts. This increased use of 3D model-based workflows and rapid advancement in computer interface design and hardware make augmented reality a tool for overcoming these challenges.</td></tr>
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APPROXIMATE CONVERSIONS TO SI UNITS				
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		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
ADA	Americans with Disabilities Act
AEC	architecture, engineering, and construction
AI	artificial intelligence
AR	augmented reality
AU	Autodesk University
BIM	building information modeling
CADD	computer-aided design and drafting
CAVE	cave automatic virtual environment
CIM	civil integrated management
DOT	department of transportation
E&C	engineering and construction
EDC	Every Day Counts
FHWA	Federal Highway Administration
FOV	field of view
fps	frames per second
GNSS	global navigation satellite system
GPS	Global Positioning System
HMD	head-mounted display
IowaDOT	Iowa Department of Transportation
iOS	iPhone™ Operating System
IR	infrared
LOD	level of detail
MEMS	microelectromechanical systems
MEP	mechanical, electrical, and plumbing
MR	mixed reality
NCHRP	National Cooperative Highway Research Program
NDOT	Nevada Department of Transportation
NEPA	National Environmental Policy Act
ODG	Osterhout Design Group
OJT	on-the-job training
OS	operating system
OST	optical see-through
QA	quality assurance
QC	quality control
QR	Quick Response
R&D	research and development
ROI	return on investment
ROW	right-of-way
SDK	software development kit
SLAM	simultaneous localization and mapping
STA	State transportation agency

TRB	Transportation Research Board
UDOT	Utah Department of Transportation
UI	user interface
VIO	visual-inertial odometry
VR	virtual reality
VST	video see-through

CHAPTER 1. INTRODUCTION

BACKGROUND AND SIGNIFICANCE OF WORK

State departments of transportation (DOTs) are charged with providing a safe, efficient, accessible, and convenient transportation system that meets vital national interests and enhances the quality of life for users of State DOT facilities, today and into the future. To that end, highway projects must be delivered with a high standard of quality, with adaptable and scalable processes allowing for future innovations, and be effective at meeting public expectations and State DOT goals.

Three-dimensional (3D) model-based design and construction workflows are becoming more common on highway construction projects, and the Federal Highway Administration (FHWA) is promoting these workflows and other innovations through its Every Day Counts (EDC) program to identify and deploy innovative solutions to accelerate the delivery and cost effectiveness of highway projects, enhance safety, and protect the environment (FHWA 2019).

Challenges in highway construction management and field operations include the lack of real-time and integrated information, gaps between planned solutions and practical implementations, quality assurance (QA), and effective project communications. The increasing use of 3D model-based workflows and the rapid advancement in computer-interface design and hardware have made augmented reality (AR) a technology that can help overcome these challenges.

AR is an immersive technology that combines computer-generated information with the real environment in real time. AR enhances the user's perception of reality and enriches information content—content that can help project managers and engineers deliver their projects faster, safer, and with greater accuracy and efficiency. The ability to navigate through all phases of a construction project enables managers to catch errors before construction and potentially improve design and construction details. Managers may also be able to use AR technologies for training, inspection, and stakeholder outreach. Considering its benefits and success in the entertainment and video-game industries, leveraging AR will likely be a significant advancement in construction management of highway infrastructure assets.

RESEARCH OBJECTIVES AND APPROACH

A key objective of this study was to identify the availability, accessibility, and reliability of using AR technologies for construction inspection and review, QA, training, and improved project management using real-time information in a real-world environment. AR has the potential to reduce construction cost, improve delivery time, and assist with overall management of construction projects. For this study, researchers documented potential advantages, limitations, shortcomings, and costs of using AR, as well as potential future challenges.

Additional study objectives included documenting methodologies for managing the data flows required to support AR and its integration into highway agency design and planning workflows—particularly how AR workflows are compatible with building information modeling (BIM) workflows already in use or being developed by transportation agencies.

A final objective was to identify current AR case studies that highlight and promote AR in construction management of highway infrastructure. The study identified and documented the implementation of emerging AR technologies currently used in construction and present best practices and lessons learned from successful AR use in other industries.

While AR use in the architecture, engineering, and construction (AEC) industry is just beginning, formal documentation to catalog its potential advantages, limitations, and applications will help lay a foundation and identify promising future paths.

REPORT ORGANIZATION

The first chapter of this report provides an overview and definition of AR, including the various terminologies currently in use, similarities and differences between AR and the more familiar virtual reality (VR), and the emerging overall descriptor, mixed reality (MR).

Chapter 2 includes the results of a market review of AR technologies. The chapter features descriptions of AR technologies, products, workflows, and software applications for highway applications—several of which are available today. The chapter also contains a discussion of implementing AR in 3D design and construction workflows.

Chapter 3 outlines the characteristics of available AR systems, including displays, user interface (UI), sensing, and portability, and it describes the reliability, applicability, strengths, weaknesses, and challenges of available AR systems in construction applications. This chapter also outlines how AR technologies can be implemented in a BIM workflow supporting construction.

Chapter 4 summarizes research on state-of-the-art AR applications in highway construction and related design and construction activities, describes highway construction scenarios and applications of AR tools, and outlines relevant technology and data workflow strategies. This chapter also reviews AR applications and workflows in construction-related fields, such as design, planning, and inspection.

Chapter 5 reports the outcomes of the two workshops hosted by FHWA. The workshops provided a forum for discussion of AR tools and potential applications in highway construction. The goals of the workshops were to inform the research priorities and anticipate future directions and opportunities for AR in highway construction. The workshops involved technology and application developers, State DOT representatives, contractors, consultants, and other practitioners who explored how AR can be used to support construction-management functions during highway construction, ranging from construction inspection and review to QA, training, and improved project management through real-time information in a real-world environment. Five hypothetical use cases for AR applications that would positively impact highway construction were developed and ranked by potential impact and by feasibility of implementation as an outcome of the workshops.

Chapter 6 summarizes the five case studies of potential highway construction AR applications developed from the outcomes of the two workshops and refined using the results of the study research. Each use case is outlined in a narrative format with a description of the AR technology and workflow used. The chapter also outlines an AR framework that delineates the specific data, workflows, and technologies required to implement AR for these types of highway construction AR activities.

Chapter 7 summarizes the report with key observations derived from the study and includes some conclusions resulting from the research and associated workshops.

OVERVIEW OF AR

AR Versus VR or MR

AR and VR are often part of the same conversation, and the difference between the two may be confusing to those who have not used the technologies. Azuma (1997) proposed a widely accepted definition of AR that states AR must combine real and virtual elements, be interactive in real time, and be 3D registered. This definition does not require a specific output device nor does it limit AR to visual media (Azuma 1997).

AR provides an intuitive and direct connection between the physical world and digital information. AR applications range from smartphone apps that annotate the starry sky to complex augmentation gear that delivers simulated military training scenarios to soldiers in the field. Implementing AR presents complex technical challenges, such as real-world 3D registration, real–virtual object occlusion, and devices that are wearable (Ren et al. 2016).

AR is a general term applied to a variety of display technologies capable of overlaying (or combining) alphanumeric, symbolic, and graphical information with a user's real-world view to provide aligned, correlated, stabilized, contextual, and intelligent information that augments a user's understanding of their real-world view. VR, by comparison, provides a complete replacement to the visual world experienced by the user (Aukstakalnis 2017).

MR is becoming more common in product literature and can be more confusing than AR and VR. Milgram and Kishino (1994) defined the relationship between AR, VR, and MR, and developed a diagram comparing them along an axis they call the reality–virtuality continuum, which is illustrated in figure 1.

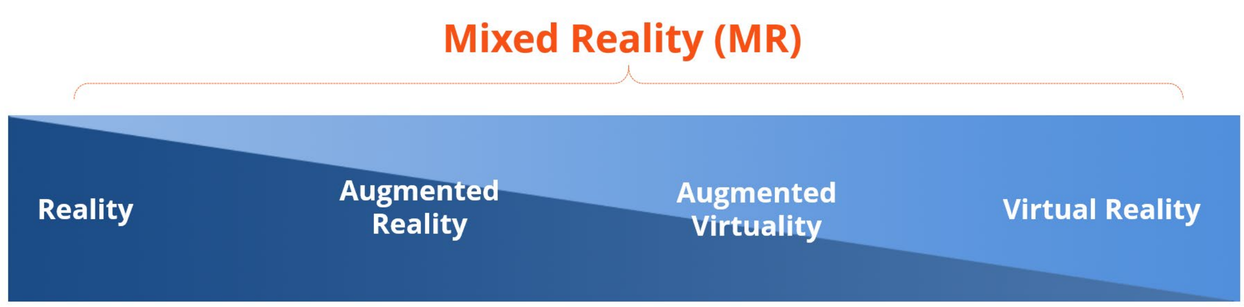

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Figure 1. Illustration. The reality–virtuality continuum.

Full reality is at one end of this continuum, and complete VR is at the other end. The entire region, from full reality to VR, is considered MR. AR is a subset of MR and lies near the reality end of the continuum. A significant portion of the MR experience is the real world, which is then augmented by computer-generated contextual data. Milgram and Kishino (1994) created the term "augmented virtuality" to identify systems near the other end of the MR spectrum where the main experience is mostly computer generated. Variations in augmented virtuality include real-world imagery, such as adding texture-mapping video to virtual objects (Milgrim 1994). For construction applications, real-world perception provided by AR and its association with virtual data and imagery can be a powerful combination.

Virtual Imagery and Scale in AR

The virtual information displayed over the real-world image can take many forms, ranging from graphical annotation and conceptual information to accurate 3D representations of a proposed design or construction scenario. The latter most often comes to mind when considering applications for AR in construction; however, for inspection and training applications, more informational text or graphics will undoubtedly be part of the presentation. Displaying associated metadata or 3D-model attribute information beside relevant 3D elements or real-world objects will enhance the user's understanding of the displayed imagery and environment.

Most currently available AR applications and device platforms allow for displaying virtual 3D-model imagery at different sizes, or they display varying model scales relative to the real world. For example, a 3D-building design can be displayed on a desktop at a scale like the view of a scale physical model, or the model can be displayed at true scale adjacent to or around the viewer and explored as if the user is in the proposed environment. This display at true scale can provide the user with a powerful sense of immersion and presence in the 3D model. The sense of reality and immersion is enhanced by the quality of the display technology (especially if the display is stereoscopic) and by the fidelity and quality of the 3D virtual imagery.

Specific Opportunities for AR BIM in Construction

The use of 3D models and associated metadata for design and construction planning is commonly referred to as a subset of the BIM process. Georeferencing and visualizations of 3D or other BIM data overlaid onto a view of a construction site have three main use categories:

- Visualizing what is not yet constructed (proposed).
- Viewing buried elements or elements obstructed from view.
- Viewing abstract informational data, such as alignment information, easements, site boundaries, or environmental boundaries (i.e., flood levels or sea level–rise data).

There are many opportunities for visualizing information onsite because of the data-rich nature of BIM. BIM data can be geolocated directly on the construction site while using AR to communicate project information during construction. Overlaying BIM data onto existing site elements could benefit site inspectors or contractors checking construction progress. Overlaying 3D models in AR can help confirm the best installation locations for construction components and locate materials, equipment, safety zones, and construction and project components to better prepare site workers. Hazardous work areas and critical emergency information highlighted in AR views can enhance onsite safety (Abboud 2014).

Collaboration in AR

Collaboration involves two or more individuals working together to solve a problem or repair or assemble something. AR can support collaboration between team members involved in construction and engineering. Traditionally, AR allows field personnel to see engineering designs displayed over real-world images, which helps the construction team understand design goals and the engineering team understand constructability challenges. In the field, AR devices with built-in cameras can transmit an onsite team member's view to remote team members with images and annotations to help describe it in an AR-registered view.

Several examples of this approach to collaboration were found in manufacturing and assembly operations where remote users could assist an onsite user by sending remote users virtual images or 3D models to match to real-world objects, sending them data about the objects, and annotating or sketching over real-world objects in their view (Welch 2016). There is significant potential for AR collaboration in construction training and inspection applications.

CHAPTER 2. AR TECHNOLOGY MARKET REVIEW

This chapter provides detailed information on AR technologies and software applications, including technologies and applications that support AR implementation at a construction site. The review focuses on technologies and applications that support design, planning, and construction of highways.

CLASSIFICATION OF AR TECHNOLOGIES

This section provides an overview of technologies currently in use or likely to be used in the future to support AR applications for construction. The section includes descriptions of both hardware and software technologies that support AR. First is an overview of display types and characteristics, followed by an explanation of display hardware technologies. Next is a description of technologies for tracking the position and orientation of a device or user in the real-world environment and the user within the virtual environment relative to the real world. Also included is a description of currently available AR-enabling software and applications.

AR Hardware

Display Types

A key component that enables AR systems is the display configuration, which allows the blending, or augmenting, of real-world imagery with virtual representation. This blending is typically achieved by using a see-through display. There are two categories of displays that achieve this blending: video see-through (VST) displays and optical see-through (OST) displays. Another category of augmented display described by Schmalstieg (2016) is spatial projection where virtual imagery is projected onto real-world objects, but the limitations and applications of this technology do not seem particularly suited for construction applications.

VST displays use digital video and a graphics processor to combine real-world imagery and computer-generated imagery, which is then presented to the user on the display. A VST head-mounted display (HMD) has three components that must be calibrated and tracked: the user's eye(s), the display, and the camera (Schmalstieg 2016; Aukstakalnis 2017). When used with AR applications, tablets and smartphones can be considered VST devices because they capture real-world imagery through the camera on the device and combine that with virtual imagery, which is then displayed on the device's screen. VST displays need not be present in the real-world environment being captured. The video imagery and virtual imagery can be combined and displayed in a remote location, similar to what occurs with video conferencing systems today. Remote AR is being used in the industrial sector for remote maintenance and collaboration.

OST displays commonly use an optical element that is partially transmissive and partially reflective, such as a semitransparent mirror, to overlay a virtual image onto a real-world image. Users view the real world looking directly through monocular or binocular optical elements, which simultaneously display virtual imagery (Schmalstieg 2016; Aukstakalnis 2017). One challenge with OST devices is controlling the brightness of the virtual elements compared to real-world objects. Some devices on the market use advanced optics, such as a special optical prism, to reflect and refract light outputs. Some devices use a separate image sensor to monitor environmental illumination so that the virtual display can be set relative to that brightness for better visibility. OST HMDs have the display set at a fixed distance from the eye. Each time an HMD is used, it must be calibrated to the user's eye. Calibration can be performed quickly and automatically with devices that use eye trackers mounted inside the HMD.

Table 1 lists advantages and disadvantages of some AR display types.

Table 1. AR display types and their advantages and disadvantages.

Visual Displays	Advantages	Disadvantages
VST	• Implementation is inexpensive and easy. • Reality is digitized. • Brightness and contrast of virtual objects are adjustable. • Head movement is better tracked.	• Reality displays in low resolution. • Field of view is limited. • Distance adjustments can result in user disorientation. • Eye strain and fatigue are common occurrences.
OST	• Safely enables user to see with no power. • High-resolution display is included. • Simplicity allows for no frame delay. • Wide FOV benefits the user.	• Reduction of brightness and contrast of virtual objects is poor.

Display Characteristics

Various characteristics of displays can affect the quality of the AR imagery and the user's experience, comfort, and perhaps most importantly, sense of immersion in both the real and virtual environments.

Ocularity and Stereoscopy

AR displays can be classified as either monoscopic or stereoscopic. Stereoscopic displays often produce more realistic and immersive experiences. Monocular devices present images only to one eye. A monocular HMD can be used for AR, but these types of devices are not as popular because they are not as immersive as biocular devices. Google Glass™ is an example of a monocular display. Biocular devices present the same image to both eyes concurrently, which maintains a monoscopic view. VR presentations of panoramic images on mobile devices, such as Google Cardboard™ and Google Daydream™, are typically biocular views of the same panorama presented to each eye. Binocular displays present separate images to each eye, resulting in a stereoscopic effect and a stronger sense of immersion. The tradeoff in using binocular displays is that images must be captured or rendered separately for each eye, thus increasing system requirements (Schmalstieg 2016).

Stereoscopy and Perception of Scale

Human vision is binocular and relies on disparities between each eye to perceive depth and the true scale of objects. VR and AR systems present images to each eye with the same geometry a user's eyes would see in the real world; therefore, users experience an immersive and realistic view of the scene that represents depth and scale close to how a user would perceive objects in the real world (Howard 1995).

Resolution and Refresh Rates

The resolution of the AR display has a direct correlation to the fidelity of the display image and is restricted by the type of display and optical system. VST display resolution is restricted by the type of video camera on the device used to capture real-world imagery. OST displays present a real-world view and will thus have higher perceived image quality because the real-world imagery is independent of display resolution.

Conversely, the disparity in image quality can be detrimental. The refresh rate of the display, how rapidly individual video frames are displayed, influences how well the device renders scenes or objects in motion. For rendering fast motion without image lag (latency) or ghosting, which is when multiple versions of the same object are perceived, higher frame rates (120 Hz or higher) can be advantageous. For most AR devices, frame rates above 60 Hz are desired (Schmalstieg 2016).

Field of View

A key consideration of any AR HMD is the field of view (FOV). FOV refers to the total angular size of the virtual image visible to both eyes, expressed in degrees (Aukstakalnis 2017). FOV, image resolution, and refresh rate are interrelated, as more pixels are needed for a wider FOV. More pixels, or higher resolution, to cover a wider FOV requires more system performance to maintain the same refresh rate. A limitation on many of the currently available OST devices is the FOV of the overlaid computer image due to technological constraints. Many current devices are limited to a viewable field of 60 degrees or less.

The typical human binocular FOV is 120 degrees, which is combined from the left and right eye views, as shown in figure 2.

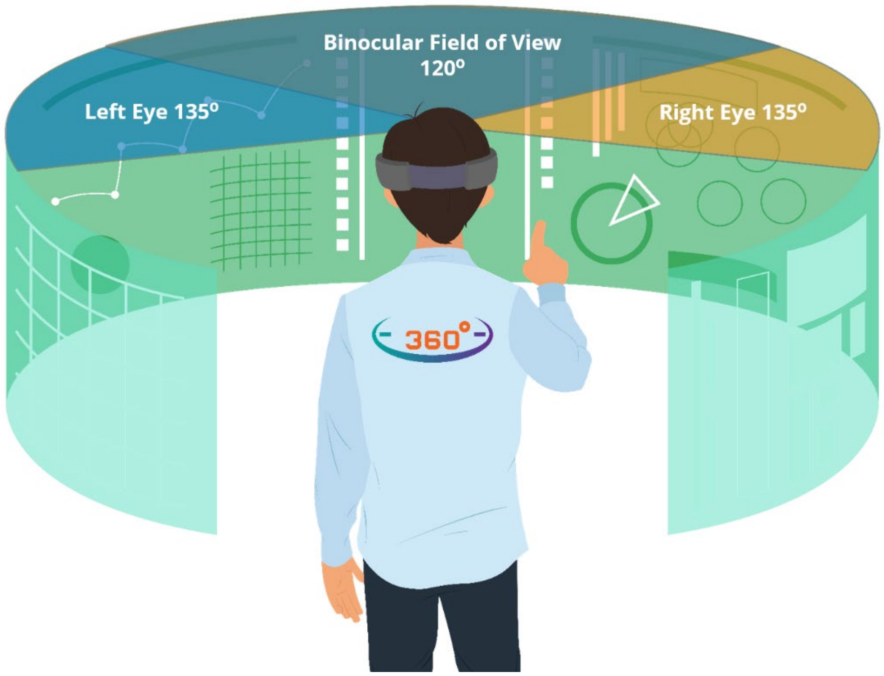

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Figure 2. Illustration. Typical human binocular FOV (120 degrees).

The typical FOV in a current AR display device is approximately 60 degrees, which is half of the binocular field, as shown in figure 3. This reduction in FOV limits what can be displayed by the AR device and can result in the viewer having to move his or her head back and forth to view the entire virtual scene, which can lead to fatigue and discomfort.

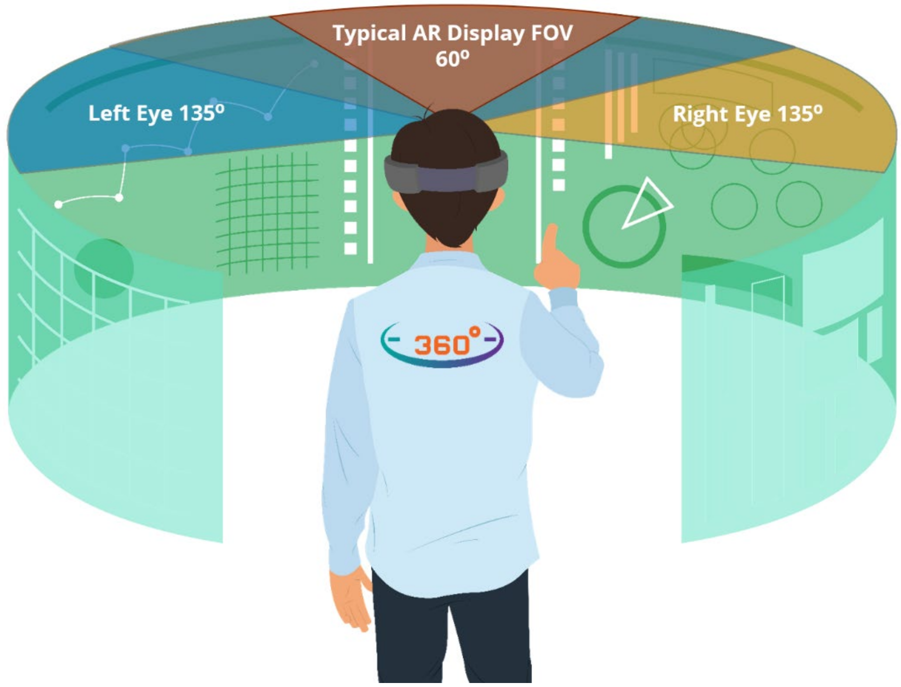

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Figure 3. Illustration. Current AR display FOV (typically 60 degrees).

The FOV on VST devices is based on the camera rather than the display, and the camera's FOV is often wider than that of the display. This difference can result in the displayed image appearing compressed with a slight fish-eye effect. Handheld AR devices, such as tablets or cellphones, typically have cameras with a larger FOV on the back of the phone than the angle of view presented on the display, which is noticeable when the device is held at arm's length. HMDs benefit from a wide FOV, which can only be accomplished by either increasing the size of the HMD or by placing the display device or optics closer to the eye (Schmalstieg 2016).

Occlusion

Occlusion refers to objects that should be hidden from view once the real-world image is fused with the virtual rendering (i.e., when a virtual object is placed behind or in front of a real object). Occlusion is an important visual cue to convey realistic scene structure. AR applications use a variety of rendering techniques to deal with occlusion; the success of these applications can depend on many factors and influence system performance.

User Discomfort with Display Technologies

One challenge that has faced the adoption of VR and AR display technologies is an effect alternately referred to as "VR motion sickness," "cyber-sickness," or "simulator sickness." The effects vary between users with some people being more sensitive to the effects than others. One factor that contributes to this sensation is a mismatch between visual sensory input and vestibular input (i.e., there is a mismatch between the perceived movement and the physical body movement or motion sensory input from the inner ears). This effect is most pronounced in

HMDs, and the mismatch is due to visual computing systems not being able to provide updated imagery at a high enough frame rate to match the movement of the head and body. The delay in delivering updated frames is measured as latency and generally occurs with faster head movements. Research shows that at least 90 frames per second (fps) should be delivered to keep that discrepancy within tolerable levels (Buker 2015). Stereoscopic displays have two frames that would need to be delivered in at least 90 fps. Many currently available VR HMDs are designed to achieve 90 fps, but the computing system delivering the visual content to the device ultimately controls the frame rate (Hecht 2016).

A second factor that contributes to VR motion sickness is the virtual movement of the user's viewpoint in the virtual environment—an effect called vection. The problem with vection comes from the disparity between what the eyes and the vestibular system tell the user. The eyes show forward movement, but the vestibular system feels no such motion. This problem occurs more with VR systems because there is usually a need to move the user's viewpoint as the user explores the virtual environment. One strategy sometimes used to reconcile the disparity involves placing the user in a virtual element that moves with the user, such as a driving simulator, which typically includes interior elements of the simulated vehicle. Vection will most likely not be a critical issue with AR display systems because the user's motion is tied to the real-world environment.

A third factor that affects user comfort, primarily in stereoscopic displays, is vergence—the positioning of the eyes in opposite directions to fuse two images into a single binocular image. The eyes sense this fusing movement separately from their sense of accommodation (i.e., how much the eye adjusts its focal distance to bring an object into focus). The two cues can conflict if the actual distance of the object differs from the apparent distance—and the mismatch is larger when the actual focal point is on a screen close to the eye in a VR or AR HMD. Vergence can affect the user's ability to place a virtual object into a real-world environment comfortably and at the correct distance (Hecht 2016).

Display Hardware

AR displays can be roughly categorized by the distance of the viewing mechanism from the user's eye. The three categories are head space, represented by HMDs; body space, which includes handheld displays, such as tablet or mobile devices; and world or environment space, including projected displays and immersive rooms, such as cave automatic virtual environments (CAVEs). Key considerations of HMDs include FOV, resolution, and refresh rates. The ideal HMD must have a wide FOV and be comfortable, unobtrusive, and lightweight.

HMDs

Visual 3D-display technologies are categorized into four classes: stereoscopic approaches, holographic displays, light-field displays, and volumetric displays. Stereoscopic approaches rely on sending separate images to each eye. This is the most commonly used approach in HMDs because binocular near-eye devices, or those with displays close to the viewer's eyes will have to send separate images to each eye. Stereoscopic displays using glasses (polarized or active shutter glasses), such as projected 3D films, fall into this category as well. Holographic and light-field displays use light waves to generate and then recreate images in 3D space. Holographic devices use coherent (laser) illumination, and light-field displays use incoherent light. Volumetric displays use multiple light sources projected at points in space to create a 3D image. Visual AR displays use one or more of these technologies to create or project virtual images in space that are perceived by the user from multiple viewing angles (Schmalstieg 2016).

Handheld Display Technology

Handheld devices, such as tablet computers and mobile phones, are currently the driving force behind AR in the gaming, entertainment, and AEC industries. Handheld displays are VST devices that use the back-facing cameras on the device to capture video of the real-world environment and display that image on the front screen. AR applications then align and render virtual data over the real-world imagery on the screen.

A user typically needs to hold the handheld device close to eye-level at shoulder height and at arm's length to capture the widest FOV. This position can be difficult for a user to maintain over long periods and could prove challenging in a construction environment.

Stationary Displays

Stationary displays that can be used in AEC environments include desktop configurations and possibly even immersive CAVEs with projectors. Desktop displays are composed of a desktop computer or laptop with a built-in webcam whose video image can be used to create a VST environment. Desktop AR systems will have uses in collaborative AR applications in addition to video conferencing. Users in office locations could potentially collaborate with users on construction sites through their desktop computers or by using CAVE facilities that allow viewing the real-world environment through the onsite user's device, and communication can occur via the remote user's VST device. It is possible that a large-scale immersive CAVE room could be used for collaborative AR applications, which could allow several people to communicate directly with remote users on construction sites through their AR device.

Device Tracking—Sensing Movement Within the Real-World Environment

In real time and with a high level of accuracy, AR devices need to follow a user's movement in relation to position and orientation in the real-world environment. This process is referred to as tracking and is a significant challenge in the design of AR devices. The position of devices is typically measured in x, y, and z coordinates relative to real-world position in geodetic or project-based coordinates. Orientation, or the view direction of the real and virtual cameras, is measured in angles around the positional coordinates as angles in x, y, and z (i.e., Euler angles) or in camera-relative angles referred to as pitch, yaw, and roll. Changes in position and orientation represent movement in three axes of measurement or a total of six degrees of freedom.

The combined measurement of position and orientation is sometimes referred to as the device or camera pose. AR systems must follow the user's position and orientation in real time and update the pose of the virtual camera to match that of the real-world camera in real time. Registration is the term used to describe the alignment of the virtual model that coordinates to the real-world position and orientation (Schmalstieg 2016). The positioning and orientation of the user in a virtual world relative to the real world is referred to as localization, particularly in the robotics navigation field.

Optical Tracking Configurations

Optical tracking for AR devices, such as HMDs, can be divided into two categories based on the location of cameras and sensors. Outside–in tracking refers to systems in which cameras are placed in stationary locations and the user is tracked within a fixed environment. The external cameras track the user's HMD, which has passive or active markers attached. This tracking method produces highly accurate position and orientation results. One limitation of outside–in tracking is the camera or sensor locations—the object cannot be tracked when it is out of the line of sight. These types of systems are limited to the range of the cameras and the working space defined by their locations. Outside–in systems will most likely prove to be impractical for most construction sites due to this limitation to a configured environment and the need for installed devices in the environment. AR/VR devices, such as Oculus Rift™, HTC Vive™, and Sony PlayStation® VR use outside–in tracking.

Inside–out tracking uses cameras or sensors placed on or inside the AR device. This approach allows for a greater sense of freedom because the user is not limited to a specific tracking space defined by fixed camera locations. The camera or sensors view the surrounding environment to determine how their position changes in relation to the real world. These systems are limited only by the size and performance characteristics of the sensing technologies they use. AR/VR devices, such as Microsoft HoloLens™ and DAQRI and Microsoft MR devices, such as the Samsung HMD Odyssey use inside–out tracking (Ishii 2010).

Tracking Sensor Technologies

Sensors in AR systems help track the location and orientation of the user and the location of real objects and markers in the environment using real-world coordinates. Many technologies can be used to track position and orientation; each has its own performance characteristics, costs, ease of use, and mobility for the user. Tracking technologies include sensors that monitor satellite network position, such as global navigation satellite system (GNSS), or wireless networks, such as those used in mobile devices. Tracking technologies also include inertial sensors, optical sensors that include video and infrared (IR) sensors, simultaneous localization and mapping (SLAM) devices, and sensors that can perform 3D scanning of environments concurrently with the user's change of viewing direction.

Each of these tracking technologies have their advantages, but for outdoor environments, hybrid systems combining inertial sensors and optical tracking technology provide the most robust and accurate positioning for AR applications (Holloway 1997). At construction sites, highly accurate tracking is necessary, as well as long ranges, high bandwidth, and the ability to process large amounts of data. The challenges of tracking in an outdoor environment include sensitivity to static and dynamic errors and potentially less control over the environment. Construction sites are always changing, which may limit or even eliminate the ability to place static sensors or markers onsite.

Table 2 outlines some advantages and disadvantages of tracking methods found in AR devices.

Table 2. Tracking methods and their advantages and disadvantages.

Tracking Method	Advantage	Disadvantage
Satellite Position Tracking (GNSS)	• Stable when enough satellites are available. • Available in a broad area. • Accuracy is improved with DGPS and/or CORS. • Absolute position is obtainable.	• Unavailable inside buildings. • Only position is obtainable, orientation is not. • Vertical accuracy does not match horizontal accuracy.
Wireless LAN	• Available inside buildings. • Stable when enough stations are available. • Unnecessary installation when enough WLAN stations are already installed. • Absolute position is obtainable.	• Low level of accuracy. • Only position is obtainable, orientation is not.
Inertial sensors	• Unnecessary to install in the environment. • Computational load is low.	• Accuracy decreases over time because of accumulation of drift error. • Other methods need to be used concurrently to obtain absolute position or orientation.
Vision sensors (marker-based)	• Inexpensive compared to most other tracking methods. • Scalable tracking system. • Accurate and stable when enough markers are visible.	• Necessary to install markers; positions and orientation must be measured in advance. • Available only when markers are visible. • Necessary to install a large number of markers when a broad area needs to be covered.
Vision sensors (markerless or natural feature based)	• Installation not necessary while in the environment. • Less expensive for executing tracking. • Scalable tracking system. • Accurate and stable when enough features are visible. • Trackable area can be extended online by using SLAM devices.	• Require significant processing overhead. • Accuracy and stability depend on environment. • Unstable in a dynamic environment in which features are not static.

CORS = Continuously Operating Reference Stations; DGPS = differential global positioning system; WLAN = wireless local area network.

Satellite Position Tracking

GNSS uses communication signals between satellites to provide precise location positioning anywhere on Earth. The United States' satellite system is called the Global Positioning System (GPS). Higher accuracy can be obtained using networks of servers and base stations. The servers and base stations send correction signals through Wi-Fi™ or radio waves to the GPS receiver on the device. Real-time kinematic or differential GPS satellite navigation and the National Oceanic and Atmospheric Administration network of Continuously Operating Reference Stations are technologies used to enhance the precision of position data derived from satellite-based positioning systems. Two drawbacks of GPS positioning include sensors that do not work well indoors and vertical precision (z) that can be less accurate than ground positioning (x and y). The accuracy and consistency of these systems are not currently ideal for the high-accuracy tracking required for AR devices in situations in which virtual imagery need to match real-world imagery exactly. Virtual imagery matched using GNSS alone may move relative to real-world imagery displayed in real-time through the device (Pesyna et al. 2014). Mobile device–based AR applications in which exact registration of virtual and real-world imagery may not be required will most likely be based on GNSS tracking and positioning.

Wireless Networks

Wireless networks include Wi-Fi, Bluetooth®, and mobile phone networks. These networks can be used to determine a user's or device's position. Wireless networks differ in bandwidths, latency, fluctuations, and availability. To support an AR device, a wireless network must have low latency, good mobility, and high bandwidth (Sharma 2014). Vertical precision can be an issue with these systems. The accuracy of systems, like GNSS or GPS, is often not ideal for the tracking requirements of AR devices. Combinations of wireless networks can be used to improve coverage, speed, and accuracy of user positioning. Combined wireless sensor networks and jobsite Wi-Fi networks are valuable to the construction industry. These combined networks will prove to be a critical and useful component on the jobsite by providing tracking and localization for AR devices as well as access to 3D models and other data associated with AR applications (Domdouzis 2004; DeWalt 2017).

Inertial Sensors

Inertial sensors measure the motion of a device in space and can include gyroscopes and accelerometers. Gyroscopes measure rotational inertia while accelerometers measure linear inertial displacement. A magnetometer, or electronic compass, measures magnetic fields. The output of a magnetometer is used to determine absolute north, east, south, or west, like a compass. Gyroscopes and accelerometers are used in conjunction with magnetometers to determine both position and orientation (Collin 2013). Combining the three sensors allows for rapid and accurate position and orientation determination with minimal latency. Modern inertial measurement unit sensors are based on microelectromechanical systems (MEMS) technology. MEMS are being used more frequently in the development of AR hardware because of their small size, low cost, and low latency.

Vision Sensors and Visual Tracking

Using vision or optical methods for tracking requires small digital cameras, which function as sensors. The camera captures specific features in the environment and uses those features to determine relative orientation and position. Many vision-based systems use IR scanning sensors and/or multiple cameras that allow capturing 3D real-world data. Tracking methods for vision sensors can be defined as either marker based or markerless based depending on whether markers, or graphical targets, are placed into the scene. These markers are placed in the scene and are typically objects designed to be easily detected, such as circular or square shapes. The position of the markers must be measured beforehand in the real-world position, and those locations are used by the system to register the virtual model as the locations are detected. Many off-the-shelf AR applications and toolkits use graphical markers for tracking. Marker-based tracking systems are not ideal for large-scale outdoor environments because the size of the markers varies too much between closeup and distant views. One study used markers in large indoor nuclear facilities, and the markers proved to be relatively successful for navigation and inspection tasks on the site (Ishii 2010).

Markerless or natural-feature tracking uses real-world objects to compute the camera position and orientation and to align virtual objects in the scene. If a reference model is provided to the system before tracking, an approach referred to as model-based tracking, then the imagery from the camera is compared to the model and aligned to the real-world position. A few of the AR development kits on the market, such as Vuforia™ and VisionLib™, support tracking using reference models (Schmalstieg 2015; Vuforia 2017; VisionLib 2020). Markerless tracking is more flexible and effective because there is no need for a prepared environment with markers.

Model-free, markerless tracking uses a relative method of position calculation and can only place virtual objects spontaneously and not registered to real-world objects. AR systems can combine this camera-based, model-free visual tracking with inertial sensor data to more accurately and efficiently calculate movement and position, a process referred to as visual-inertial odometry (VIO). VIO algorithms are being built into many of the AR software platforms currently under development. A similar software process to VIO is SLAM, a process whereby the system concurrently maps the real-world environment in 3D and calculates the user’s position and orientation within that environment (Leutenegger 2014).

Current VIO systems can maintain relative position with high accuracy and for considerable distances with access to real-world objects that can be tracked effectively. When a real-world position is provided to the system for accurate registration of the virtual model in the real-world environment, these systems maintain their position relative to the real-world, and hence the virtual world, very accurately. Many AR application developers are exploring hybrid solutions for AR devices that establish real-world coordinates with a marker first, then continue to track the user’s position and orientation with VIO tracking. A user first places a marker at a known location in the environment. An AR session begins when the user scans the marker with the AR device. The AR device registers the real-world view to the virtual model environment, then the system maintains position and orientation with the tracking process. Some case study examples of this type of implementation using the DAQRI and Microsoft HoloLens devices were presented at a recent industry-sponsored event by Chen (2017) and Jahangiri (2017).

User-Controlled Positioning and Navigation

AR devices and applications use different methods for user navigation within the virtual environment. Tablet devices and phones typically support swiping and touch controls on the device face. Many AR device manufacturers have developed gestural controls that allow the user to navigate and control virtual elements with hand and finger motions. Intel® RealSense™ and Leap Motion™ devices natively support these gestural navigation controls. The Microsoft HoloLens supports audio-based commands and controls as well as gestures. Most devices support interaction with menus and virtual objects with a technique called gaze and dwell. A reticle in the user's view shows where the user's view is focused. When that view is fixed for a certain amount of time on an object or menu (the "dwell" in the gaze and dwell technique), the object is selected, or the menu command is processed.

The types of controls available on construction-focused AR applications will be a critical aspect of implementation and adoption due to safety and convenience concerns by users in an active and complex construction environment.

AR-ENABLING SOFTWARE AND APPLICATIONS

AR software systems need proper framework, networks, data storage, and data access. Two important requirements for AR software are platform and user-interface abstraction, both of which allow reusability and extensibility of the interface. Platform abstraction is necessary for AR software to run on various systems and displays. Platforms contain an operating system (OS) that is deployed on a device and built off software development kits (SDKs). SDKs are collections of multipurpose libraries, such as ARToolkit™, Apple ARKit™, Google ARCore™, and Microsoft Windows Mixed Reality™, that are used to build software on independent platforms. Cross-platform compatibility allows developers to reuse source code for target systems. Reusability of software components is important because new AR applications and devices are constantly being developed. Platform independence avoids proprietary vendor software and promotes the adoption of new, more innovative hardware. AR UIs consist of real and virtual objects and need to be able to react in real time to changes in the user's view and the real-world environment. There is currently no standard UI paradigm for AR interaction (Schmalstieg 2016).

Computer-Aided Design and Drafting/BIM AR Applications

AR applications for construction will be developed around either the display of annotation and graphical information that enhances the understanding of real-world objects, or they will be developed around 3D design and construction models that will be overlaid in position in the view of the real-world environment. This is the direction many of the current AR applications have taken, and most are based on workflows and tools that are already in place in support of BIM applications for design and construction. These computer-aided design and drafting (CADD)/BIM tools will be an obvious starting point for the development of AR tools, and many AR applications will eventually become extensions of current BIM and 3D model workflows rather than discreet processes.

Nearly all major vendors for 3D design applications have implemented tools and workflows that support the deployment of 3D models to mobile devices for viewing in the field, and most support the built-in georeferencing capabilities of the devices. The platforms support the review and collection of data in the field through mobile devices, which can then be synchronized with project models and data in the design office. Many vendors have enabled deployment of these 3D models to one or more of the AR HMD models through these mobile platforms. While most of the tools offer means for optimizing models and model display on mobile devices with more limited processing power and storage, this optimization will be even more important for AR devices and applications that typically require sufficient graphics performance to support real-time stereoscopic rendering of the 3D models. Current limitations of most AR HMDs include processing power, memory, data storage, and connectivity.

Autodesk 360 Tools as an Example of Cloud-Based Project Information Sharing

Autodesk® developed a cloud-based sharing and collaboration framework for its design and construction planning tools that allows online access to project design information. The Autodesk 360 family of tools includes integration platforms and mobile-device-based viewing and data collection tools that can leverage data from all its applications. The Forge platform is Autodesk's open-source development platform for third-party developers that supports access to all their CADD tools and platforms, as well as cloud-based collaboration and delivery of several data types via web-based applications. The BIM360 Docs tool is built on Forge and provides web and mobile-device access to most data types, including 3D model/BIM data.

At Autodesk University (AU) 2017 in Las Vegas, DAQRI™ (developer of AR HMD devices) presented a tool under development in partnership with Autodesk on the Forge platform using BIM360 Docs to prepare and deliver a 3D model to the DAQRI device via a wireless connection. The preparation process included the ability to optimize the model by editing the extent of the model and hiding unnecessary objects to reduce the overall size so that it would run effectively on the DAQRI device. With the model loaded and the user onsite, a printed target image was used to register the virtual model to real-world coordinates. The user was then able to navigate around the site while the model remained registered to the real world. The user could access and display data embedded in the virtual model that was imported from the original design model (Chen 2017).

Currently, only InfraWorks 360 for mobile devices supports geolocation within a project model through GNSS localization on enabled devices. Recent discussion on the Autodesk Knowledge Network has focused on geolocation being provided for mobile-based 360 tools. These mobile-based tools remain a powerful way of bringing virtual two-dimensional (2D)- and 3D-model data to a construction site where that information can be compared to existing site conditions as evidenced by their adoption in 3D model-based workflows. This platform will most likely be the framework in which AR applications within the Autodesk family of products would be developed. At AU 2017, Autodesk was demonstrating a marker-based VIO-tracking AR model viewer running on a tablet device that was connected to an online version of the model through the Forge platform. Several presentations were made at AU that showed examples of users adopting some of these tools for project sites.

In one example, the Autodesk InfraWorks 360 on a mobile device was used to display a 3D design model for a highway widening and parking area project in Oregon, and the view of the model on the device roughly lined up with real-world views of the site (Iliyin 2017).

Bentley Systems

Bentley Systems is advancing VR and AR through their CONNECT 3D modeling programs and through a recent partnership with Analytical Graphics, Inc. The CONNECT programs include LumenRT, OpenRoads, AECOSim Building Designer, OpenPlant, and Context Capture (Bentley Systems 2017).

Bentley LumenRT is Bentley's visualization and reality modeling software tool that allows the creation of immersive 3D virtual environments. Immersive LiveCubes can be created to share the VR models on desktop computers or export them to VR displays, such as Oculus, HTC Vive, and Samsung devices. OpenRoads allows users to develop 3D models of existing and proposed infrastructure, including roads, bridges, subsurface utilities, and buildings. Context Capture can generate millimeter-accurate 3D reality models from digital photographs. Bentley's suite of tools allows designers to develop 3D virtual models and environments that can be used with AR devices.

Trimble Systems/SketchUp

Trimble has developed survey- and reality-capture technologies, and Trimble has also developed several products intended to support mobile devices in the field and the deployment of 3D-model data to those devices. Trimble Connect™ is a cloud-based data portal platform that supports model integration using all of Trimble's 3D model formats (including SketchUp™) as well as several of the more commonly used 3D design platforms from other vendors. Trimble Connect supports viewing and georeferencing of those models on several mobile-device platforms. Trimble Catalyst™ is a software subscription-based tool that supports enhanced GNSS positioning on mobile devices. Trimble states that, with a plug-and-play antenna device and the Catalyst software, submeter accuracy for positioning is possible in many locations.

Synchro Software

Synchro Pro™ is the viewing and collaboration tool that supports the deployment of Synchro 3D and four-dimensional (4D) models onto mobile devices for use in the field. Synchro Pro also supports a connection directly with AR devices, such as the Microsoft HoloLens™, for AR viewing. At the time of this writing, Synchro has been acquired by Bentley Systems and will become part of the Bentley Connect Suite of tools.

Deploying AR Applications in the Field

AR in construction will inevitably require bringing project design data into the field. Project design data will most likely be in the form of 3D digital models. These 3D digital models are typically large and complex. A workflow involving segmentation, optimization, streaming, or control over the level of detail (LOD) displayed or deployed to the field will be needed. This need for optimization will especially be true with AR applications where devices will have much higher performance requirements to maintain display frame rates and rendering quality.

In addition to the use of a 3D cloud-based model distribution and sharing platform, such as those described earlier in this section, 3D model optimization schemes, whether through software tools, such as Umbra™ and Microsoft's Simplygon™, or manual methods by designers, will need to be used to simplify the 3D models for AR.

This challenge of bringing large 3D models to the work site is similar to the challenge currently being faced by agencies and contractors transitioning to BIM and 3D model-based workflows (sometimes referred to in the highway design disciplines as Civil Integrated Management, or CIM) These model-based workflows are now being adopted by agencies and will be helpful in the adoption of AR tools for construction. AR could become an extension of this evolution of 3D tools in supporting construction. Many challenges faced by agencies will be the same as those encountered in the development of CIM as outlined in the National Cooperative Highway Research Program (NCHRP) Project 20-68A, Scan 13-02, *Advances in Civil Integrated Management (CIM)* (Adam 2015), and the associated publication NCHRP Report 831, *Civil Integrated Management (CIM) for Departments of Transportation, Volume 1: Guidebook* (O'Brien 2016).

The key CIM-related technologies identified in NCHRP reports that would support AR technologies include the following:

- 3D engineered–models and e-construction processes.
- GIS systems and geolocated data.
- Mobile-device use in construction.
- Electronic document management systems.

The use of consistent geolocated coordinate systems for 3D geometry as part of a 3D-engineered model workflow is essential for AR. One case study in NCHRP 20-68A refers to the careful consideration of LOD in the 3D model, and that just enough detail is modeled to support the goals of the model in visualization and analysis. This approach will be critical in AR applications because device performance will be dependent on model size and complexity. Most devices currently available have limited onboard memory, storage, and processing power to support display of large and complex models.

NCHRP Report 831 identified technology investments that would help agencies advance CIM, including required investment in information technology hardware and software. These same technology investments would benefit the advancement of construction-based AR. The CIM Guidebook authors examined the investment in software applications required to perform the necessary functions in the office and in the field. Investments can include database management systems, surveying and design software, and mobile applications for smartphones and tablets. There could also be additional costs for specialized equipment, depending on performance specifications.

Mobile devices and wearable AR-viewing devices will require high-bandwidth Wi-Fi connections for communication and model downloads. Construction site-based Wi-Fi networks for communication and localization will likely become more common on construction sites and an important supporting option for AR applications.

AR-READY PRODUCTS AND APPLICATIONS

There are relatively few AR products on the market with tools developed specifically for the construction market, but several commercial AR products and computer applications are available for the entertainment market. Some of the vendors in the AR space have started targeting construction applications and have developed marketing materials and prototypes directed toward the construction field.

AR-Ready Viewing Devices—Handheld Tablet Devices

Trimble SiteVision GNSS

One AR device targeted directly for use on construction sites is the SiteVision GNSS tracking AR device, which will be supported through Trimble's Connect platform (figure 4). The SiteVision GNSS tracking AR device is a VST handheld tablet, enabled with VIO tracking technology. The device can accurately overlay virtual 3D-model data based on position and orientation captured through the onboard GNSS tracking device in combination with Trimble's Catalyst software. The Tango 3D capture technology tracks the position and view angle of the device relative to the real world so that the overlaid image does not appear to move over the video image.

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Figure 4. Photo. Handheld AR tablet device with GNSS tracking hardware.

AR-Ready Viewing Devices—HMDs

Two types of augmenting HMDs are available: binocular and monocular displays. Binocular displays are intended for general consumers but have branched out to a broader market for professionals (figure 5). Monocular displays are intended to aid technicians in completing specific tasks more efficiently.

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Figure 5. Photo. User viewing outdoor site through an HMD.

Binocular and monocular HMDs can be directly compared by their image resolution, display frame rate in fps, and virtual image FOV in degrees. Table 3 compares currently available HMDs and lists the optical specifications and intended uses (based on manufacturer specifications).

Table 3. Comparison of optical specifications and uses for HMD AR Devices.

Device	Resolution (Pixels)	Frame Rate (fps)	FOV (Degrees)	Intended Uses
Binocular AR HMDs	—	—	—	—
Sony Smart Eyeglasses SED-E1	419 × 138	15	20	Gaming, entertainment, AEC applications
Epson Moverio BT-300	1,280 × 720	30	23	Industrial and enterprise applications
DAQRI Smart Glasses	1,360 × 1768	90	44	AEC applications
ODG R-7	1,280 × 720	80	30	Surgeons, pilots, inspectors, construction
ODG R-8	1,280 × 720	90	40	Surgeons, pilots, inspectors, construction
ODG R-9	1,920 × 1080	60	50	Surgeons, pilots, inspectors, construction
NVIS nVisor ST50	1,280 × 1024	60	50	Training, simulation, research
Microsoft HoloLens Gen2	1,280 × 720	60	52	Gaming, entertainment, enterprise applications
Magic Leap One Creator Edition	1,280 × 960	N/A	50	Gaming, entertainment, enterprise applications
Monocular AR HMDs	—	—	—	—
Vuzix M100 Smart Glasses	420 × 240	N/A	15	Manufacturing and enterprise applications
Google Glass Enterprise Edition 2	640 × 360	N/A	15	Manufacturing, logistics, and healthcare

—No data available.
N/A = not applicable.

AR-Ready Software Applications

While no AR applications specific to construction management could be found at the time of this research, several applications have been released that focus on the architectural design market. 3D applications designed to facilitate viewing 3D design models on different devices have been on the market for a few years. Many of the developers of these applications are targeting AR devices that are becoming commercially available. This trend will continue to evolve, and as these applications and the supported devices become more stable and portable, the highway construction industry will see construction site–specific tools emerge.

__Mobile Device–Based AR-Viewing Applications__

Several off-the-shelf AR applications allow the user to display a 3D model over the live video feed of a mobile device. The application is provided a graphical target image, such as a plan, rendering, or photograph. The image is printed, and when the application on the mobile device recognizes the target image, the 3D model is displayed in alignment to the image as defined in the application. The view of the model is locked to the position of the target image in the video feed (figure 6). Many of these applications import standard 3D model formats, such as OBJ, DAE, or FBX®.

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Figure 6. Photo. 3D view overlaid on live video on a mobile device.

A photograph can be taken in the field and used as the target image for the AR application, which allows a 3D model to be embedded in a contextual view relatively accurately as though in a photo-simulation. The mobile device can then be pointed at the real-world scene from the same viewpoint, and the AR application will recognize the target image and superimpose the 3D model in the view. The simulation only works if the viewer remains stationary. No examples of applications specifically aimed at construction could be found, but these types of applications could be used to display a 3D model or graphical image of a project element or equipment when the device is pointed at a target image, potentially even a view of the real-world scene captured as a photograph.

Unity Support for HoloLens

The Unity development platform includes support for both the HoloLens HMD and the Windows 10 Mixed Reality specification and devices. Many features and functionalities of the devices, including image recognition and tracking via Vuforia and gestural/audio navigation and controls, are supported in the gaming platform (Unity Technologies 2017).

In a presentation at AU in 2017, the presenters demonstrated an implementation of the Unity/HoloLens platform for wall prefabrication and construction planning. The presentation covered strategies for deploying Autodesk Revit-based design models to the HoloLens and registering those models to real-world construction sites using a printed target image placed in the project site. The presentation showed a prototype live bidirectional connection between the HoloLens user viewing the model remotely on the construction site, and the deployed virtual model being displayed from the Revit design model in the design office (Jahangiri 2017).

Trimble SketchUp Viewer for HoloLens

The SketchUp 3D modeling platform now includes a separate 3D product called SketchUp Viewer, which supports porting of SketchUp models to mobile devices and the Microsoft HoloLens HMD. Using the Viewer and the VR/AR extension to the SketchUp Desktop product, design models can be scaled and explored either in desktop mode or in full-scale immersive mode via the HoloLens. Scaling, navigation, and menu access are supported by HoloLens hand-gesture tools. A video demonstration shows a HoloLens user aligning the virtual model with a real-world scene to provide a registered and tracked AR view of the virtual model (Wheeler 2016).

CHAPTER 3. CHARACTERISTICS OF AVAILABLE AR SYSTEMS

INTRODUCTION

AR is part of a spectrum of technologies that integrates digital information with the user's environment in real time. AR is designed to augment a scene while a user maintains a sense of presence in the real world. The applications for using AR in construction are still evolving, but AR has the capability of augmenting traditional 2D drawings with digital 3D images to help facilitate construction inspection and review, QA, worker safety, training, and improved project management. A close companion to AR is VR, which involves a fully immersive environment in which a person's senses are under control of a system, usually through an HMD. VR applications are also still being developed, but VR's use for reviewing project design alternatives and stakeholder communication is showing strong potential, especially in collaborative environments.

CHARACTERISTICS OF AR SYSTEMS

General AR system architecture can be described by the type of sensory input devices used, including any form of haptic input used for navigation or interaction with the scene and the display device (e.g., phone or tablet, eyeglasses, or head-mounted system, or HMD); tracking devices and software; the type of computing device (e.g., smartphone, tablet, onboard processor or remotely connected computing device); some form of media representation (e.g., textual/2D graphic and/or 3D imagery); and data-input mechanism (figure 15).

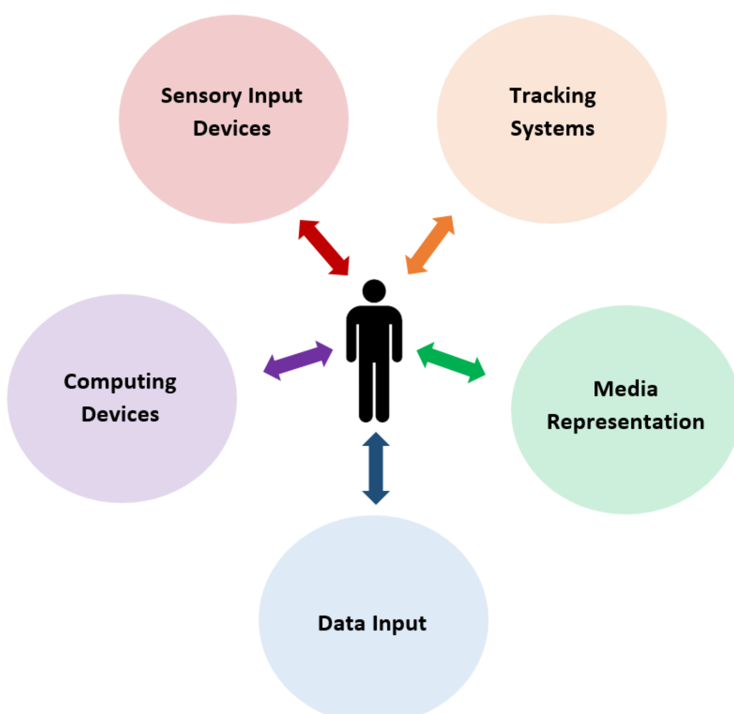

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Figure 7. Illustration. AR system architecture.

AR Display Technologies

Two categories of display types are found in AR systems: handheld devices, such as smartphones and tablets, and HMD devices, such as headsets or eyeglasses. The two display types offer different capabilities and provide unique challenges. The display types differ most in the way they display imagery to the user and in the way the devices track their position relative to the real world.

Handheld Devices

These handheld devices are typically VST displays, which use the back-facing camera on the device to capture video of the real-world environment and display that image on the front screen. AR applications then register and render virtual data over the real-world imagery on the screen. With these displays, a user should hold the device above chest height close to eye level and at arm's length to capture the widest FOV. Holding a device in this position can become difficult for a user over extended periods of time and could prove challenging in a construction-site environment because the user's attention will be on the device and not on potential hazards at the construction site.

Handheld devices typically use GNSS tracking to determine the initial user location within a few meters and then use the inertial movement of the device to change the view as the device is moved around the environment. Some vendors have demonstrated prototype applications that optically track the imagery in the video feed to support registration with the real-world view and to support tracking of user movement. Many commercially available AR applications use a marker-based positioning tool in which a target is placed in the real world and viewed by the video feed. This target is recognized by the software and used to register the user's position in the real world relative to the virtual model.

One vendor has developed a unique solution that uses software and a powerful antenna to locate a mobile device to within a few centimeters. The device VIO sensors in combination with proprietary algorithms to help register the orientation of the device with the real world in real time.

HMDs

HMDs are typically OST displays. A virtual image is presented to the viewer overlaid on the view out from the device and into the real world. The most commonly used approach in HMDs is a form of binocular near-eye displays that feed separate computer-generated images to each eye. Binocular near-eye displays offer more immersive and realistic experiences than handheld devices because the real-world view is the direct view out, not a video feed, and the virtual view is typically stereoscopic. The scene changes as the user moves his or her head, creating a direct connection to the user scanning the real-world scene. Most HMDs on the market use a combination of inertial and visual tracking methods and are effective at tracking the real-world scene once a position for the user has been established.

As with handheld devices, the initial positioning of the user with an HMD relies on GNSS localization or a marker in the field that the AR application recognizes and registers with the virtual model. AR application tools exist that allow 3D model elements from the real world to be transferred to the device and used to register to the real world. These virtual model elements can be viewed over the real-world view then used to line up or register the elements from the model to the identical elements in the real world.

AR Information Display Options

There are several distinct categories of information display that AR can present to a user, each of which has unique applications on a construction site.

Display What Is Not Yet Constructed

Incorporating AR into a BIM workflow allows users to see 3D design models in the real-world context. This is one of the most powerful opportunities with AR. The ability to overlay future construction on the real-world view allows users to do the following:

- Compare design alternatives in context.
- Check relationships between existing/future elements.
- Examine site logistics and equipment movements.
- Preview complex installation procedures.
- Illustrate construction methods and sequencing.
- Explore opportunities for training onsite.
- Check traffic management plans/and temporary structures.

Display What Was Intended to be Constructed

AR allows the user to overlay and compare the 3D design models (design intent) onto what was constructed in the field. Some potential opportunities this capability provides a user include the following:

- Inspecting and validating sites.
- Checking for code/standards compliance.
- Checking quantities and work progress.
- Inspecting training opportunities.
- Checking traffic management plans/and temporary structures.

Display What Is Hidden from View

AR technology allows for the 3D display of existing elements not visible to the user in the real-world scene. This approach might provide challenges in display; for example, foreground objects need to be represented as transparent or cut-open for viewing what is behind them. This capability allows the user to visualize existing elements, such as buried utilities or structural components and elements obstructed from the current view.

Display Abstract Information Aligned with Real-World Context

AR technologies allow the alignment and display of abstract information that would typically only be available in a drawing plan view or virtual 3D model. These drawing elements can be aligned and scaled in 3D to match visible real-world elements. Information that would prove useful on a construction site include the following:

- Alignment information, easements, site boundaries, and right-of-way (ROW) boundaries.
- Environmental boundaries, such as flood levels or sea level–rise data.
- Archeological and historic sites.
- Work-zone hazards.
- Metadata tagged to associated real-world objects.

AR could potentially support displays of other types of remote information, including video feeds from another user or documentation, instructions, or user guides that could be associated with real-world objects or activities. Abstract information geared toward the safety of the user could be displayed through AR; the system could monitor and display unsafe areas or risks, or the system could guide users safely through a complex construction site.

Challenges for AR Systems in Construction

Construction sites, especially highway construction sites, are particularly challenging for AR systems because these sites are typically large, outdoors, and bright and often do not contain a variety of contextual information required for AR visual tracking systems. Buildings and structural sites contain a lot of 3D information that can be compared with virtual models to support localization and tracking for the AR user. Another issue will be the types of elements in a highway project. Elements of a highway project are typically large, smooth, and flat, and do not contain many fine details, which makes it much more difficult for 3D modeling systems to represent these projects in a virtual view where they will be easily recognizable by the user and the AR system. These 3D elements are much more difficult to simplify and optimize for display performance, which requires more forethought and preparation for their use in AR systems.

AR systems provide many technological challenges, some of which apply to all AR applications and some of which are specific to construction applications.

Performance and Portability

AR systems require significant processing power to support tracking processes and the real-time display of the virtual 3D model concurrently. AR devices must be standalone and portable to be used effectively in a construction environment. This means processing for tracking and display need to be onboard the device. Some systems are tethered to a separate wearable computing device, which reduces the necessary weight of an HMD. Larger 3D models, more accurate tracking, and increased display quality require more processing power. As AR systems evolve, there will inevitably be a tradeoff between the performance of the system and the size, weight, and comfort of the AR device.

Portability of the 3D virtual model assets will be a challenge as well. 3D project models can be quite large, depending on the LOD and the area covered. The AR device must include onboard storage adequate for the model assets or use some form of connectivity solution that allows the model to be streamed in as required. One example of this was described in a presentation at AU 2017 in which the Microsoft HoloLens was used with Autodesk Revit. A remote Revit model was converted in real time to a displayable format, displayed, and updated via a Wi-Fi connection to the HoloLens device on the construction site (Jahangiri et al. 2017).

Display Brightness

A key challenge with HMDs is the brightness of the overlaid virtual image onto the real-world view. In an OST AR device, the quality of the virtual image directly depends on the brightness of the real-world environment. Bright, outdoor scenes are the most difficult for the display systems to match. A typical highway construction site will be outdoors and bright, limiting the quality and usefulness of most current AR HMD devices.

Handheld devices are VST when used for AR, and the real-world display on the screen is controlled by the device. Device control allows the video display and virtual displays to be better matched in overall brightness, and it allows for better quality and greater realism of the displayed scene. In the next few years, handheld devices will most likely provide better opportunities for AR technologies on outdoor construction locations. Future HMD solutions based on VST technology could be viable solutions for this display challenge.

FOV

The available FOV presented to the user is a limiting factor of current devices. In handheld devices, the display screen size and the video feed limit the FOV. If the FOV of the video feed does not closely match the FOV displayed on the screen, there is a disconnect with the real-world view. Additionally, the user must pan the device to view a large area, which could be prohibitive over long periods.

Current HMD technology used in available devices is very limited in the FOV of the overlaid virtual model view, which is what the user sees. Most currently available devices display approximately 60 degrees of virtual view. To view a large area, the user must pan his or her head back and forth to fill in the scene. This can be distracting and tiring over a long period.

As vendors improve the ability of devices to display larger FOVs, performance requirements for tracking and virtual model processing by the systems will increase.

Occlusion

It is straightforward for AR systems to display virtual models on top or in front of the real-world image, regardless of the challenge of tracking and registering the two. In complex construction environments, there may be situations in which virtual elements in the model are behind real-world elements, which is called occlusion. The occlusion, or masking, of the hidden elements behind real-world elements is a complex problem for the AR system both in the calculation of the occlusion and in the display. When the occlusion is ignored or displayed poorly, the realism and immersive quality of the displayed scene are significantly affected. Current commercially available systems do not yet support occlusion rendering.

Safety

Safety issues on a construction site are of concern. Handheld devices must be held in front of the user, taking up one of the user's hands and potentially blocking visibility of the site in front of the user. HMDs, even though they are hands-free tools, can limit the user's peripheral view and block some of the audio, or site sounds, available to the user. As with any display device, some of the user's focus may be on the device and not entirely on the user's surroundings. These devices could be designed to be aware of safety issues and risks for the user because the device would potentially know the user's precise location on the site.

Tracking Technologies

GNSS tracking is the most straightforward method for localization in outdoor sites, but GNSS tracking requires visibility of the satellite network. GNSS provides reasonable precision for location but does not provide information on the orientation of the device. Solutions such as Trimble's SiteVision device use a software/hardware combination that increases localization precision and provides orientation with GNSS as the primary tracking source. Tracking within a site can be enhanced with the addition of other position information, such as total stations or localized Wi-Fi networks.

Most commercially available AR systems use a marker-based initialization of the scene to set position and orientation then use inertial and optical sensors to manage tracking and movement of the device. Optical tracking sensors require detail in the visible scene because the sensors calculate the movement of that detail in the optical imagery for tracking. A highway construction site will typically not include a lot of visual detail because they are typically flat. One solution to this lack of detail is to add more details to the real-world scene, such as markers or target images, or another type of 3D object. These systems could also be enhanced with the addition of Wi-Fi nodes or position beacons.

Data Support for AR Systems

A key requirement for AR systems to be effective is the ability to register a virtual dataset to the real-world environment. Whether the AR system is tracking to a form of 2D information, such as a target or a position, or registering the real world to a virtual 3D scene, there are requirements for virtual scene data to be available to the AR system. This scene data will most likely be in the form of 3D digital models. These models are typically quite complex. Depending on the system used and the area of coverage, the models can include very large datasets. Current systems portable enough for construction applications typically need to carry the datasets onboard the AR device or the device must be tethered to the processing unit.

AR technologies used in construction will require bringing project design data into the field. A workflow that involves segmentation, optimization, and streaming—control over LOD displayed or deployed to the field—will be needed. This workflow is especially important with AR applications in devices that have much higher performance requirements to maintain display frame rates and needed rendering quality. In addition to using a 3D cloud-based model distribution and sharing platform, 3D-model optimization schemes, whether through software or manual methods by designers, will need to be used to simplify the 3D models for AR workflows.

AR systems require front-end planning and setup to optimize these datasets for the AR system and application being used. This setup would typically involve filtering the dataset down to the most critical 3D elements for tracking and registration; the 3D elements need to be visualized in the AR system for the task being performed.

Devices, such as tablets, smartphones, and some HMDs, allow wireless connections to an outside network. For these devices to work effectively in real time in the field, they would require a robust, high-bandwidth connection, most likely through a Wi-Fi network installation. Many construction sites now implement Wi-Fi networks to support communications and often to support a BIM workflow involving access to 3D datasets in the field.

Software vendors have begun to develop cloud-based collaboration and distribution platforms to support the vendors' design and construction support tools. Most vendors have demonstrated some support for AR devices and deployment of 3D models to the devices. AR-ready platforms include the following:

- Autodesk: BIM360 Platform, Forge cloud-based developer's platform.
- Bentley: Bentley CONNECT Tools and Connection Client.
- Trimble: Trimble Connect platform and Catalyst Tools.

BIM Model Workflows for the Construction Site

AR applications for construction will most likely focus on either the display of annotation and graphical information that enhances the understanding of real-world objects or the 3D design and construction models that will be overlaid in position in the real-world environment view. Most AR applications are based on workflows and tools that are already in place in support of BIM applications for design and construction. These CADD/BIM tools will likely be a starting point for the development of AR tools, and many AR applications will eventually become extensions of current BIM and 3D model workflows rather than distinct processes. AR display of abstract or graphical information not georeferenced to the 3D design models will require new workflows and a different method for locating and registering data within the viewer's real-world scene. The applications that would use this type of abstract virtual information need to be developed using the AR platform tools or AR hardware development tools currently available.

Major vendors for 3D-design applications have implemented tools and workflows that support the deployment of 3D models to mobile devices for viewing in the field, and most support the built-in georeferencing capabilities of the devices. Most platforms support review and collection of data in the field through mobile devices, which can then be synchronized with project models and data in the design office. Most of these vendors have also enabled deployment of 3D models to one or more of the AR HMD models through mobile platforms. While most of the tools offer methods for optimizing models and model display on mobile devices with more limited processing power and storage, this optimization will be even more important for AR devices and applications that will typically require enough graphics performance to support real-time stereoscopic rendering of the 3D models. Processing power, available memory, data storage, and connectivity are limitations of most available AR HMDs.

CHAPTER 4. STATE OF THE PRACTICE OF AR

INTRODUCTION

To provide a full picture of AR implementation challenges, potential costs and benefits, and technology use, further research was conducted into current AR implementations to document activities using AR technologies that support highway construction and related AEC applications. The research examined exploratory efforts into AR use for inspection and gathering of project data in the field using AR technologies. While very few instances of AR implementation that focused specifically on highway construction could be found during the investigation, several research studies and product prototype development activities were identified that were closely related to highway construction and inspection. These prototype development activities represent workflows and technology applications that would be an important aspect of the development of highway construction–specific applications. These activities are documented in this chapter.

CURRENT APPLICATIONS OF AR SYSTEMS IN HIGHWAY CONSTRUCTION

The research team conducted an online survey of current research activities and a review of presentations and papers at highway and technology-related conferences. No project-level applications of AR systems were found in the highway construction area, but several research efforts and vendor product prototype studies were identified that were directed toward using AR systems in the highway construction area. Inspection and training applications of AR systems were also part of the research activities survey, and a few key research applications in these areas were identified and are included in this chapter. These examples do not show a complete beginning-to-end application using AR, but the studies demonstrate capabilities of AR technologies required to implement AR applications, such as the case studies described in chapter 6 of this report. These individual AR technologies would inevitably be part of a larger process required for the development of a commercial AR application intended for highway construction.

Viewing Design Data in the Field with AR

Several examples of research were found where simplified, and sometimes relatively complex, 3D-model data were ported to an AR device for display in the field. As described in chapter 3 of this report, this process is currently unique to the device and system platform being used. The 3D model data flows required are similar to BIM-to-field workflows being developed by 3D modeling and CADD software vendors. These workflows have been developed for the most common mobile-device platforms. For specific HMD devices, the workflow is unique to that device.

Trimble Connect is a platform that enables the deployment of 2D and 3D data to several different AR devices, including HMDs and mobile devices (Trimble 2018). In 2018, Utah Department of Transportation (UDOT) conducted a prototype study that explored the use of the Trimble Connect platform for porting and displaying simplified 2D and 3D design information onsite using the SiteVision mobile-device tool. In the UDOT study, the device was used to portray 2D

CADD information, such as ROW lines, edges of pavement, and other 2D design data, from Bentley MicroStation design files over a live video feed of the site.

Researchers needed to separate the AR-viewable design data from CADD design files and then translate the design data to their correct proposed or existing elevation in 3D. This process is separate from typical 2D CADD design processes and must be completed before porting to the AR device and bringing the device to the field, which then allows for those 2D CADD data to be displayed correctly in elevation relative to the real world, as shown in figure 8. The UDOT study also explored bringing in a few 3D design–model components. As shown in figure 9, some drainage pipes and other mechanical, electrical, and plumbing (MEP) elements were transferred as 3D model elements into the SiteVision device and then could be viewed overlaid on video of the real-world context. In this AR view (figure 9) the MEP components are shown as being underground using a 3D model of a cylindrical hole in the ground in front of the viewer.

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Figure 8. Graphic. Display of design data overlaid on the video display of a tablet device.

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Figure 9. Photo. Display of 3D MEP overlaid on the video display of a tablet device.

The UDOT study demonstrated the basic 3D-model data flows that are required of any AR application. Localization on this device is achieved by using basic GNSS tracking enhanced with proprietary Trimble sensing hardware and software, which are part of the SiteVision device. Trimble has focused its efforts on handheld, mobile devices for customized AR applications for construction primarily because of the display and tracking challenges of HMD devices. The Connect platform does, however, support data flows to the most common AR HMD devices.

Bridge Lighting Design Application

A contractor conducted bridge lighting-design field tests using an HMD AR device and 3D-model data ported from Autodesk 3DS Max into the Unity platform. The HMD software supported display and application development on top of the Unity platform. The 3D bridge model and lighting-design data were relatively high in detail and required some optimization and geometry reduction to get the model to port over and display on the HMD device, which must keep all data onboard for untethered field use.

Figure 10 shows a screen capture of an AR view of a bridge model with one of several design alternatives for custom lighting proposals overlaid onto the real-world view of the bridge. To enable these views, the user manually aligned the 3D model view with the real-world view in the field by using a virtual camera in the model that represented the onsite location. Once the view of the virtual model was close to the real-world bridge, the virtual model was nudged by the user in the display's view until the model lined up as closely as possible to the real-world bridge in the viewer. Other studies have mentioned nudging the view to align virtual and real objects (Chen et al. 2018). The onboard tracking device maintained good registration after this alignment as the viewer moved.

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Figure 10. Graphic. Display of a 3D bridge lighting model in an AR HMD device.

This example demonstrated another key advantage with some HMD devices: the use of built-in audio commands to change view parameters. Audio controls help maintain hands-free operation by the user. The team that developed this bridge application mentioned the challenge of using see-through AR devices outdoors during the day. The bright light affects the ability of the virtual display of the device to be adequately visible over the real-world view. The device also had more difficulty tracking the position/orientation in bright light.

Autodesk BIM360 Docs Workflow

Autodesk BIM360 Docs is an established platform for sharing data in the cloud and is used extensively on collaborative design and construction projects. An AU 2018 presentation by Chen et al. explored the results of a collaboration between DAQRI, Autodesk, and a contractor that leveraged the BIM360 Docs platform to support an AR application for validating design information in the field. The application was developed using the Autodesk Forge system, which is used to create data flows and interfaces within the 360 platforms. The application developed by the team accomplished several things that will be essential to AR workflows such as direct connection to a BIM 3D model workflow; deployment of 3D models from BIM360 directly to the AR device over Wi-Fi networks, and optimization of the 3D models within BIM360. The application used the DAQRI Smart Glasses wearable device.

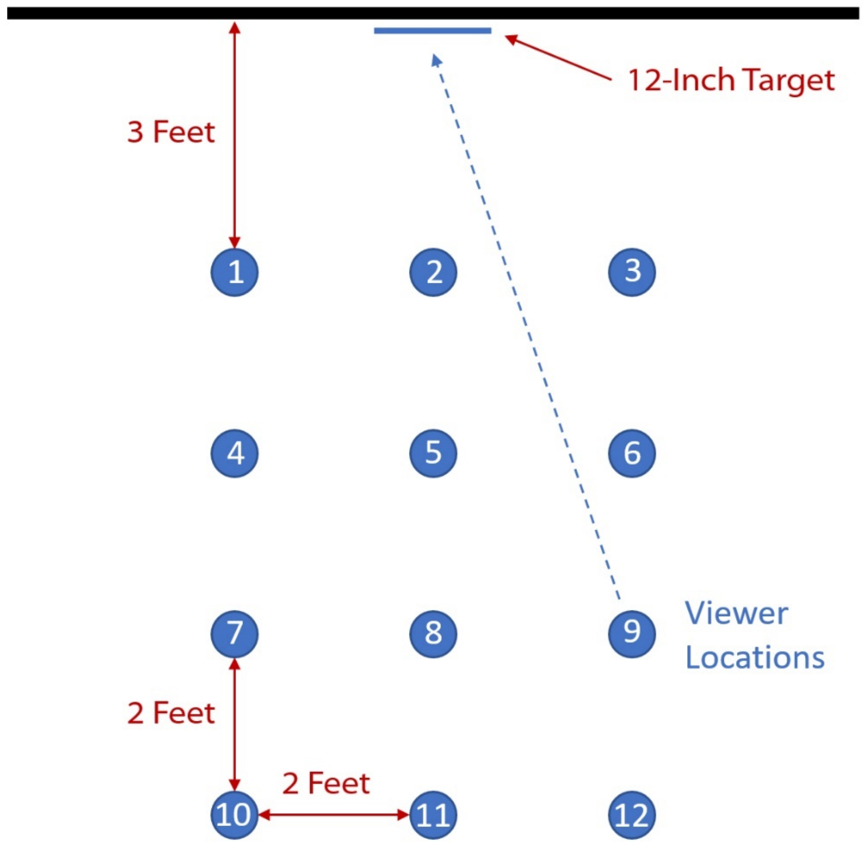
In this prototype application by Chen et al., 3D models were initially uploaded to the BIM360 platform using workflows similar to traditional collaborative BIM process. The application demonstrated the ability to use multiple 3D-model types. One feature of the AR application allowed the user to select a model on the BIM360 platform and segment the model down to a manageable size using a 3D clipping box that could be changed in any dimension interactively.

After the user segmented the model to a manageable size, the AR application prompted the user to insert a unique QR-coded target into a known location in the 3D model; the target is then used in the field to initialize the position and view of the model with the HMD. The user logs the DAQRI headset into the BIM360 Docs platform via Wi-Fi, and the model(s) for the fieldwork is selected and downloaded to the device. When the user is in the field, a printed version of the target is placed in the real-world scene that coincides with the virtual marker in the 3D model. The user initiates the field session by pointing the HMD at the target, after which the correct model is automatically loaded into the device for viewing. The model can be moved or nudged slightly to improve alignment in the view. The demonstration illustrates the concept that AR could eventually become a viewing extension to existing and future BIM 3D model workflows.

The DAQRI device used in this application also exhibited a useful characteristic for interaction and navigation called gaze interaction. In gaze interaction, a reticle, or white dot, in the view is placed over menu items for a certain period and a selection is made, which opens interface menus, for example. This method allows for hands-free operation of the device and is not affected by background noise in the environment.

AR Systems Supporting Inspection Activities

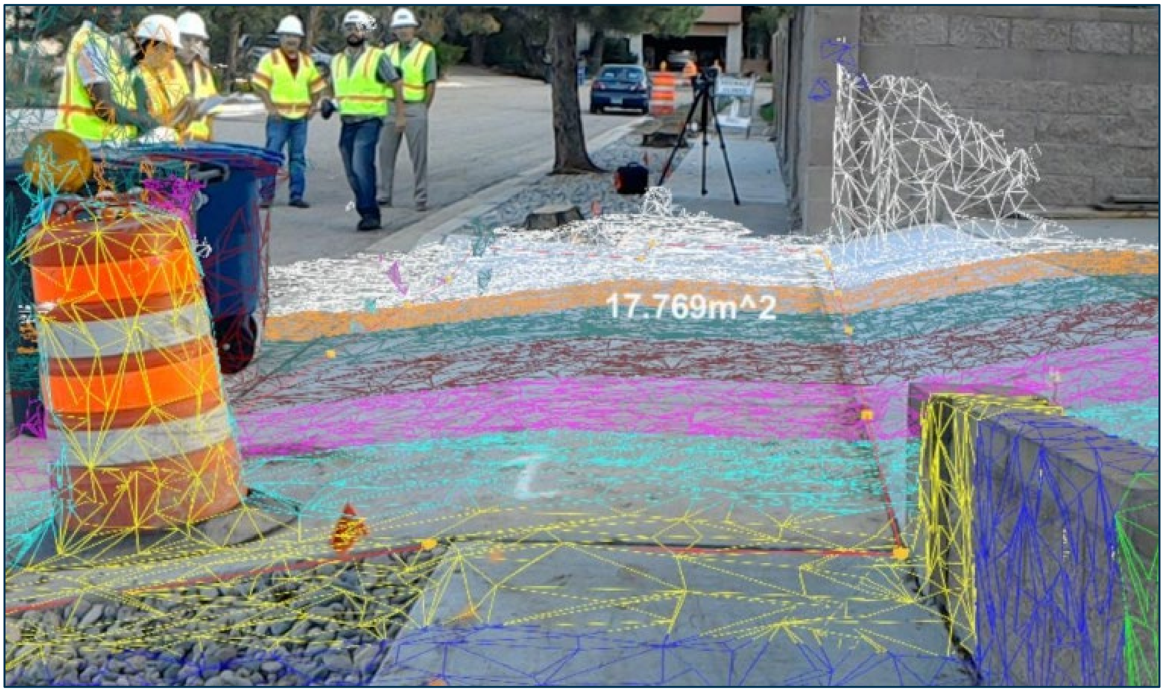
Applications supporting onsite inspection will require digital capture or measurement of installed elements in the field; this is called inspection quantification. The process of inspection quantification is a key aspect of the construction-inspection process. Several studies identified field measurement using AR devices. One study applicable to highway construction was jointly conducted by the University of New Mexico, Los Alamos National Laboratory, and Los Alamos County (Moreu 2018). The study illustrated good results in collecting inspection data in the field using an AR HMD device. This study not only demonstrated the capture of linear and surface information in the field but also featured tests to evaluate the potential precision of the process of measurement in the field using the HMD device. In one test, a user measured a 12-inch target using the HoloLens from 12 separate locations on a 2-ft by 2-ft grid, thus providing various distances and angles to the target. Figure 11 illustrates the layout of viewer locations. Researchers found that the measurements were accurate within 1 to 2 percentage points, a precision the researchers felt was equivalent to the error of eye–hand movements with the device.



© 2019 WSP.

Figure 11. Graphic. Using an HMD to measure a target object.

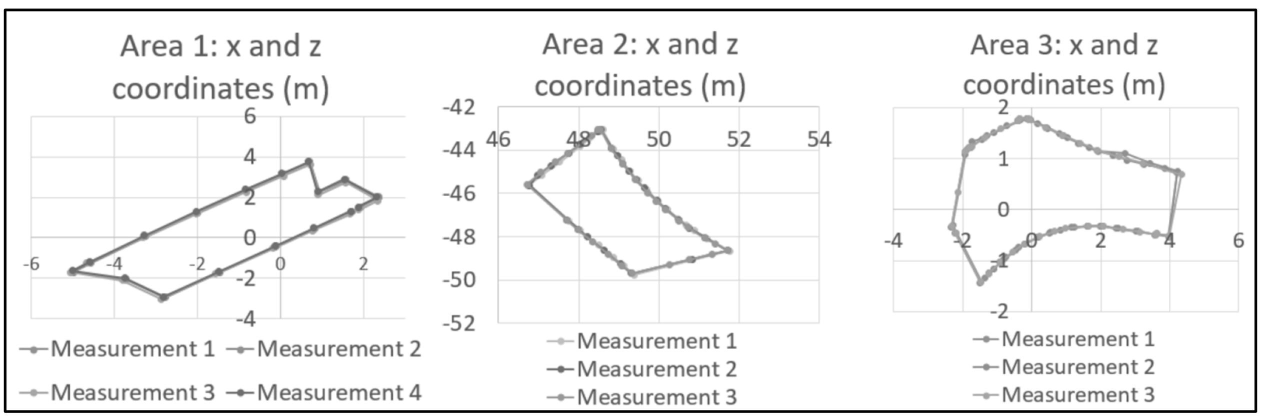
In another application presented by Los Alamos County, users measured areas of newly installed concrete pads to calculate contractor payment amounts (Moreu 2018). The user captured points using a cursor within the AR device that is placed over real-world points, such as corners and points along an edge, and uses finger gestures to activate the capture. Those points along with the surface of the existing condition are captured by sensors on the HMD, and then the points and surface data were downloaded and postprocessed in a 3D system in the design office to interpret the 3D locations of the points and the areas of the surfaces. Figure 12 shows 3D surfaces and points captured by the AR workflow process overlaid on the real-world view.



Source: LANL.

Figure 12. Graphic. 3D surfaces and points as captured by an AR HMD (Moreu 2018).

In addition to collecting data using an HMD, standard survey devices were used to collect a separate set of concrete pad measurements. The HMD measurements were then compared to the standard survey measurements (figure 12, figure 13, and table 4). The HMD measurements were found to be within 1 to 2 percent of the survey data—a differential the research team concluded to be within tolerances acceptable to contractors.



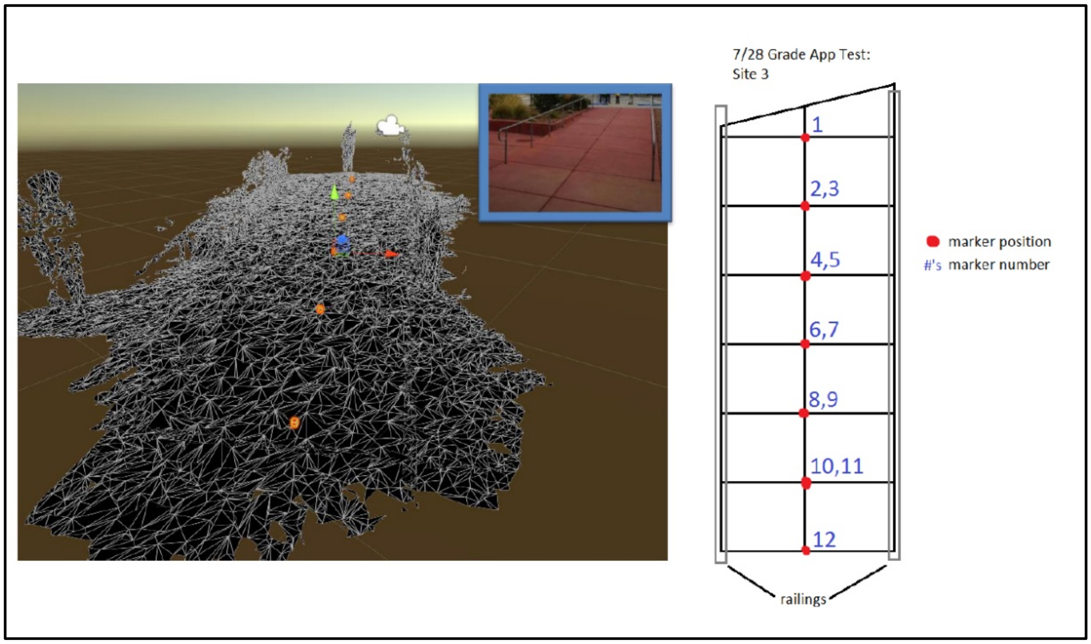
Source: LANL.
Note: All axis measurements are in meters.

Figure 13. Graphs. Results of postprocessing surfaces and points as captured by the AR HMD device (Moreu 2018).

Table 4. Comparison of HMD field measurements against county measurement.

Area	County Measurement (ft2)	HoloLens Average Measurement (ft2)	Difference (ft2)	Percent Difference
1	187.98	191.5	3.52	1.9
2	147.67	149.0	1.33	0.9
3	129.00	127.4	1.60	1.2

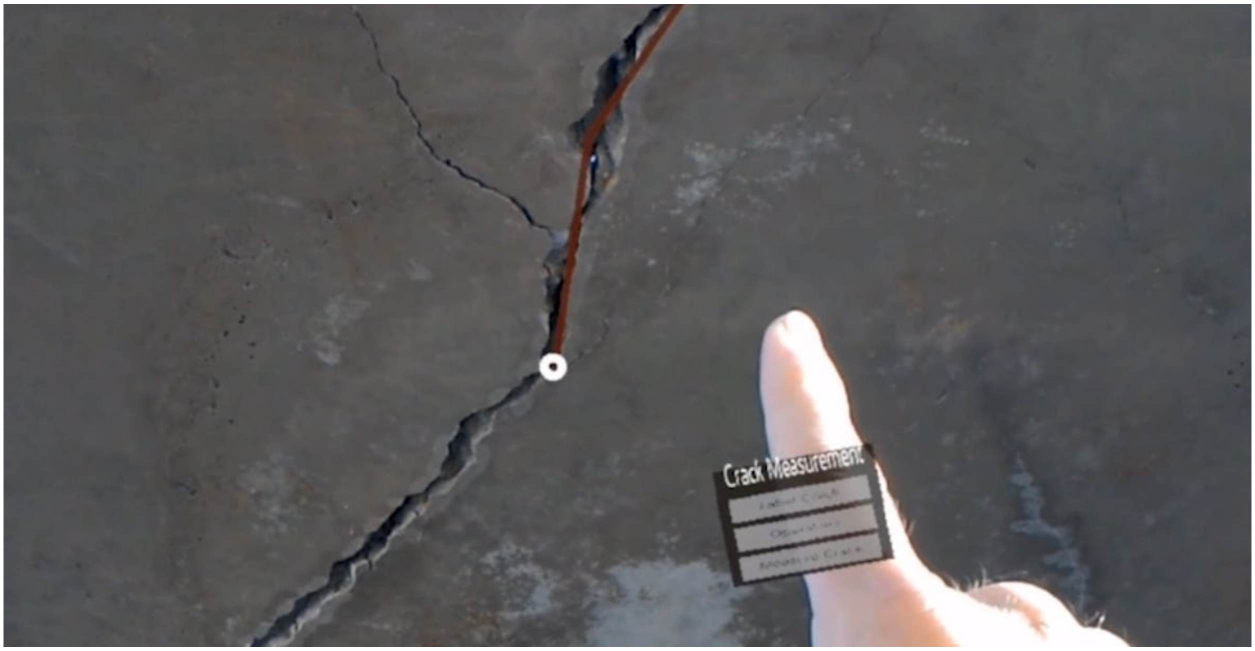
Los Alamos County field tests also included a demonstration of measuring ramp slopes to evaluate potential requirements for compliance with the Americans with Disabilities Act (ADA). The user collected 3D points along the ramp using the HMD, and then the points and scanned surface were processed to determine point elevations and the slope of the measured ramp (figure 14).



Source: LANL.

Figure 14. Graphic. Surface and points captured in ramp grade measurements made in the field with HMD (Moreu 2018).

In a separate study, researchers at the Los Alamos National Laboratory demonstrated AR applications for inspecting the condition of concrete structures (Moreu 2018). The types of applications explored included measuring the deformation of structures after an event and the volume of damaged areas on structures. One application tested in the field was a crack measurement tool. In this prototype application, an inspector traced the line of a crack through the HoloLens device, and the device captured the drawn line and the scan of the surface of the concrete (figure 15). The user was able to add comments and metadata when using the application.



Source: LANL.

Figure 15. Graphic. Screen capture of an AR tool for measuring cracks in concrete structures (Moreu 2018).

Tablet-Based AR Field Applications

Applications like those described earlier in this chapter, which illustrate using HMDs for collecting 3D field data, could not be found for tablet-based devices. Applications on tablet or smartphone devices would inherently be less precise when capturing points through the screen interface in the field. However, tablet devices will most likely be the platform on which AR applications will be developed in the near future because of their low cost, simplicity, and ability to be used outdoors. One negative aspect of using tablets and smartphone devices, however, is their need to be handheld, thus eliminating the opportunity for hands-free operation. Tablets are more abstracted from reality, like looking at a photograph, and less immersive than HMD devices through which the viewer is seeing the world directly. Nevertheless, tablets and handheld mobile devices have the advantage of allowing multiple users to concurrently see the same view on a single device.

CONCLUSIONS

While these examples do not represent comprehensive AR applications for construction, and are not all specific to highway construction, they do represent key technologies and workflows that would be essential to highway construction AR applications. The examples demonstrate that the required building blocks, or capabilities, of AR technologies exist. The investment needs to be made by technology developers to refine AR technologies and integrate them into larger construction-focused applications. Workflows and applications are used as examples to develop the case studies described in chapter 6 of this report.

CHAPTER 5. AR FOR TRANSPORTATION CONSTRUCTION WORKSHOPS

INTRODUCTION

AR is widely recognized as a cutting-edge technology to augment human perception. This technology consists mostly of proof-of-concept prototypes in design and construction. This current state of technology presented the research team with the unique opportunity of engaging industry stakeholders to identify future needs of AR in transportation construction, which will help guide future AR development to maximize its impact.

Two workshops were conducted to explore AR's application in transportation construction. The first workshop was held on May 9, 2018, at FHWA's Turner-Fairbank Highway Research Center in McLean, VA. The second workshop was held on January 16, 2019, at the Transportation Research Board (TRB) Annual Meeting in Washington, DC. Both workshops involved executive and senior-level participants from State DOTs and FHWA with diverse backgrounds, senior-level representatives from private consultants and contractors, and representatives from AR hardware and software industries.

The goals of the workshops were to inform the research priorities and anticipate future directions and opportunities for AR in highway construction. The workshops included technology and application developers, State DOT representatives, contractors, consultants, and other practitioners who explored how AR technology can be used to support construction-management functions during highway construction, ranging from construction inspection and review, QA, training, and improved project management through real-time information in a real-world environment. The workshops also informed participants on the current capability of AR technologies and related applications in MR, identified potential new applications for AR technology in transportation construction, and prioritized future applications of AR technology in transportation construction. Finally, the workshops involved interactive experiences for the participants that explored the capabilities of the different types of AR devices and facilitation of meaningful dialog about future applications.

WORKSHOP HIGHLIGHTS

Workshop 1

Both workshops followed similar agendas. The first workshop began with an overview of AR technologies and characteristics. This first session served as a synopsis of chapters 3 and 4 of this report. The next session of the workshop included presentations by vendors of AR technologies and supporting software applications. The last session was comprised of facilitated discussions, or brainstorming sessions; all participants explored opportunities for and benefits of using AR technologies in highway construction and the associated challenges each participant group found in implementing the AR technologies. A short list of the technologies and opportunities was captured, and participants' input on each case's impact and feasibility for development was obtained through electronic polling. Workshop 1 produced five defined use cases of AR technologies in transportation construction, which are described in the Results section.

Workshop 2

The second workshop was divided into two parts. Session 1 began with an overview of FHWA's exploration of immersion environments. This overview was followed by a state-of-the-practice review completed by the research and published in chapter 4 of this report. The review was then followed by a case study of Nevada Department of Transportation's (NDOT's) use of virtual technologies to simulate construction phases during a project's development. The session concluded with a presentation of the five use cases of AR technology in transportation construction (which were identified in workshop 1) and electronic polling regarding each case's impact and feasibility for development. Session 2 of the workshop included several presentations that explored R&D work involving AR and VR by several DOTs and consultants.

Results of the Polling

Based on polling data from both workshops, use cases were ranked in terms of their potential overall impact on transportation construction as well as the feasibility of developing each use case. This final ranking was as follows:

1. **AR SUPPORT OF ROW ACQUISITION.** Provide project visualization to property owners to better understand a project's impact and to show design options to the property owner.
2. **VISUAL VARIANCES.** Tag variances in the field regarding schedule and quality issues to ensure all parties are viewing the same issue.
3. **INSPECTOR'S TOOLKIT.** Use AR technology to verify that work is being installed properly by providing the correct information in the correct format for the inspector in the field.
4. **NEXTGEN TRAINING AND CERTIFICATION.** Use AR technology to support training and certification for construction inspection.
5. **AUTOMATED INSPECTION.** Use AR technology to support automated code/standard-compliance checking of installed items through machine learning.

The following sections review the outcomes of each workshop and examine how the preceding rankings were achieved.

WORKSHOP SUMMARIES

Workshop 1 Summary

Session 1

Workshop 1, held at FHWA's Turner-Fairbank Highway Research Center in McLean, VA, began with an overview of AR technologies and characteristics. The participants were encouraged to engage in the discussion of challenges and opportunities for AR technologies introduced in the presentation from their individual perspectives. No specific examples reflecting the use of AR in highway construction could be identified at this time, so examples from related industries were summarized and shared with the audience to elicit commentary and feedback. Key points of the presentation and discussion were transcribed and included in the following sections:

- **AR is evolving.** There are several emerging advanced visualization technologies, including VR, MR, and AR. Of these, VR is the most mature technology. There are primarily two forms of AR display types: handheld and HMD. Handheld displays are becoming increasingly more common due to advances in camera and display capabilities of smartphones. While AR has traditionally used marker-based tracking systems, GNSS and Wi-Fi networks and optical sensors are advancing AR tracking.

- **AR has limitations.** Limited FOV, which is common among current HMDs, restricts AR technologies. AR devices are typically intended to be portable; therefore, their performance relies on the processing speed of the portable devices. While the performance of AR devices is being addressed by technology developers, the increasing desire of having AR devices interact with an environment rather than simply displaying information poses additional challenges to the processing performance of future AR systems. Another limitation of AR technology is difficulty when seeing AR displays in bright environments. These limitations, coupled with the challenges of AR tracking in outdoor environments, are significant when using AR in construction applications.

- **AR display options are varied.** Among the AR prototypes that have been explored in construction, AR display options include displaying what is not constructed, displaying what is hidden from view, overlaying or tagging abstract information, using remote communication, and ensuring safety.

- **AR can be used to influence both performance and behavior.** AR technologies can reduce planning and construction time, errors, and rework. In terms of behavior, AR technologies can more effectively identify safety hazards.

- **AR-ready platforms already exist.** Construction-specific platforms for AR devices include Autodesk BIM 360 (Forge), Bentley CONNECT, and Trimble Connect. General AR platforms include Apple ARkit, Google ARCore, Windows Mixed Reality, AR Toolkit, and WebAR.

- **Future questions about AR remain.** How much information does the user overlay? Does the user show specific details, or do they show the overall project? How does the user utilize AR to display uncertainty, especially regarding uncertainty in accuracy? (There are two types of accuracy: accuracy of the model and accuracy of the overlaid AR display.) Is there a way to verify the accuracy of the model? This verification should occur during the modeling process, not in the field.

Session 2

Session 2 included presentations by vendors of AR technologies and supporting software applications. Vendors responded to an invitation to participate in the session, and each vendor gave an overview of the technologies and the potential application for highway construction. After the presentations, participants had the opportunity to test the technologies firsthand and discuss the tools directly with the vendors.

Session 3

The last session of the workshop included facilitated discussions and brainstorming. All participants explored opportunities for and benefits of using AR technologies in highway construction and the associated challenges each participant group found with potentially implementing AR technologies. A list of the technologies and opportunities was captured, and participants voted on the application they felt provided the most opportunity for improving the state of the practice from the perspective of their discipline.

Session 3 began with a series of brainstorming activities that encouraged participants to examine the potential application of AR technologies in transportation construction. The first brainstorming activity focused on different activities related to construction and how AR technologies could be applied to those activities. Discussions on potential AR construction applications were coordinated around four subjects: inspection applications, preconstruction, human resource development (training), and project management. The subcategories of applications are detailed in the next section. Within these four subject areas, there were a few trends that emerged in the brainstorming discussions. One trend focused on visualization of design information, especially information that would be easily accessible from existing 3D model workflows, including simplified 3D model components or abstract information, such as ROW or alignment information. Another trend that emerged were applications that would support construction-inspection activities, such as comparing as-built components with as-designed virtual information or with inspection criteria and specifications. A third trend was using AR for training, particularly for construction-inspection activities.

Use of AR to Support Inspection Activities. The brainstorming discussion focused on the use of AR to support the inspection process, which ranged from helping the inspector identify what needs to be inspected to providing the inspector with the information to complete the inspection. Specific applications of AR technology for assisting with inspection include the following:

- AR-guided site inspection:
    - Use AR to locate where the inspector needs to go.
    - Use AR to provide the right information in the right format to the inspector and provide situational measurement (e.g., virtual checklists help the inspector verify the work is being installed properly and the right materials are being used).
- Remote inspection:
    - Use AR technology to capture inspection data (visual) that can be viewed later. Video capture of inspection would be especially helpful when inspecting remote sites.
- 4D inspection:
    - Visualize just what the inspection needs, which will be based on the contractor's schedule.
- Bridge inspection:
    - Use AR for validating of rebar installation, checking bridge deck thickness, and mapping of cracks on structures.
- Earthwork:
    - Ensure ADA compliance by verifying that slope percentages comply with ADA specifications while also noting the x, y, and z coordinates of each ramp.

- Automated inspection:
  - Integrate the use of AR technologies and machine learning to allow the AR application to measure if the system/component has been installed correctly.

Use of AR in Preconstruction. The ability to visualize design details on a proposed site using AR technology helps to examine in exact context potential conflicts between design and actual site conditions, which can be difficult in VR or when using a 3D model. Specific applications of AR technology during preconstruction that were discussed include the following:

- Constructability reviews:
  - Use AR technology to visualize clash detections by overlaying proposed design changes within the context of the built environment.
  - Examine site layout including access planning, temporary resources, execution.
  - Provide the contractor with an AR model to allow the contractor to better understand the risks when developing cost estimate.
  - Use AR technology to visualize phasing/mobilization/initial start.
  - Use AR technology to visualize the boundaries of neighboring/simultaneous construction activities to help facilitate site coordination.
  - Apply AR technology to support automated code/standard compliance of proposed designs.
  - Use AR technology to support real-time site evaluation of safety hazards to help establish safe work zones.
  - Use AR technology to alert craft workers of active hazards (e.g., overhead loads or unsecured oxygen/acetylene tanks).
  - Use AR technology to capture the knowledge and virtually share lessons learned to field supervisors and construction crews. An idea was described by participants of AR having the capability to visually recognize the scene and identify relevant lessons learned.
- Utility relocations/ROW acquisition:
  - Capture newly installed utilities (location, material, etc.) digitally for future work.
  - Provide visualization to the property owner to show options and to understand a project's impact.
- Claims avoidance reviews:
  - Tag variances visually in schedule and quality so that both sides are viewing the same issue (if the property owner and contractor are looking at the same issues in real time, a claim may never be filed).
  - Verify distances and installation with a digital recording of the project being built so that details can be reviewed later if needed.
- Stakeholder outreach (communication):
  - Streamline and assist with National Environmental Policy Act (NEPA) requirements and upholding other project commitments (e.g., assisting the public and other Federal partners to better understand a project's impact, and visualizing technical alternatives and their impacts on NEPA commitments).
  - Design visualization with project stakeholders (e.g., how the project will impact neighboring businesses).

Human Resource Development (Training). With the current workforce shortage in transportation construction, discussions focused on the use of AR technologies to facilitate training. Topics included the following:

- Support junior inspectors by having onsite senior inspectors observe a scene remotely, essentially sharing the view.
- Provide virtual and intelligent training manuals and videos and animations for inspectors for training.
- Supporting training and certification for construction inspection using AR technology.

Project Management. Using AR technologies to monitor progress, track QA, and analyze traffic maintenance was explored in the brainstorming discussion. Topics included the following:

- Progress monitoring/quantity tracking:
    - AR technologies support automated as-built models.
    - AR technologies support obstacle avoidance on heavy machinery.
    - AR technologies facilitate faster approval of pay estimates (the AR technology shows what is being claimed in the pay estimate has been installed [i.e., visual checkbox of installed items]).
- QA:
    - Overlay defect maps based on nondestructive evaluation data on the installed facility.
- Asset management:
    - AR technologies support real-time availability of onsite construction assets.
    - Automated inventory of roadside assets using AR.
- Traffic management/maintenance of traffic:
    - AR technologies support work-zone safety (highlighting current areas of hazards during construction).
- Automated layout of onsite installations:
    - Systems that guide the contractors during installation (sequencing and location). Currently used in MEP, but there are similar complex systems in bridges, transit systems, lighting, toll buildings, toll gantries, and conduit.

Challenges for AR Applications in Construction

During the third session, participants were asked to provide examples of potential challenges. The brainstorming session focused on two areas. The first area included technical challenges related to the AR system's hardware and the 3D-model workflows required to support AR applications. The second area that emerged focused on the challenges within agencies when implementing AR systems, both culturally—the change in workflows and the acceptance of new and untried technologies—and financially, specifically the potential costs required for new computing systems and for the labor required to support more advanced 3D-modeling workflows.

Technology-Related Challenges. Technical challenges for AR applications in construction include actual technical performance as well as the perception of the AR's performance, which can be attributed to its limited use in transportation construction. Challenges were discussed regarding the efforts required to develop AR systems and related applications for the transportation-construction field. Specific challenges include the following:

- **Model size versus AR system capabilities.** Distilling a large project model down to a size that can be supported on a mobile device to support AR display can be a challenge. Some elements in the model can be simplified (e.g., bolts) without affecting the fidelity of the mode; however, the model may need to be adjusted to precisely fit the mobile device's capability. Currently, this workflow between BIM and AR systems is a very tedious and nonautomatic process.

- **Research and development (R&D) needed for AR applications in transportation construction.** Participants discussed challenges related to the level of R&D required to support the development of new technology, including AR technology for construction. One challenge focused on not knowing the anticipated return on investment (ROI) if AR technologies are successfully developed and implemented. This challenge could be addressed through State transportation agencies (STAs) exploring and examining the use of AR technology on a pilot project to support the assessment of value. Private industry might race to implement higher-risk technologies to gain market share, so, alternatively, a pilot project might not make the most sense for public agencies.

- **System durability.** The commercial use of AR systems in exterior working environments remains challenging. Part of the challenge relates to the comfort of using HMDs for 8 to 10 continuous hours. Additional challenges include the poor quality of displays in direct sunlight and battery life over an 8- to 10-hour workday. Better understanding of how much display information is required to make AR systems effective could address the challenge of using AR systems in an outdoor working environment. There is also uncertainty regarding ADA requirements for the use of AR across a broad community. Questions also remain regarding the amount of technical support required as well as the ability of the devices to work independently without Internet connectivity.

Implementation-Related Challenges. Participants identified that expertise in 3D modeling, required training, and information security are current challenges to AR implementation. Challenges to agency implementation include:

- **Existing use of 3D modeling.** Not all State DOTs use 3D modeling and AR technologies effectively. Targeting one or two potential application areas to demonstrate the value of AR will help advance adoption.
- **Training and implementation.** Participants identified challenges in the lack of successful implementation plans, training tools, and demonstrated enterprise approaches to successfully implement AR technologies. One strategy for successful implementation is to make the AR interface simple. Voice-activated AR systems are not necessarily intuitive.
- **Security.** Some agencies do not want models of existing structures on a cloud-based server. Future strategies should focus on data warehousing and how it can be used to support AR technologies.

Electronic Ranking of Application Concepts

Workshop participants voted on the applications that they felt would have the most impact on highway construction processes from their professional perspective. The top ten application ideas were captured for further polling using electronic voting devices and software that could rank and plot voting results. The top ten applications included the following:

- AR to support site planning and logistics.
- AR support of automated code/standard compliance of proposed designs.
- AR support of road safety audits and hazards and hazard recognition to the traveling public.
- Visualization to the property owner to better understand a project's impact and to show options to the property owner.
- Visually tag variances in schedule and quality issues so that both sides are viewing the same issue.
- Streamline/assist with NEPA requirements and upholding other project commitments.
- AR to support training and certification for construction inspection.
- Verification that work is being installed properly by having the right information in the right format for the inspector.
- AR to facilitate faster approval of pay estimates.
- Automated layout of systems.

Participants were then provided electronic voting devices and were asked to vote on each application based on the following criteria:

- What would be the impact (positive) of the application from their professional perspective?
- What would be the feasibility of developing and implementing the application from their professional perspective?

Each application idea was ranked according to its impact and feasibility. Rankings ranged from 1 (lowest) to 10 (highest) for each criterion. Results were tabulated and plotted by impact versus feasibility. Data were collected from 26 respondents; the breakdown of the voters by discipline was as follows:

1. Federal: six voters (23 percent).
2. State: six voters (23 percent).
3. Technology Developer: two voters (35 percent).
4. E&C Industry Firms: nine voters (11 percent).
5. University: three voters (8 percent).

Workshop 1 Results

The top five applications ranked in order of potential impact (high to low) are listed with their overall impact and feasibility ratings (based on average of rankings from 1 to 10).

1. **INSPECTOR'S TOOLKIT.** Use AR technology to verify that work is being installed properly by providing the correct information in the correct format for the inspector in the field.
   Impact: 7.54; Feasibility: 3.70.
2. **NEXTGEN TRAINING AND CERTIFICATION.** Use AR technology to support training and certification for construction inspection.
   Impact: 7.24; Feasibility: 4.73.
3. **AR SUPPORT OF ROW ACQUISITION.** Provide project visualization to property owners to better understand a project's impact and to show design options to the property owner.
   Impact: 7.12; Feasibility: 6.10.
4. **AUTOMATED INSPECTION.** Use AR technology to support automated code/standard-compliance checking of installed items through machine learning.
   Impact: 7.08; Feasibility: 3.44.
5. **VISUAL VARIANCES.** Visually tag variances in the field regarding schedule and quality issues to ensure all parties are viewing the same issue.
   Impact: 6.92; Feasibility: 4.54.

Plotting the Results of Workshop 1

Figure 16 shows distribution of the polling results for the original 10 application concepts from workshop 1. The results are plotted with impact on the industry versus feasibility of development and implementation of the proposed AR applications for the overall group of participants.

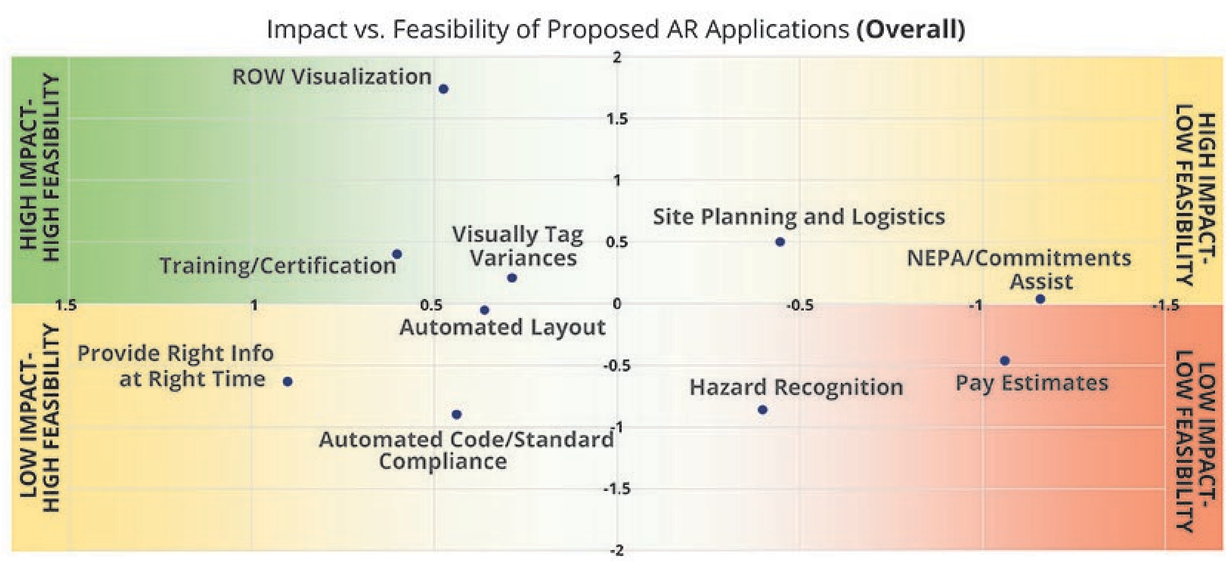


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Figure 16. Graph. Overall polling results based on workshop 1.

Figure 17 through figure 19 show distribution of the rankings regarding impact on the industry versus feasibility of development and implementation of the proposed AR applications based on the participants' discipline.

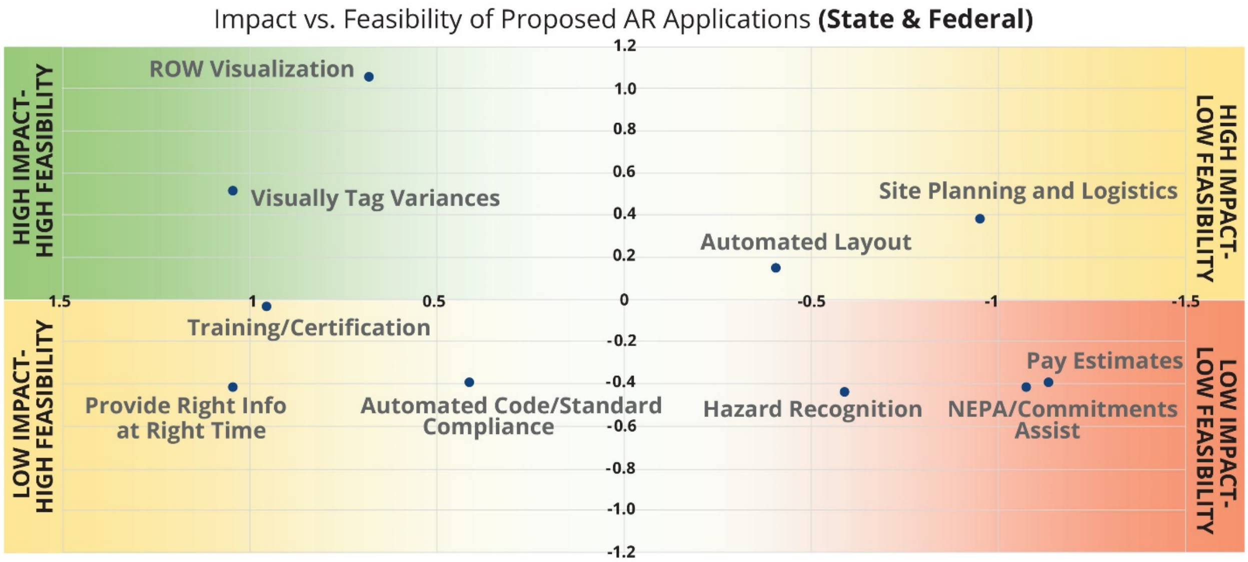

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Figure 17. Graph. State and Federal respondents' polling results based on workshop 1.

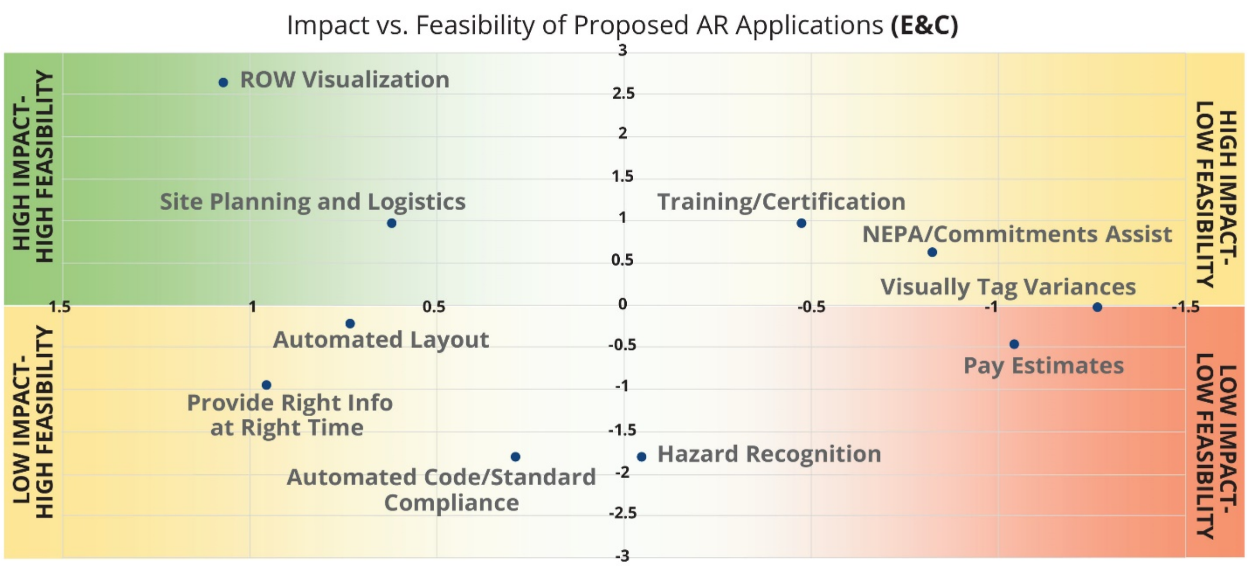

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Figure 18. Graph. Engineering and contractor respondents' polling results based on workshop 1.

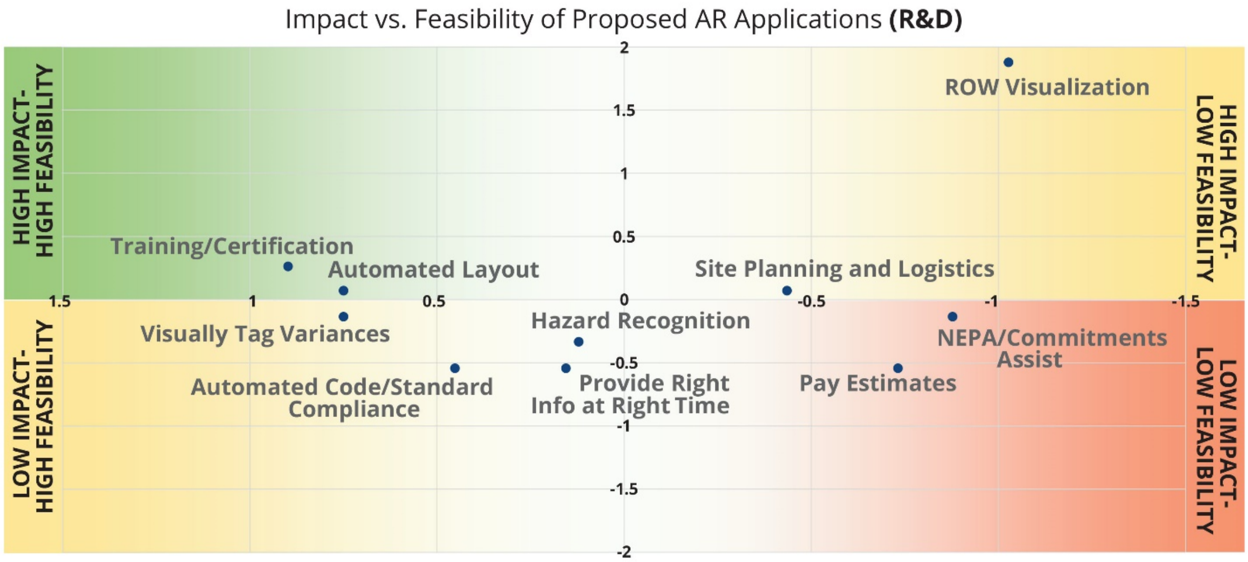

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Figure 19. Graph. Research and developer respondents' polling results based on workshop 1.

Workshop 2 Summary

The second workshop at the 98th Annual Meeting of the Transportation Research Board (TRB) was intended to bring technology and application developers, State DOT representatives, contractors, consultants, and other practitioners together to explore how AR technologies can support construction-management functions during highway construction. Topics ranged from construction inspection and review, QA, training, and improved project management through real-time information in a real-world environment. Like the first workshop, the second workshop was designed to educate participants on the current capability of AR technologies and related applications in AR/VR/MR, identify potential new applications for AR in transportation construction, and prioritize future applications of AR in transportation construction. The workshop was designed as an interactive experience for the participants to explore the capabilities of the different ranges of AR devices and to engage in meaningful dialogue about future applications.

Session 1 of the workshop began with an overview of FHWA's exploration of immersion environments, which was followed by a state-of-practice review completed by the researchers and included in chapter 4 of this report. These presentations were followed by a case study of NDOT's use of virtual technologies to simulate construction phases during a project's development. The session concluded with a presentation of the five application use cases of AR technology in transportation construction identified in the May 2018 workshop, and electronic polling regarding each case's impact to highway construction and feasibility for development and implementation.

Polling Results of the Use Cases

Participants were provided electronic voting devices as in the first workshop and were asked to vote on each application based on the following criteria:

- What would be the impact (positive) of the application from their professional perspective?
- What would be the feasibility of developing and implementing the application from their professional perspective?

Prior to polling on each use case, participants identified their primary affiliation, which included the following:

1. Federal: 16 percent.
2. State: 20 percent.
3. Technology Developer: 8 percent.
4. Engineering and Construction Industry Firms: 32 percent.
5. University: 24 percent.

Workshop participants voted on each application according to its impact and feasibility from their perspective. The uses cases are ranked below by the newer potential overall impact and feasibility rating with **results from the TRB workshop only** (based on average of rankings from 1 to 10):

1. **AUTOMATED INSPECTION.** Use AR technology to support automated code/standard-compliance checking of installed items through machine learning.
   Impact: 7.42; Feasibility: 3.61.
2. **VISUAL VARIANCES.** Visually tag variances in the field regarding schedule and quality issues to ensure all parties are viewing the same issue.
   Impact: 7.00; Feasibility: 5.15.
3. **AR SUPPORT OF ROW ACQUISITION.** Provide project visualization to property owners to better understand a project's impact and to show design options to the property owner.
   Impact: 6.94; Feasibility: 5.67.
4. **NEXTGEN TRAINING AND CERTIFICATION.** Use AR technology to support training and certification for construction inspection.
   Impact: 6.61; Feasibility: 5.70.
5. **INSPECTOR'S TOOLKIT.** Use AR technology to verify that work is being installed properly by providing the correct information in the correct format for the inspector in the field.
   Impact: 6.51; Feasibility: 4.55.

Figure 20 shows the distribution of polling results regarding impact on the industry versus feasibility of development and implementation of the proposed AR applications for the overall group of participants **in workshop 2.**

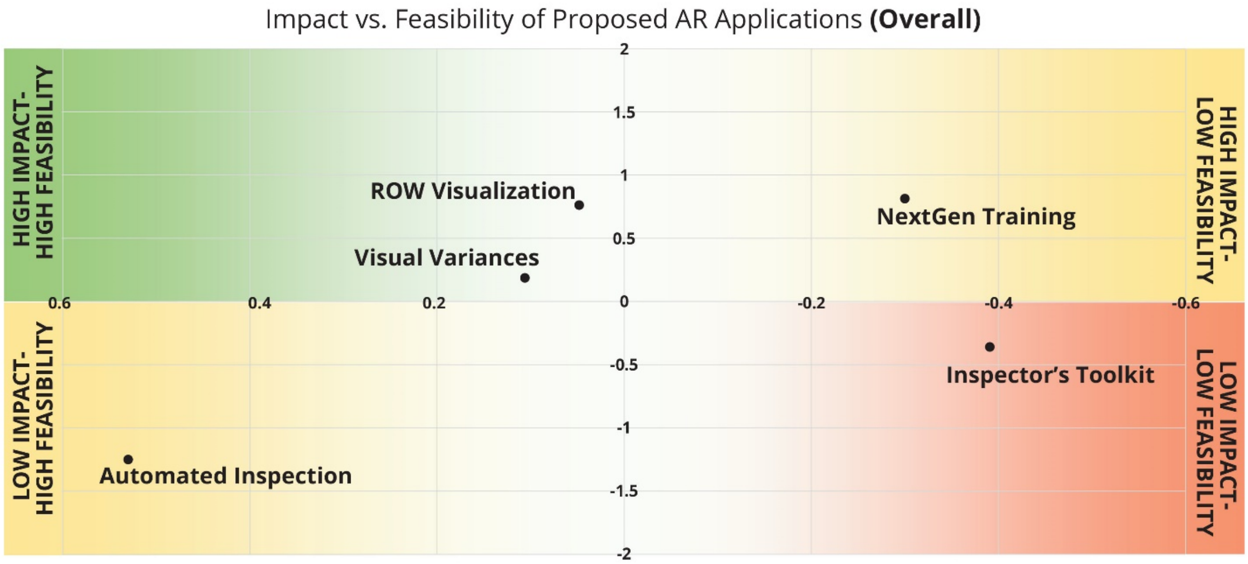

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Figure 20. Graph. Overall polling results based on workshop 2.

Figure 21 through figure 23 show distribution of the rankings regarding impact on the industry versus feasibility of development and implementation of the proposed AR applications based on the participants' discipline.

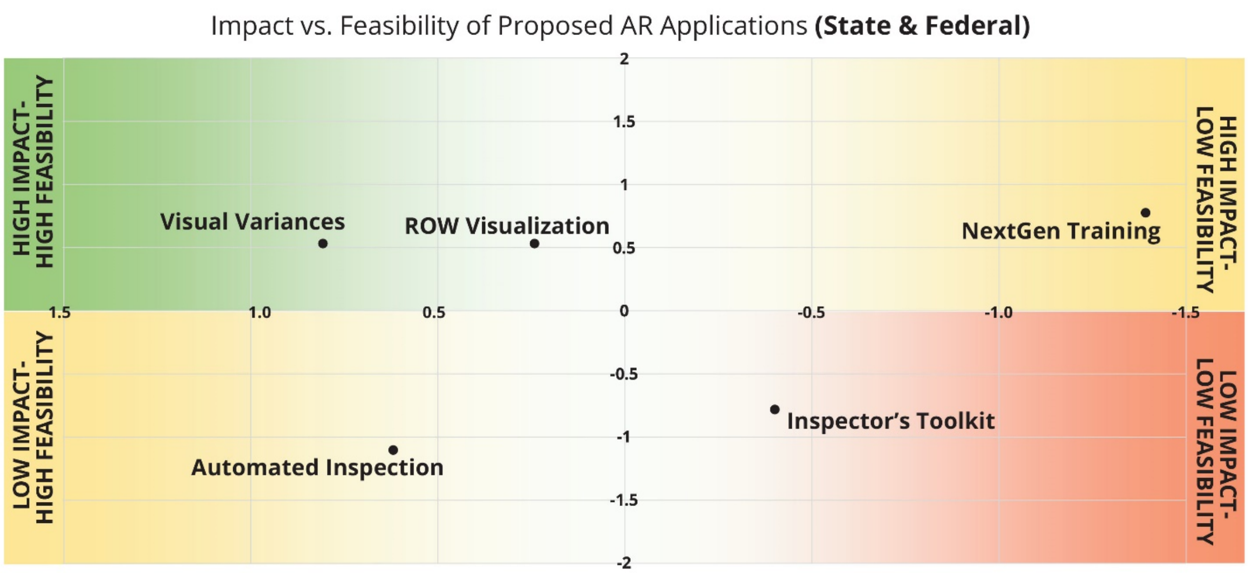

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Figure 21. Graph. State and Federal respondents' polling results based on workshop 2.

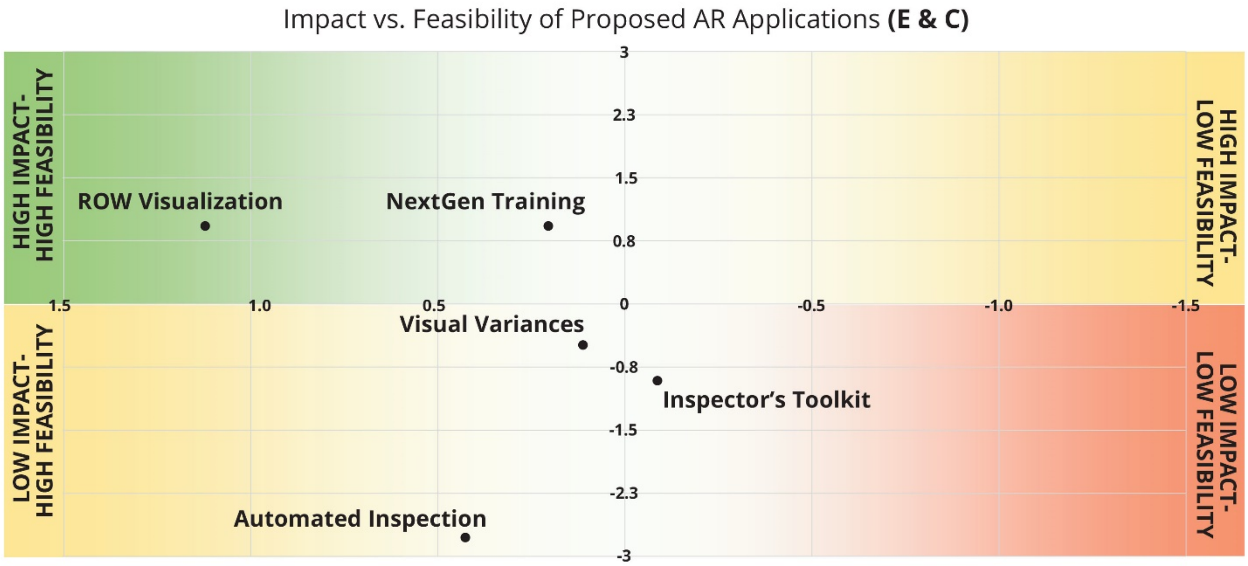

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Figure 22. Graph. Engineering and contractors respondents' polling results based on workshop 2.

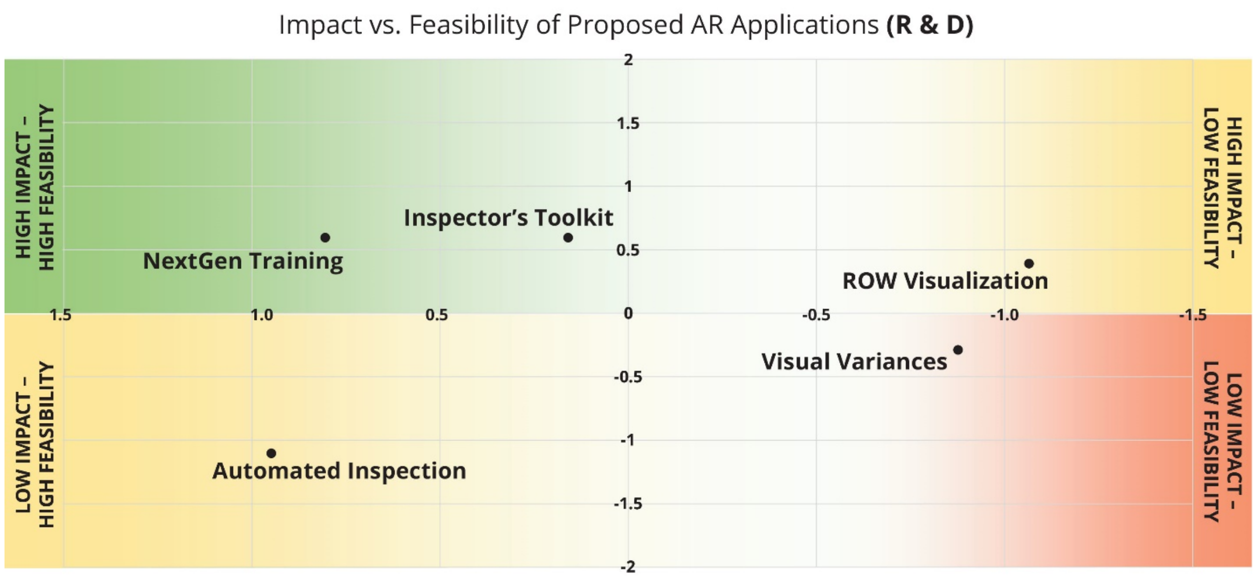

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Figure 23. Graph. Research and developer respondents' polling results based on workshop 2.

After polling was completed, participants explored hands-on demonstrations of AR systems provided by several invited technology developers already in attendance at the TRB Annual Meeting.

Session 2

Session 2 included several presentations that explored R&D work involving AR. The presentations included the following:

- **Iowa Department of Transportation's (IowaDOT's) Use of Virtual Reality in Design.** The presentation highlighted IowaDOT's use of VR, including VR's use in design reviews and influence on driver behavior.
- **UDOT's Use of SiteVision (Trimble).** SiteVision is an AR system designed for exterior environments. At this time, the system is in development and being beta tested; one pilot test was conducted on a UDOT project.
- **Hybrid Reality: Visual and Structural MR (Heriot-Watt University).** Research at Heriot-Watt University has explored the use of MR systems to support both design visualizations and hazard-recognition training.
- **Use of Advanced Visualization Techniques for Explorations in Built Environments (University of Southern California).** Research supported by the National Science Foundation highlighted the use of visualization technologies to explore human behavior during emergency events.
- **AR for Bridge Lighting.** AR was used to explore different lighting options on existing bridges.

FINAL RANKING OF THE AR APPLICATIONS

When the polling data from both workshops 1 and 2 were combined, 87 responses from industry experts provided the following final ranking:

1. **AR SUPPORT OF ROW ACQUISITION.** Provide project visualization to property owners to better understand a project's impact and to show design options to the property owner.
   Impact: 7.02; Feasibility: 5.84.
2. **VISUAL VARIANCES.** Visually tag variances in the field regarding schedule and quality issues to ensure all parties are viewing the same issue.
   Impact: 6.97; Feasibility: 4.88.
3. **INSPECTOR'S TOOLKIT.** Use AR technology to verify that work is being installed properly by providing the correct information in the correct format for the inspector in the field.
   Impact: 6.88; Feasibility: 4.27.
4. **NEXTGEN TRAINING AND CERTIFICATION.** Use of augmented reality supported training and certification for construction inspection.
   Impact: 6.88; Feasibility: 5.27.
5. **AUTOMATED INSPECTION.** Use of AR to support automated code/standard-compliance checking of installed items through machine learning.
   Impact: 6.71; Feasibility: 4.17.

The distribution of the polling scores based on both workshops is shown in figure 24 through figure 27.

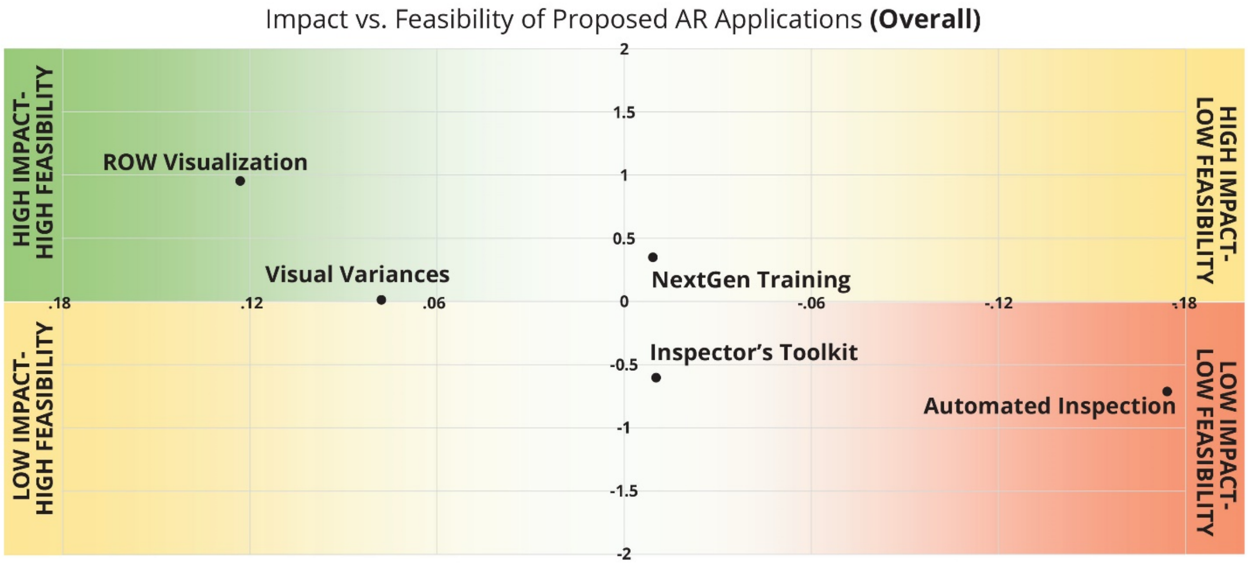

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Figure 24. Graph. Overall polling results based on both workshops 1 and 2.

When the overall polling data are segregated by the demographics from both workshops (figure 24 through figure 26), differences by the type of respondent appear. Respondents from Federal and State DOTs indicate ROW visualization as the top impact followed by visual variances, nexgen training, automated inspection, and inspector's toolkit (figure 24). While E&C and R&D participants viewed other use cases as having a higher impact, both groups of participants gave visual variances a relatively low feasibility score (figure 26 and figure 27), which suggests the visual variance use case is an application requiring a relatively long-term time frame to develop. The ROW visualization use case had the highest feasibility score among Federal, State, and E&C respondents (figure 24 and figure 25). While ROW visualization ranked relatively lower on the impact scale, it may still be an application worth exploring through a pilot effort to explore AR technology's impact but also explore the general use of AR technology in a transportation-construction environment. The challenge of developing a georeferenced AR system that integrates with a BIM model among Federal, State, and E&C respondents was noted as a significant technical challenge in developing the ROW acquisition use case. This use case, however, ranked relatively high in terms of its feasibility among all respondents.

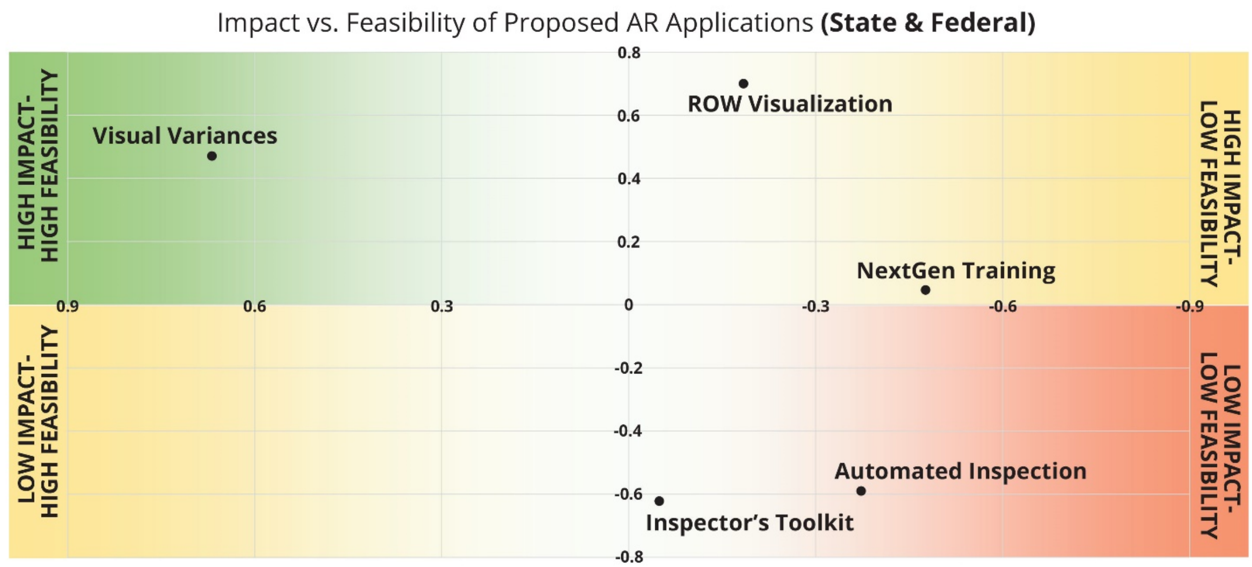

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Figure 25. Graph. State and Federal respondents' polling results based on both workshops 1 and 2.

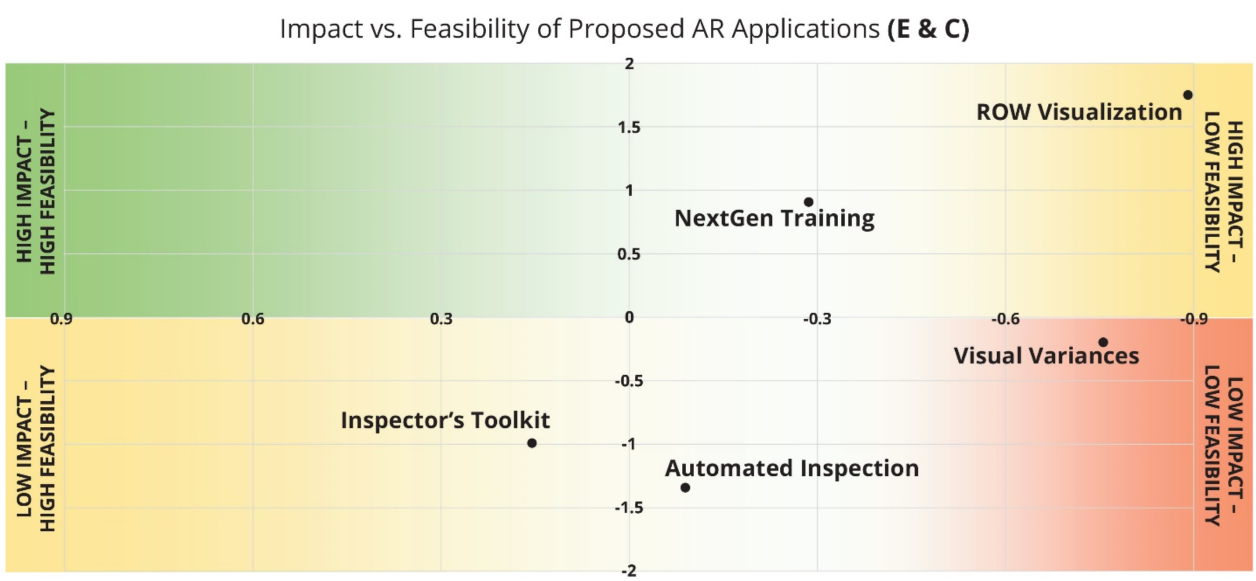

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Figure 26. Graph. Engineering and contractor respondents' polling results based on both workshops 1 and 2.

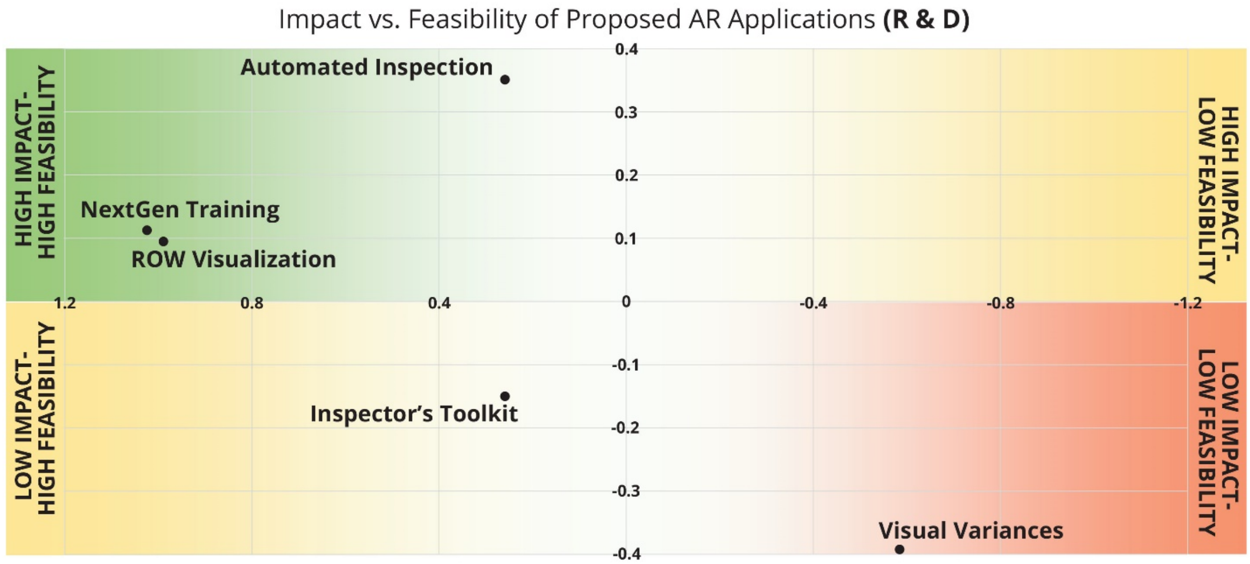

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Figure 27. Graph. Research and developer respondents' polling results based on both workshops 1 and 2.

The preceding use cases are described in more detail in chapter 6 of this report along with detailed descriptions of the potential data requirements and data flows, AR technologies, and user workflows that would be required to implement the activities.

CHAPTER 6. AR FOR CONSTRUCTION MANAGEMENT, INCLUDING INSPECTION AND TRAINING

INTRODUCTION

Based on audience input and discussions in the workshops described in chapter 5 (i.e., workshops 1 and 2) and the research results of this report, the top five AR application use cases identified in both workshops have been expanded and augmented in this chapter to include the following additional criteria:

- A summary of the goals of the individual activity.
- A detailed description of the use case.
- AR technologies that would be required to support the application.
- A potential data/technology framework for the application.

DEVELOPMENT OF DATA FLOW AND AR TECHNOLOGY FRAMEWORK FOR THE USE CASES

The research team developed a framework to describe the AR data, workflows, and technologies required to implement the use cases. The framework is based on the characteristics of AR systems, as outlined in chapter 3. Figure 28 is a flowchart representing the developed framework. Each box, or stage of the workflow, represents a critical step that would potentially be unique to each activity using AR technology. Each stage will be different for different data types; the data type will be driven by the specific requirements for the onsite activity.

Different data types will have different delivery requirements depending on size and complexity, and the data platform will depend on the AR technology being used. Details in the framework stages will vary depending on whether tablet- or HMD-based display technologies are the target platform for the AR application. Localization, the positioning and orientation of the displayed data relative to the real-world view, will depend on how accurately the data must be overlaid, or registered, in the real-world view to accomplish the given activity. The onsite delivery and collection of information will be driven by the activity requirements but will also depend on technologies applied, such as display type and accuracy of localization.

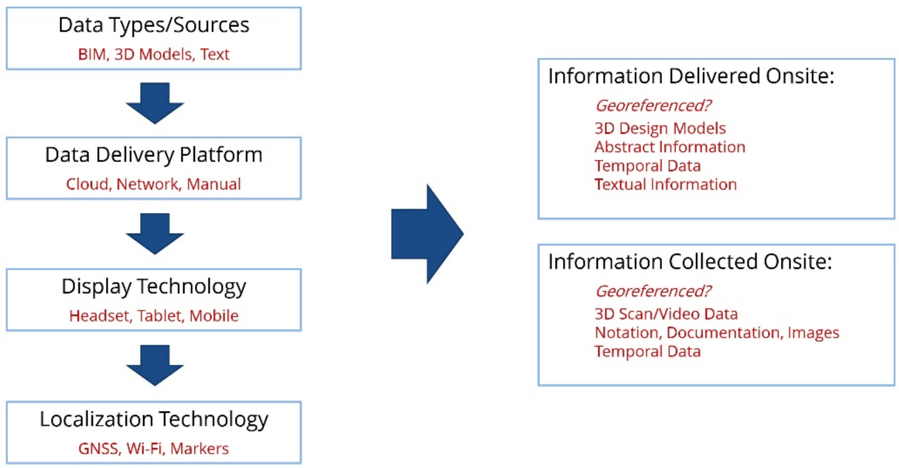

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Figure 28. Flowchart. AR technology process.

Key aspects of the technology framework process include the following:

- **Data Types/Sources (data requirements for specific activities):**
  - 3D design/BIM data.
  - Other (e.g., text or unstructured data).
- **Data-Delivery Platform:**
  - Cloud/network based.
  - Manual transfer.
- **Data-Delivery and -Collection Devices:**
  - Mobile- or tablet-based.
  - HMD.
  - Other (e.g., smartphone and measuring/camera).
- **Localization Technology (driven by the accuracy of position and orientation required for the activity):**
  - GNSS.
  - Marker-based.
  - Local Wi-Fi/emitters/beacons.
- **Information Delivered Onsite (requiring localization):**
  - 3D information on existing conditions.
  - 3D design information.
  - 4D or temporal information.
  - Additional 3D information (e.g., ROW and temporary easement).

- **Information Delivered Onsite (not requiring localization):**
  - Information on existing conditions.
  - Design information.
  - Other information, (e.g., design criteria and specification requirements).
- **Information Collected Onsite (requiring localization):**
  - Notation, documentation, images.
  - 3D design changes.
  - Other information, such as request for information and queries.
- **Information Collected Onsite (not requiring localization):**
  - Notation, documentation, images.
  - Other information (e.g., worker headcount).

USE CASE EXAMPLES

This section provides a detailed description of the five case studies and outline of the framework applicable to each based on the preceding technology framework description, and includes describing the AR data, workflows, and technologies that would be required to implement the use case applications as described.

USE CASE 1: AR SUPPORT OF ROW ACQUISITION

Provide project visualization to property owners to help better understand a project's impact as well as to show design options to property owner.

Goals of the Application

The acquisition of ROW is a critical step in a project's development. The acquisition often requires negotiating and purchasing private property to support a new route or realignment of an existing roadway. Traditionally, negotiating involves displaying the proposed ROW requirements using 2D plan sets (figure 29), and, when possible, using flags and survey stakes on an actual property to show the extent of the ROW requirement. Staking the proposed ROW can be a visual estimation without having to use a survey crew, which can be expensive and subject to time delays. Using 2D plan sets to show the extent of the ROW requirements can be difficult for a private landowner to understand, which can lead to misunderstandings that can cause significant disruption during construction.

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Figure 29. Screenshot. Mockup of interface for an AR ROW application.

Use Case

A fundamental step in acquiring ROW on transportation projects is paying the owner of the property just compensation. Two critical components of this process are the valuation of the property and the presentation of the offer to acquire the property. The process can involve multiple negotiations stemming from disagreements on the valuation of the property, which can be due to a lack of a common understanding of the proposed ROW boundaries. AR technology allows for the ability to overlay the proposed ROW acquisition in a 3D context of the actual property, which can then be easily viewed from multiple perspectives.

In addition to showing the boundaries of a proposed ROW, AR technology could provide other benefits, including the following:

- Better understanding of proposed grade changes that may be involved along the boundaries of the ROW.
- Improved community relations through enhanced communication of the project to project stakeholders.
- Improved communication between a private landowner and the designer on different design options with varying ROW boundaries.

The ability of AR systems to provide the visualization of a ROW is feasible with current AR systems. The ability of AR systems to tailor information to a specific geolocation has been used in prior commercial applications, although the accuracy of these applications may not be sufficient to support negotiation and presentation of a proposed ROW. Highly accurate AR applications that can operate in an exterior environment are currently being developed by at least one technology developer. The use of tablet or HMD applications would support this application; tablet devices would have the advantage of being accessible to multiple users simultaneously.

AR Technology Framework

Data Types/Sources

Primary data types to best support this application include design-based (e.g., CADD) information, such as ROW lines, alignment centerlines and stationing, edge of construction lines (e.g., paving/grading, and simplified 3D models of design elements. Most of these elements would be part of a typical design dataset; the elements would need to be separated from other data. These types of data are typically 2D, except for alignment and corridor surface data that could be generated from civil design tools. 3D alignment and corridor surfaces would most likely need to be sorted out and reduced in complexity from the overall design model. 2D data are typically developed with a *z*-value, or elevation of zero. To display this information correctly in the field, the data would need to be translated to the correct elevation of the data for the proposed design. If the terrain or proposed line work involves complex terrain, the 2D data may need to be draped or converted to 3D using *z*-values from the terrain. This is a step that would need to happen before porting to the AR device.

Data-Delivery Platform

Datasets required for this application would be relatively small depending on the complexity of the project and the area of coverage. The data required could be feasibly transferred between platforms using standard wireless connectivity or transferred directly using portable media, such as USB drives. If a construction site were set up for wireless communication, then it would be feasible to access data directly from the device in the field.

The ideal implementation would be to use existing BIM workflows and tools; AR would then become a display extension to the workflow.

Data-Delivery and -Collection Devices

This type of simplified abstract design information can be easily understood with a tablet or mobile device. The simplicity of using a tablet or smartphone device display is advantageous because the information can be shared with multiple users. The display of design information or project alternatives might be enhanced and would potentially be more immersive and easier to understand with the use of HMD devices, particularly for large 3D elements, such as structures or utilities. These elements would benefit from a stereoscopic display format because they would be rendered more realistically and true to scale.

Localization Technology

Visualization of ROW lines, annotation, and other associated abstract CADD information may not require the same localization accuracy that displays of 3D models or design information would require. If accuracy within a few inches or feet is sufficient for the activity, then GNSS or local network systems could potentially be adequate. One vendor has demonstrated a system that would provide accuracy within a few centimeters using GNSS systems combined with inertial sensing within the mobile device. When more accuracy is required, a marker-based system with targets placed in the environment would most likely be needed. Several examples of marker-based applications currently exist on the market.

Information Delivered Onsite

The primary information delivered to the user will be line work representing potential boundaries (and alternatives) for ROW, alignment centerlines and stationing, edge-of-construction lines (e.g., paving/grading), and simplified 3D models of design elements. Line work for other design information, as well as textual annotation that helps support communication, could also be delivered to the user. All 2D information will need to be converted to 3D so that it is displayed at the correct elevation that matches the existing conditions viewed through the device. Future AR systems will undoubtedly be developed so that they will display associated information, such as textual labels and annotation, correctly in the AR view adjacent to the associated 3D elements.

Information Collected Onsite

As planned, this application would communicate ROW effectively without the need to collect any information onsite. If alternative boundaries are displayed, then capabilities would exist to collect georeferenced notes or annotation as input, as well as to collect photos, general comments, or audio recordings. These capabilities would be relatively easy to add with a tablet-based application and potentially with some HMD-based systems. As shown in studies described in chapter 4 of the document, it is possible to collect 3D point, line, and surface data in the field to validate or measure existing conditions. This capability would most likely require an HMD-based AR system. The process has only been demonstrated in the field on one type of device.

USE CASE 2: VISUAL VARIANCES

Visually tag variances in the field regarding schedule and quality issues to ensure all parties are viewing the same issue.

Goals of the Application

A challenge with inspection is communicating to the contractor and other project stakeholders when variances are found either in terms of discrepancies between design versus as-built conditions and the planned versus actual schedule of installed components. Variances are traditionally communicated through either verbal or written communication, which can lead to misunderstandings between different parties and the inspection team. Miscommunication can lead to delays in correcting the variance or additional errors in modifying installed items that may not be considered a variance. Furthermore, accurately documenting a variance when it is observed by an inspector is challenging when documenting the variance's location and its context on a jobsite.

Use Case

Once an inspection uncovers an issue with an installed, the next step is to communicate the issue to all responsible parties. There are instances when inspectors may be able to share the discovery of the variance immediately so that affected parties can see the variance firsthand, but there are other instances when the variance may need to be viewed later. However, coordinating logistics between an inspection team and a contractor for simultaneous viewing can be challenging.

The ability to visually tag a reference through an AR interface so that another party can visually inspect the variance through another AR device would improve communication and likely expedite the necessary resolution to correct the variance. Furthermore, the ability for an individual on a jobsite to share the variance visually with parties in other locations could help facilitate the expertise of offsite personnel.

AR Technologies for This Application

AR technologies' ability to overlay images that identify objects in variation to a project's contract documents is achievable in current AR systems (figure 30).

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Figure 30. Screenshot. Mockup of interface for AR visual variance application.

However, the ability to use an AR interface to tag a variance once it is discovered and then store the variance and its georeferenced location so that other parties can then view the same variance requires capturing the information (i.e., images or 3D data) onsite and postprocessing of the data for future retrieval. An extension of this application could involve integrating the georeferenced information of the observed variance with the original design model so that the variance could be viewed in the context of the full system design. This approach would offer greater capability of identifying possible resolutions even after the inspection was conducted. However, this level of integration between an AR view and the design (i.e., BIM) model would require further development, but integration could offer a significant improvement in not only resolution of variances but also aiding the development of an as-built model. The basic capability of capturing 3D data onsite to support inspection and measuring variances was demonstrated in work performed by the Los Alamos team described in chapter 4.

AR Technology Framework

Data Types/Sources

The primary data type that best supports this application is design-based (e.g., CADD) 3D-model information, such as 3D models of design elements used in a BIM workflow. Most of these elements would be part of a typical 3D design dataset, but they would need to be separated from other data and potentially simplified in detail for display in the AR system. The display would need to maintain enough detail to adequately measure the variances being checked for at an adequate precision. This required precision may vary with different construction components (e.g., checking that a metal guardrail is installed based on the design criteria for barrier placement, plus or minus some measurement with design tolerances). Supporting information about these criteria for the placement of design elements would be useful for the inspection activity and the evaluation process. Such supporting information could be graphic or textual and preloaded ahead of time or included in a searchable database delivered to the inspector onsite and on the device.

Data-Delivery Platforms

Datasets required for this application could be relatively large depending on the complexity of the project and the area of coverage. Large datasets could be transferred between platforms using standard wireless connectivity or transferred directly using portable media, such as USB drives. If a construction site were set up for wireless communication, then it would be possible to access data directly from the device in the field. This is an application where preconfiguration of models ahead of time, similar to the demonstration described earlier by Autodesk and DAQRI using BIM360 Docs, would be helpful.

Several working platforms have been described in this report, particularly those described as part of documented workflows earlier in chapter 4. As suggested previously, the ideal implementation would be to use existing BIM workflows and tools; AR would then become a display extension to the workflow.

Data-Delivery and -Collection Devices

This type of 3D model information would be easily understood with a tablet or mobile device. The simplicity of a tablet or mobile-device display, especially with the ability to share information among multiple users, is advantageous. Displaying graphic or textual information is more easily achieved with a tablet device or possibly a mobile phone. HMD devices are currently limited in resolution and display quality, which is not conducive to reading or viewing detailed graphics. The display of design information or project alternatives might be enhanced and would potentially be more immersive and easier to understand by using HMD devices, particularly for large 3D elements, such as structures or utilities. If small variances need to be seen closely by the inspector, this would be displayed more effectively by an HMD. These elements would benefit from a stereoscopic display format, which would render them more realistically and true to scale.

Localization Technology

Visualization of variances with very detailed requirements for precision will require good localization and registration between virtual objects and real-world objects. Visualization of variances will most likely require a marker-based system with targets placed in the environment to initialize the position and orientation of the viewer. A more effective approach is for the AR system to match a known point in the virtual model to something in the real world that is known to be in the correct location, such as the end of a beam or column location. Several examples of marker-based applications have been documented in chapters 3 and 4.

Information Delivered Onsite

The primary data type delivered to the user will be simplified 3D models of design elements and possibly models of existing elements to help with alignment. Additional information, such as text or graphics, could be delivered as well, but these would need to be brought up by a localized prompt or through a menu system. Future AR systems will be developed so that they will display associated information, such as text or graphics, correctly in the AR view adjacent to the 3D elements being displayed.

Information Collected Onsite

As previously described in chapter 4, this type of application would be greatly enhanced by the ability to capture existing 3D objects digitally alongside the virtual model, which would not only create a virtual record of the inspection but support as-built documentation as well. One workflow might be to separate the capture process from the measurement process by bringing the onsite captured data back to the office and then measuring variances. This would reduce the need for bringing large amounts of information to the field. Studies described earlier in the document indicate that it is feasible to collect 3D point, line, and surface data in the field to measure as-built conditions. Scanning and capturing onsite 3D information in AR would most likely require an HMD-based AR system. Currently, the process has only been demonstrated in the field on one type of device, though scanning technology has been incorporated into mobile devices. However, there are other existing methods for capturing 3D data onsite, which could support virtual inspection after the site visit.

USE CASE 3: NEXTGEN TRAINING AND CERTIFICATION

Use AR technology to support training and certification for construction inspection.

Goals of the Application

Experienced personnel are leaving State DOTs through retirement and being replaced by less-experienced personnel encountering more rapid increases in responsibility earlier in their careers than their predecessors. In some State DOTs, retiring personnel are not being replaced at all. These personnel changes are impacting all divisions of DOT personnel, particularly those tasked with the construction of highway infrastructure. Research results in NCHRP Synthesis

450 found that among 40 State DOTs between 2000 and 2010, State-managed lane miles increased by an average of 4.10 percent while the number of full-time equivalent staff decreased by 9.70 percent (Taylor 2013). Compounding these challenges are recent demographics of STA construction staff, which indicated that the most frequent age range of construction staff was 40–50 years old and that the average years of experience was 10–15. The data indicate that DOT construction staff will continue to experience a loss in knowledge and skills due to retirements. A challenge is how to efficiently develop the next generation of inspectors during their training and through certification. VR and AR offer the potential to explain complex spatial topics effectively and supplement traditional training materials.

Use Case

Workforce development involves the recruitment, training, and retention of a workforce population. Training is a critical step in the system, and it usually results in an individual achieving a public or industry-recognized certification. Inspectors complete a combination of formal classroom and on-the-job training (OJT) activities to learn engineering and construction fundamentals related to infrastructure systems. While most OJT requires hands-on learning, formal classroom training traditionally relies on lecture and 2D educational materials. A challenge in engineering and construction education involves understanding interactions of complex spatial systems (e.g., how structural systems forces function or how different components are assembled in construction). Future applications of AR technology could be used to provide 3D representations of technical concepts to facilitate the users understanding of the training material. A basic application approach could include AR applications designed to recognize 2D markers in textbooks or other types of 2D materials that would then provide a 3D representation of the concept.

AR Technologies for This Application

AR for education and training has been used throughout other industries, including healthcare, manufacturing, and aviation. Specific devices to support this application are numerous, including both handheld (figure 31) and HMD. There are minimal technical challenges to develop these applications because current off-the-shelf systems already exist. The more significant challenge, however, is to identify which training materials would benefit from 3D representations. The application could be an in-office or classroom tool, but the application could be brought to the field for onsite comparisons of real-world scenarios. An obstacle when developing this type of application is the temporary aspects of construction: construction sites change constantly, construction is eventually completed, and the AR content would not be current or accessible for long.

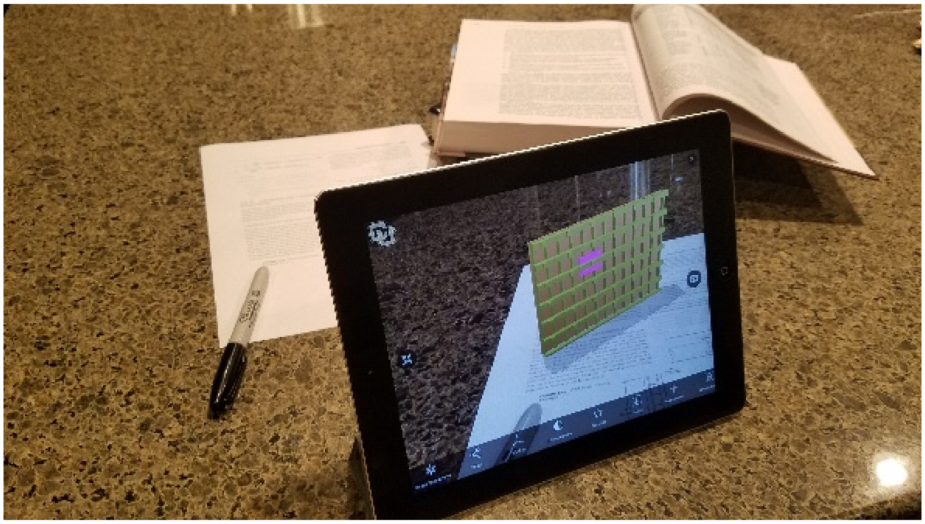
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Figure 31. Photo. Mockup of interface for AR training application.

AR Technology Framework

Data Types/Sources

The primary data types that best support this application are design-based (e.g., CADD) 3D-model information, such as 3D models of design elements used in a BIM workflow. Most of these design elements are part of a typical 3D design dataset, but they need to be separated from other data and potentially simplified in detail for display in the AR system. As these data are prepared in advance based on the support of training materials, the models are optimized and segmented accordingly. Supporting information for the training exercises includes graphic or textual information preloaded ahead of time or included in a searchable database delivered to the training as needed on the device.

Data-Delivery Platform

Datasets of the type required for this application would be relatively small, depending on the complexity of the subject matter and the area of coverage of the visualization. If the training is performed indoors and not onsite, it is likely that there would be access to standard wireless connectivity or the data could be transferred directly using portable media, such as USB drives. The information would be preloaded or delivered via browser connection in a similar fashion to other digital educational or training materials.

Data-Delivery and -Collection Devices

The type of 3D model information used for this application can be easily understood with a tablet or mobile device. The simplicity of a tablet or mobile-device display, especially with the ability to share the information to multiple users, is advantageous. The display of graphic or textual information would be much more easily done with a tablet device or possibly a mobile phone. HMD devices are currently limited in display quality, which is not as conducive to reading or detailed graphics. The display of design information or project alternatives might be enhanced and would potentially be more immersive and easier to understand by using HMD devices, particularly for large 3D elements, such as structures or utilities. If small variances need to be seen closely by the inspector, the variances would be displayed more effectively by an HMD. These 3D elements would benefit from a stereoscopic display format, which would render them more realistic and true to scale.

Localization Technology

If this type of application were used in an office or classroom, then there would be no need for registering a virtual model in a specific real-world location. The 3D representation would still be enhanced with accurate tracking in whatever environment the user is in. Markers would still be used to load the desired models and supporting materials. If an application were developed that included field demonstrations, then GNSS or marker-based initialization would be required to place the viewer properly in the scene.

Information Delivered Onsite

The primary information delivered to the user will be simplified 3D models of design elements, and possibly models of existing elements to help with understanding context. Potentially other information such as text or graphics would be delivered as well, and these would need to be brought up by some form of localized prompt or through a menu system. Future AR systems will be developed so that they will display associated information, such as text and annotation, correctly in the AR view adjacent to the 3D elements.

Information Collected Onsite

This application would be primarily developed to deliver information but also as part of a review of the trainee. When used for reviewing a trainee, the application could query the user for information or answers to questions. The application could potentially prompt the user to interact with the virtual model, asking for 3D input in the virtual scene. This functionality seems similar in technology requirements to the applications previously described in chapter 4 in which users enter 3D data in the field through an HMD device.

USE CASE 4: INSPECTOR'S TOOLKIT

Use AR technologies to verify that work is being installed properly by providing the correct information in the correct format for the inspector in the field.

Goals of the Application

Construction inspection requires processing textural and graphical data on behalf of an inspector to verify proper installation. Traditionally, inspectors have relied on a combination of training, cognition, and experience to make judgments to approve construction work. As projects have become more complex and the shortage of inspectors has increased, inspection of transportation construction components has become more challenging. The use of AR has the potential to assist new and experienced inspectors and to examine complex systems by offering the right information in the right format at the right time.

Use Case

There are many aspects to inspection, ranging from measuring quantities for payment to providing the QA and/or quality control (QC) to accept work that meets contractual requirements. This AR application would focus on assisting inspectors in providing the QA/QC support. When inspecting a project, information must be obtained from plans, specifications, manuals, and policies. Currently, much of this documentation resides in electronic and hardcopy resources; ensuring an inspector is using the most current versions of these documents in the field can be challenging. If this information were available electronically and in a central repository, then some of the challenges would be alleviated and important information would be more easily accessible to inspectors in the field.

AR in the field could take many forms for an inspector. The required information could be accessed on demand through a series of menus and tabs, thus providing a similar interface to what tablets display now. In this case, the advantage of HMD-delivered AR over tablet-delivered AR is hands-free operations. The HMD device could potentially allow inspectors to measure field conditions for QA/QC. Part of the challenge of field inspection is knowing which critical items need to be examined and when. Future applications of AR that are georeferenced and linked to schedule milestones could intelligently tailor the information displayed to the user by providing relevant inspection parameters (figure 32).

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Figure 32. Screenshot. Mockup of interface for the inspector's toolkit application.

AR Technologies for This Application

The ability of AR technologies to provide information in graphical and textural detail to facilitate QA/QC inspection is practical with current AR applications. AR systems operate through a menu-driven environment that could be navigated by a user to access the desired information. The ability of AR systems to tailor information to geolocation has been used in prior commercial applications. However, the added synchronization with schedule information to further provide time-sensitive information is a new advancement. Developing this level of synchronization is possible at the project level, although efficiently developing this at the enterprise level would likely require further efforts.

There are minimal technical challenges to develop these applications because current off-the-shelf systems already exist. The more significant challenge, however, is identifying which training materials would benefit from 3D images.

AR Technology Framework

Data Types/Sources

The primary data types that would best support this application would be design-based (e.g., CADD) 3D-model information such as 3D models of design elements used in a BIM workflow and textual design data (e.g., relevant specifications or design notes). Most of these elements would be a part of a typical 3D-design dataset; they would just need to be separated from other data and potentially simplified in detail for display in the AR system. Enough detail would need to be maintained to adequately display to the inspector what an inspector should be seeing in the field. This 3D and textual information could be relatively simple and abstract for some scenarios and very detailed for more complex construction scenarios. Supporting graphic or textual information about these design or installation elements and associated inspection criteria would be useful for the inspection activity and the evaluation process. The graphic or textual information could be preloaded or included in a searchable database delivered to the inspector onsite and on the device.

Data-Delivery Platform

Datasets of the type required for this application could be relatively large, depending on the complexity of the project, the area of coverage, and the amount of supporting graphic and textual information. This type of data could be feasibly transferred between platforms using standard wireless connectivity or transferred directly using portable media, such as USB drives. If a construction site were set up for wireless communication, then it would be possible to access data directly from the device in the field. This is an application where organization of models ahead of time, similar to the demonstration described earlier by Autodesk and DAQRI using BIM360 Docs, would be helpful.

Several BIM platforms have been described in this report, particularly those described as part of documented workflows earlier in chapter 4. As suggested before, the ideal implementation would be to use existing BIM workflows and tools, with AR just becoming a display extension to the workflow.

Data-Delivery and -Collection Devices

The type of 3D model and textual information required for this application can be easily understood with a tablet or mobile device. The simplicity of a tablet or mobile-device display, especially with the ability to share information among multiple users, is advantageous. Displaying graphic or textual information is more easily achieved with a tablet device or possibly a mobile phone. HMD devices are currently limited in resolution and display quality, which is not conducive to reading or viewing detailed graphics. The display of design information or project alternatives might be enhanced and would potentially be more immersive and easier to understand by using HMD devices, particularly for large 3D elements, such as structures or utilities. If small variances need to be seen closely by the inspector, the variances would be displayed more effectively by an HMD. These variances would benefit from a stereoscopic display format, which would render them more realistic and truer to scale. An intelligent application that would deliver the right information at the right time based on context would be complex and require significant development. A less complex application is a menu-driven system that prompts the user for information.

Localization Technology

Visualization of design components aligned accurately in the field would require good localization and registration between virtual objects and real-world objects. Visualization of design components will most likely require a marker-based system with targets placed in the environment to initialize the position and orientation of the viewer. A more effective approach is for the AR system to match a known point in the virtual model to something in the real world that is known to be in the correct location, such as the end of a beam or column location. Displaying graphic or textual information, and possibly models of example design components, would not need as precise an alignment to the real-world view and would need to be accessible to the user at the requested or appropriate time. GNSS or marker-based localization would be sufficient for achieving this precision of alignment.

Another potential requirement for an inspection application system is the integration with the construction schedule because the information an inspector needs not only varies by location but also by phases of construction. Different markers produced for specific components or time-based activities (e.g., steel beams, or an install sequence for the beams) could address this challenge. This requirement could also be addressed in the interface of the application.

Information Delivered Onsite

Information delivered to the onsite user will include simplified 3D models of design elements and possibly models of existing elements to help with alignment. Additional information, such as text or graphics, could be delivered as well; this information would need to be brought up by a localized prompt or through a menu system. Future AR systems will be developed so that they will display associated information, such as text or graphics, correctly in the AR view along with the 3D elements being displayed.

Information Collected Onsite

This application would be primarily developed to deliver information. Potentially as part of the inspection activity, however, the application could query the user for information (e.g., completion of an electronic checklist or comments on the subject being inspected). The application could potentially prompt the user to interact with the virtual model, asking for 3D input in the virtual scene. This functionality would require technology similar to that in applications previously described, in which users are entering 3D points while viewing real-world objects.

USE CASE 5: AUTOMATED INSPECTION

Use AR technology to support automated code/standard-compliance checking of installed items through machine learning.

Goals of the Application

Computer algorithms used to verify that design objects comply with industry and local building codes have been the subject of prolonged research and development efforts. The conventional practice of code-compliance checking in the construction industry has primarily been a manual process, which is costly, demanding of experienced personnel, and prone to error. A common approach to check for compliance automatically is to compare each object or system in a BIM to the constraints in a standard. The evolution of BIM and industry classes supports this development. The output is usually a list of noncompliant objects. Under this current approach, automated code-compliance checking is usually focused as a design effort rather than a construction inspection task, which would further ensure that not only are objects designed in accordance to building codes but they are also installed in compliance with those same codes.

Use Case

There are numerous sections of Federal and State standard specifications that apply to transportation construction. These standards specify several spatial aspects related to design (e.g., bar spacing, member sizes, and object orientation). Verifying that all installed objects comply with applicable standard specifications can be challenging. If integrated with sensing data (e.g., laser scanning, or in the future, scanning by the onboard sensors), then AR technology could highlight installed components that are outside of code compliance. For example, in transportation construction, AR technology could potentially highlight visually in the user's view if the proper size, shape, and length of reinforcing steel has been installed at the correct spacing (figure 33). While current capabilities of AR systems cannot sense and measure the installation of components to the level of accuracy to determine whether components have been correctly installed in compliance to standards, other technologies, such as LiDAR and laser-scanning systems, can. These data could be collected and analyzed offline. The result of the analyses could be loaded to the AR system to help visually tag the components that are out of compliance.

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Figure 33. Screenshot. Mockup of interface for automated inspection application.

AR Technologies for This Application

Using 3D imaging technologies for automated code compliance has been developed to inspect installed highway components ranging from the flatness of concrete slabs, slopes, rebar spacing, and rebar diameter. However, integrating the results of these scans in AR is a novel concept. AR systems have been explored as tools to scan and perform the analyses internally while onsite, but the accuracy of scanners within current HMD devices was found to lack the accuracy to support the function adequately. One scenario for this application is that the inspector would draw from a library of components to compare against the installation. The comparison could be achieved manually and visually by the inspector, or by implementing artificial intelligence (AI), the device's processor would be used to make the evaluation using the library component. In the future, with enough development and sophisticated AI, the device and processor could perform the compliance check automatically with some minimal input and direction by the inspector.

AR Technology Framework

Data Types/Sources

The primary data types that best support this application are design-based (e.g., CADD) 3D model information, such as 3D models of design elements used in a BIM workflow. Most of these elements would be part of a typical 3D design dataset; the elements would need to be separated from other data and potentially simplified in detail for display in the AR system. Virtual objects would need to have enough detail to adequately compare visual elements to real-world elements and with adequate precision. This required precision will vary with different construction components. To be truly automated, the application would need to draw upon design criteria that would be applied to 3D information captured by the device in the field. This would be a truly challenging application to develop; it would require significant intelligence by the system. The design criteria could be a 3D library of design components or a series of abstracted dimensions and measurements.

Data-Delivery Platform

3D datasets required for this application could be relatively large depending on the complexity of the project and the area of coverage. These datasets could be transferred between platforms using standard wireless connectivity or transferred directly using portable media, such as USB drives. If a construction site were set up for wireless communication, then data could be accessed directly from the device in the field. If the application were automated as previously described, then the platform would need to support the delivery of the library of information required to conduct the compliance analyses. In the future, this type of complex system would most likely need wireless access to process and support information in the cloud.

Data-Delivery and -Collection Devices

This type of 3D model and textual information can be easily understood with a tablet or mobile device. The simplicity of a tablet or smartphone display, especially with the ability to share information among multiple users, is advantageous. Displaying graphic or textual information is more easily achieved with a tablet device or possibly a mobile phone. HMD devices are currently limited in resolution and display quality, which is not conducive to reading or viewing detailed graphics. The display of design information or project alternatives might be enhanced and would potentially be more immersive and easier to understand with the use of HMD devices, particularly for large 3D elements, such as structures or utilities. Currently, HMDs are the only AR devices that have been demonstrated to collect 3D information on a construction site, but the same scanning technology has been deployed on mobile devices.

Localization Technology

Comparison of virtual models with installed components would most likely require high precision and thus good localization and registration between virtual objects and the real-world objects. This type of application will most likely require a marker-based system with targets placed in the environment to initialize the position and orientation of the viewer. A more effective approach is for the AR system to match a known point in the virtual model to something in the real world that is known to be in the correct location, such as the end of a beam or column location. Several examples of marker-based applications have been described in this report in chapter 4.

Information Delivered Onsite

As described above, one scenario for this application is that the user would draw from a library of 3D models of design elements to facilitate the evaluation of installed components. Other information, such as measurements, dimensions, and text or graphics, could be delivered as well; these would need to be displayed by a localized prompt or through a menu display. Future AR systems will be developed so that they will display 3D components or associated information, such as text or graphics, correctly in the AR view adjacent to the 3D elements being displayed.

Information Collected Onsite

As previously described, this type of application would be greatly enhanced by the ability to capture existing 3D objects digitally alongside the virtual model being displayed. This would not only create a virtual record of the comparison of objects but would support as-built documentation as well. One workflow that would accomplish this would be to separate the capture process from the compliance-check process by bringing the onsite captured data back to the office and then checking for compliance. This would reduce the need for bringing large amounts of information to the field. Studies described earlier in the document indicate that it is feasible to collect 3D point, line, and surface data in the field to measure as-built conditions. Scanning and capturing onsite 3D information with AR technologies would most likely require an HMD-based AR system. The process currently has only been demonstrated in the field on one type of device, though scanning technology has been incorporated into mobile devices as well. However, there are other existing methods for capturing 3D data onsite, which could support virtual inspection after the site visit.

CHAPTER 7. SUMMARY OF KEY OBSERVATIONS AND CONCLUSIONS

This study focused on documenting current AR tools and applications and their implementation for supporting highway construction—especially for supporting construction inspection and review, QA, training, and improved project management through access to real-time information in a real-world environment. While the researchers were unable to identify mature applications currently ready to implement for construction, the researchers found several activities by academic researchers, agencies, and private industry that explore the opportunities and benefits that AR solutions can add to construction management.

KEY OBSERVATIONS

The market review of AR technology identified several vendors offering AR solutions with products of varying sophistication and characteristics. AR technology is rapidly changing and improving in terms of hardware, applications, and workflows. Throughout this research project, several new AR technologies were released and existing technologies and devices have advanced and improved dramatically. Conversely, several devices documented early in the study have disappeared from the market, which is an indication of the industry's instability and rapidly changing nature. A small portion of the devices found in the study focused on the AEC market, especially for interior architectural design and construction. The HMD devices with success in this market were untethered (mobile) and robustly supported standard 3D modeling-platforms. Tablet support for AR in the AEC market is typically based on software support of the onboard display and tracking technologies found in common mobile devices.

Most of the current AR devices have very good tracking capabilities once registered to the real-world environment. Most devices and applications' tracking capabilities use markers (or target images) in known locations in the environment. Once localized, the devices track the user's movements and view with a combination of video imagery, 3D sensors, and inertial tracking. As the devices move within the environment, they maintain the registration of virtual to real-world imagery. With some devices and applications, 3D virtual–model elements are matched directly to their real-world counterparts to increase the accuracy of image registration and tracking.

This study identified several challenges with AR visualization in outdoor and unstructured open area environments. For example, see-through devices such as HMDs have difficulty displaying virtual imagery over bright real-world scenes. The tracking sensors on AR devices require adequate detail to track the real world efficiently, which highway construction sites may lack as they are typically open, flat expanses. Other challenges, especially with HMD devices, include visual display performance, durability in a construction environment, onboard digital storage capacity, and access to onsite wireless communication. Using HMDs or tablet devices safely is in an ongoing concern. These challenges will affect when these devices can be leveraged for highway construction.

Tablet devices appear to be making more rapid advances in the highway construction field because they have fewer limitations in outdoor display and viewing. The disadvantage of using tablets in the highway construction field centers on the accuracy of the tracking technology; the registration of virtual to real-world imagery might not be precise. One vendor has focused on this market with a unique combination of a tablet device integrated with special hardware and software technology to provide higher precision tracking and better registration of virtual 3D data to the real-world view.

A unique application of AR HMD devices that the research identified was the ability to leverage the 3D-scanning hardware used for AR tracking to capture existing 3D data in the field. The precision of the data depends on several factors, including available site survey information, and the scanning precision of the sensor hardware. On a typical highway construction site with good survey targets and a robust 3D model-based workflow, this capability will become an important aspect of AR implementation, especially for site inspections.

The commercially available devices identified in the research for AEC application were generally supported by 3D software applications used in design and construction. Workflows that support AR devices for this industry will be similar to 3D model-based workflows and BIM processes that are rapidly becoming more prevalent. FHWA promotes these 3D workflows through the EDC program. Challenges with data flow and 3D-model management for AR technologies will be similar to those challenges currently being addressed in BIM workflows. It is likely that the integration of AR devices into an existing BIM workflow will soon promote the early adoption of these AR devices.

Virtually all the 3D modeling and CADD application vendors supporting the AEC industry are developing application workflows that support deploying 3D models to AR devices, and most are also developing cloud-based collaboration and model distribution platforms to facilitate managing 3D-model data and deploying it to construction sites and mobile AR devices. As communication technology continues to promote Wi-Fi access through cellular or satellite communications to remote parts of the country, it will also promote onsite deployment of BIM-based AR applications.

CONCLUSIONS

The workshop findings, prototype case studies, and discussions on current technologies, opportunities, and challenges all point to potential future use of AR technology in highway construction. The individual AR frameworks described for each case study are currently available in the market or have been demonstrated in research or exploratory activities. Research activities have virtually demonstrated case study 1 identified earlier in this report. Activities described in all the case studies can be achieved at some level in the near future, but the activities require investment in specific hardware and software frameworks. The most important requirements include software development for managing the application (e.g., for the UI, data input/output, 3D-model management) and coordinating the AR hardware as an integrated working solution. The application and hardware should be seamless for users, allowing them to focus on the tasks that need to be accomplished.

This study identified five use cases of AR technologies in transportation construction. These case studies are not the only potential applications of AR technologies in transportation construction, but the case studies can serve as starting points for transportation agencies and developers to focus AR development and implementation efforts in the near and long term. One challenge raised by participants in both AR workshops is the lack of ROI to justify AR implementation. The lack of ROI is a traditional barrier to new technologies, but in this case, independent field trials have helped address the concern. These field trials have also helped further the development and implementation of technologies, such as 3D modeling and BIM. Multiple objective field trials that examine the benefits and costs of implementing AR technology in the highway construction industry based on empirical results will further alleviate the ROI challenge.

Just as construction is driving changes in technologies, such as survey, automated machine guidance, inspections, and QA using unmanned aerial systems, it will likely also drive the advancement of AR technologies. The EDC program promotes innovation (e.g., 3D-model-based workflows) and this innovation will provide opportunities for using AR technologies on highway construction projects.

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