Augmented Reality (AR) in Life-Cycle Management of Transportation Infrastructure Projects

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Submitted by:

Jie Gong
Associate Professor, Ph.D.
Rutgers University

Yi Yu
Graduate Student Researcher
Rutgers University

Center for Advanced Infrastructure and Transportation
Rutgers, the State University of New Jersey
100 Brett Rd, Piscataway Township, NJ 08854

External Project Manager
Robert Kumapley, Senior Program Manager
Port Authority of New York and New Jersey

In cooperation with

Rutgers, The State University of New Jersey
And
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7. Author(s)
Jie Gong https://orcid.org/0000-0002-7915-7304,
Yi Yu https://orcid.org/0000-0002-2553-8603

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16. Abstract
In recent years, Virtual Reality/Augmented Reality as an immersive computing and visualization technology has seen explosive development, and has very rich use cases in the realm of transportation infrastructure management. Some of these user cases include supporting inspection, construction review, QA, in-situ operation simulation, and training through real-time information. In general, there is yet a lack of understanding on how today's AR/VR technologies mesh with the current needs of transportation infrastructure management. The goal of this study is to help transportation stakeholders achieve better understanding of the utility of AR technologies and encourage wider acceptance of AR technologies in life-cycle management of transportation infrastructure systems through literature synthesis, technology evaluation, application development, and technology demonstration. To this end, this project produced new ways of providing training to transportation workforces. More specifically, two full-immersive virtual environments featuring bridges and critical facilities have been developed. These virtual environments are modeled after two real facilities. The virtual training environments can greatly improve the efficiency and effectiveness of training for transportation workforce. For example, construction crews can use the bridge VR environment to simulate the setup of work zones (i.e. placing cones and controlling traffics with flagman) and experience the resulted traffic flow in a fully immersive environment. Such training can greatly enhance the safety of construction crews and the traveling public. The facility VR environment can be used for confined space training.

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INTRODUCTION

Description of the Problem

Decades of urbanization has created large urban clusters where people and infrastructure systems are highly concentrated. After years of service to bring people into productive proximity, many of the transportation system elements such as transit stations, bridges, and tunnels are reaching towards their end of life, and are in need of repair and replacement. Nevertheless, assessing, repairing, and replacing these infrastructure elements in densely populated areas are extremely complex tasks, often requiring evaluation of impacts to current services, analysis of many what if scenarios, and provision of extensive training to operators and workers. One common challenge for facility owners is lack of means to create high fidelity digital environments to support these required tasks. Traditional way of project data analysis and training methods often falls short of helping decision makers to grasp the true complexity of many construction and maintenance tasks, which could lead to significant impacts to quality of service once these tasks are actually executed.

Relevance to Strategic Goals

The focus of this project is particularly relevant to several USDOT strategic goals, which are also the primary focus of this consortium. The focus of this project on enabling more cost-effective life-cycle management of transportation infrastructures directly relates to “improving durability and extending the life of infrastructure” and “preserving the existing transportation system”.

Background

In recent years, AR as an immersive computing and visualization technology has seen explosive development. Many tech giants such as Google, Facebook, and Microsoft have started embracing AR as the next paradigm of personal computing. In a nutshell, AR combines virtual computer-generated information with the real user environment in real-time, enhancing the user’s perception of reality and enriching the provided information content. AR has very rich use cases in the realm of transportation infrastructure management. Some of these user cases include supporting inspection, construction review, QA, in-situ operation simulation, and training through real-time information. Yet these user cases often demand various types of AR capabilities. These capabilities range from simply overlaying virtual content in real-time onto real environment to enabling complex real-time user interaction with mixed reality to drive in-situ simulation of what-if scenarios. In other words, some of the use cases are already feasible with the built-in capabilities of available AR toolsets; while others would require significant development and integration. In general, there is a lack of understanding on how today's AR technologies mesh with the current needs of transportation infrastructure management.

Research Goals and Objectives

The goal of this study is to help transportation stakeholders achieve better understanding of the utility of AR technologies and encourage wider acceptance of AR technologies in life-cycle management of transportation infrastructure systems through literature synthesis, technology evaluation, application development, and technology demonstration.

Overview of the Report

This report documents the research approach, methodology, findings, conclusions and recommendations of this collaborative research project. The following sections outline the approach and methodology. The next section presents the findings, followed by sections documenting the conclusions and making recommendations for future work and application in Life-Cycle Management of Transportation Infrastructure Projects

APPROACH

In this project, the team proposed the following approach to address these research needs.

(1) The study will document the technical capabilities, advantages, and limitations of the technology through literature analysis and hand-on evaluation of the representative AR technologies including headset based AR such as Microsoft HoloLens and Google Magic Leap and cellphone based AR such as Google Tango phone, android AR Core, and Apple AR Kit.

(2) The study will evaluate the feasibility of the above AR technologies in supporting a selected set of use cases in transportation infrastructure management. The evaluation will focus on data requirement, computing needs, and real-time performance.

(3) The team will conduct additional development on the most promising platform identified through (1) and (2) to explore the deep integration of AR technologies with project data in supporting real-time interactive computing and simulation in AR environment.

(4) The team will summarize future research needs based on the findings from (1), (2), and (3).

Throughout the project, the research team will rely on literature analysis, case studies, prototype development, and technology demonstration with project customers and potential implementers as the primary means to help transportation infrastructure stakeholders achieve better understanding of the landscape of AR technologies.

METHODOLOGY

Our technology deployment/research implementation plan is rooted in a three-prolonged approach.

(1) Technology demonstration during invited sessions and workshop to transportation stakeholders such as Port Authority of New York and New Jersey and Board of Public Utilities to convey the benefit of AR technologies

(2) Field trials with practitioners in real environment such as bridge or tunnel inspection and underground excavation to convince them the benefit of the AR technologies

(3) Webinars and presentations at conferences to ensure the reach to a larger crowd of audience

The following research tasks are planned in this project.

Task 1: A web-based kickoff meeting with customers and the research team

Deliverable: A meeting notes

Task 2: Reviewing available AR technologies with a focus on their technical specs and acquiring and assembling representative AR technologies

Deliverable: A literature summary

Task 3: Evaluating and documenting the technical capabilities, advantages, and limitations of the technology through literature analysis and hand-on evaluation of the representative AR technologies

Deliverable: An evaluation summary

Task 4: Developing a taxonomy of use cases of AR technologies in transportation infrastructure management; the taxonomy shall describe the type of required data integration and computing complexity for each type of use cases

Deliverable: A technical note

Task 5: Evaluating the feasibility of the above AR technologies in supporting a selected set of use cases in transportation infrastructure management. The evaluation will focus on data requirement, computing needs, and real-time performance

Deliverable: A technical report

Task 6: Conducting additional development on the most promising platform to explore the deep integration of AR technologies with project data in supporting real-time interactive computing and simulation in AR environment

Deliverable: New AR use applications

Task 7: Conducting demonstration sessions with stakeholders to evaluate project products and findings.

Deliverable: A technical note to summarize findings from demonstration

Task 8: Summarizing project findings in a final report and a TRB publication

Deliverable: A final report summarizing the project and a TRB paper summarizing the project findings

FINDINGS

Our findings are organized around the key questions and concepts:

(1) How available AR/VR technologies can be leveraged to improve the transportation infrastructure management practices? How to reap the benefits of AR/VR technologies, especially in assisting project managers and engineers with the delivery and accuracy of their construction projects, safer and in a timely manner resulting in greater efficiency?

(2) New software applications that are built for advanced infrastructure management applications. How these applications enable the integration of real-time information with virtual content in tasks such as infrastructure inspection and facility management?

(3) New AR/VR prototypes that can clearly show transportation stakeholders the benefit of AR/VR.

(4) New AR/VR-based training modules to support workforce training in a virtual reality environment to maximize training effectiveness while minimize training cost.

Task 1: A web-based kickoff meeting with customers and the research team

Throughout the project, the research team conducted many onsite meetings with stakeholders to develop a collaborative research effort. We have met with stakeholders from Port Authority of New York and New Jersey, New Jersey Board of Public Utilities, highway construction unions, private industries on a number of occasions during the project. The kickoff meeting was the initiating effort to these follow-on meetings.

Task 2: Reviewing available AR technologies with a focus on their technical specs and acquiring and assembling representative AR technologies

Available VR, AR, MR, XR technologies: Before reviewing these technologies, there is a need to make clear the definition and nature of them. The definitions from various sources have been reviewed and compiled. The Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) are emerging technologies utilizing a variety of digital immersion overlays contents on the real world, or even replace the real world, creating a digital world that users can interact with.(Noble 2018)

Virtual Reality (VR) usually establishes immersive experiences and presents digital contents via a VR head mounted display. In this virtual reality, all contents are generated by computer. The user is immersed in virtual world and isolated from the real world, because the real world environment is replaced with a new 3D digital environment.

Augmented reality (AR) overlays computer-generated content on top of the real world. This superimposed digital overlay can superficially interact with the environment in real time. AR is primarily experienced via a wearable glass device that equipped with transparent display or through smartphone apps that combines camera captured real time background image with the AR application's own digital content.

Mixed reality (MR) combines several technologies into one wearable device. MR lenses or headsets present an overlay of digital content that interacts with objects in the real world in real time. The products are, in most cases, in research and development phase.(Noble 2018) But since MR is viewed through transparent wearable glasses, it is more closely related to AR than VR. Also, tech companies tend to use their own definition, making it more prone to confusion.

Extended Reality (XR) is a newly added term to the dictionary of the technical words. Extended Reality refers to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearable devices. Extended Reality includes all its descriptive forms like the Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). In other words, XR can be defined as an umbrella, which brings all three Realities (AR, VR, MR) together under one term.(Northof41 2018)

As mentioned above, there are many sources of VR/AR/MR definitions, even the different definitions are similar, and it is still a challenge for the less tech savvy general public to understand. Lots of companies define their content, including 360 videos, as "Virtual Reality", leading to more public confusion. In order to fill this definition gap, the Consumer Technology Association (CTA), a division of the company that produces CES (Consumer Electronics Show), stepped in. (Fink 2016) CTA's AR/VR Working Group finalized a set of industry definitions to help companies better explain to consumers the spectrum of experiences their technologies deliver, CTA's shorter definitions are:

"Virtual Reality" (VR) creates a digital environment that replaces the user's real-world environment.

"Augmented Reality" (AR) overlays digitally-created content into the user's real-world environment.

"Mixed Reality" (MR) is an experience that seamlessly blends the user's real-world environment and digitally-created content, where both environments can coexist and interact with each other.

"360° Video" or "360 Video" allows the user to look in every direction around him/her.

"Immersive Experience" is a deeply-engaging, multisensory, digital experience, which can be delivered using VR, AR, 360° video, MR and/or other technologies.

With the help of these definitions, the current available and upcoming VR/AR devices can then be classified and compared for us to understand the current technological level.

Review of current available and upcoming VR/AR devices

Generally speaking, nowadays, virtual reality is a concept understood by most people. VR has been heard by public for decades. And now, it has managed to find its place in popular culture, especially the gaming industry. But, it isn't quite the case for augmented reality or mixed reality.

AR has not managed to get the same level of public awareness, even though many people already use it every day. And MR is even further behind, and to make things worse, it is generally equated to AR by many, even within the industry. There is room for much debate in this conversation but simply put, one could say MR is AR 2.0.(Lodola 2018)

In order to simplify the classification of devices, despite some companies' naming convention call their product MR devices, devices in this study are divided into two general categories: VR and AR. Almost all current VR/AR devices investigated in this study are in the form of glasses, goggles or helmets, so they can provided user visual and acoustic information through their built-in display and headphone. The main criteria for distinguishing the two categories are whether a headset is equipped with transparent screen, so the user can see the real world image through the display.

VR types

If an immersive experience device doesn't have transparent screen, all visual content the user can see come from the onboard display, then this is a VR device. There are many kinds of VR devices are available to deliver virtual reality experiences to user. Some device require a tethered connection to a computer or game console, some are fully standalone with onboard computing capability, and others use a smartphone as both display and computing device. (Cherdo 2018) So, the three VR device types discussed here are: Tethered VR, Standalone VR, and Smartphone VR.

Tethered VR: Tethered VR means that the headset is physically connected to a computer by cables, such as HDMI, DisplayPort, USB and power. The headset itself basically only serve as display and tracking device. They usually don't carry their own power, and additional base station (motion tracker) may be needed. Currently, tethered VR headsets can deliver high-quality experience, they are much more immersive than other types of VR. But, these systems require certain amount of setup space as well as constant cable connection to a powerful gaming PC or console. Some manufacturers are trying to create PC VR headsets that use onboard PC, but mobile computing typically means sacrifice in tracking accuracy capability and graphics quality. Also, there other creative solutions, such as HP Z VR Backpack PC, a computer that can be put on the back of the user, making a tethered VR headset system "almost wireless". This kind of design combine the best of both worlds: mobility and high quality computing power.

Standalone VR: Standalone VR means the VR headsets have onboard processors, memory, displays, sensors, and battery, so they don't require constant connections to computer or smartphone, so users also called them all-in-one VR headsets. Since standalone VR are wireless, users don't have to limit themselves to certain play area, enable them to move freely. But there is a downside, standalone VR headsets are much less powerful than those tethered VR headsets. They usually offer lower-quality graphics and lower screen refresh rates. Currently, tech companies seem to be putting similar amount of efforts into developing tethered VR and standalone VR. They are trying to make tethered devices wireless or make standalone devices more powerful, maybe similar results can be achieved by taking different routes

Figure 1 Tethered VR.

Smartphone VR: Smartphone VR, as indicated by their name, use smartphones as the core devices to provide the VR experience. One of the simplest smartphone VR examples is Google Cardboard, named for its fold-out cardboard viewer. The Cardboard is made of a piece of cardboard pre-cut into a precise shape, combined with lenses, magnets or capacitive tape, a hook and loop fastener, a rubber band, and an optional near field communication (NFC) tag. Once assembled, a compatible smartphone is inserted in the back of the device, when running the VR application installed on the phone, it will split the smartphone display image into two, one for each eye. VR apps will also apply barrel distortion to each image to counter the pincushion distortion that caused by the lenses. The quality of the VR experience indeed depends on the smartphone being used, varying factors include the type of screen, screen resolution and its refreshing rate. It is better to use recently released smartphones, which tend to be the most powerful. So, smartphone VR devices can be viewed as a low-cost system to encourage users' interests and inspire development in VR applications, but they are not suitable for heavy gaming or industrial purposes.

Figure 2 Smartphone VR

After sorting out the VR device types. 21 current and upcoming VR devices' information were collected and compared. Their technical specifications details are analyzed and will be discussed in subsequent sections.

AR types

Similar to VR devices, AR devices also comes in several types, if an immersive experience device have transparent screen, or having other way to show real surroundings, visual content the user can see come from both onboard display and background environment, then it is an AR device. Some AR devices may require a tethered connection to another computing device, some are fully standalone with onboard computing capability, and some are as simple as a smartphone app. So, in this study, AR devices are broadly divided into three categories. There are Tethered AR, Standalone AR, and for the smartphone with AR apps, to some extent, they can also be considered as Smartphone AR.

Tethered AR: AR devices, like "DreamWorld DreamGlass", "Epson Moverio BT-300", "Meta 2", are some examples of tethered AR headsets. In order to use them, they need to be powered by other device like PC, tablet or smartphone, thus wired connections are needed. Among these tethered AR device, some of them may mainly serve some specific purposes, like the Epson Moverio BT-300, is primarily designed to be used with drones. There are also some so called smart glasses products on the market specifically designed for bicycle riders, but due to their extremely limited range of applications, these smart glasses should not be considered as AR headsets here. Tethered AR devices are usually priced below 1 thousand dollars, cheaper than standalone AR devices.

Standalone AR: Just like standalone VR devices, standalone AR devices also have their full suite of onboard power and computing components. A typical example of standalone AR is Microsoft HoloLens, now the company – Microsoft also announced HoloLens 2, an upgraded version, with better processor, display, and added eye tracking capability. Another example, the Magic Leap One, is the Microsoft HoloLens' main competitor, also comes with eye tracking. Magic Leap One's appearance may confuse some consumers, because tis headset is connected to some waist-mounted box through wire, people may consider it as a tethered AR. But since the Magic Leap One still don't require external devices, this headset with distributed computing unit are still part of the device itself, no outside components are used, and all system components are mounted on the user. So it should still be considered as standalone AR. These standalone AR devices are relatively expensive, prices range from 1 to 3 thousand dollars.

Figure 3 Tethered AR

Figure 4 Standalone AR

Smartphone AR: The smartphone AR usually are just smartphone with AR apps, to some extent, they can also be considered as Smartphone AR devices. Their specs like screen resolution, field of view, refresh rate, all depend on the smartphone. Some popular smartphone AR app examples are: “SKETCHAR”, “MONDLY”, “POKÉMON GO”, “WALLAME”, and “GOOGLE TRANSLATE”. Smartphone AR can be very useful in mobile gaming, navigation, and other applications.

Figure 5 Smartphone AR

In this study, eleven current and upcoming AR devices’ information were collected and compared. Their technical specifications details are analyzed and will be discussed in subsequent sections.

After classification and evaluation of current VR/AR systems, based on their specification and their companies’ back ground, the HTC Vive and Microsoft HoloLens are selected for this project. The detailed explanation and comparison of all candidate VR/AR systems are shown in next section.

Task 3: Evaluating and documenting the technical capabilities, advantages, and limitations of the technology through literature analysis and hand-on evaluation of the representative AR technologies

In last section, HTC Vive and Microsoft HoloLens were selected as the best candidates based on their overall technical specification and their company background. In this part, more detailed comparison and evaluation are shown to compare these devices. The technical capabilities, advantages, and limitations of the representative technologies were evaluated and documented through literature analysis and hand-on evaluation. All these specs are collected from various internet sources, most of them come from manufacturer’s website. But since some manufacturers do not share their products’ full technical details, some user forum website posts and news website reports are also used as reference.

VR device evaluation

There are 21 candidate VR devices in this review, they are made by both old established companies and start-up companies. All of them are released in the last five years, and most of them are even just released in the last two years. Since vision is the most important human sense in VR/AR experience, this comparison mainly focused on the display of these headsets. Generally, with higher screen resolution, bigger field of view, and higher refreshing rate, users can have better immersive experience, so the comparison is mainly focused on these specs. Eye tracking is a new trend in VR, it can add more flexible and expansive features to VR systems, so it is also got our attention.

Table 1 Comparison of VR devices

Device Name	Release Year	Screen Resolution Per eye	Wireless	Field of view	Refresh rate	Eye tracking	Price $	Device Type
HTC Vive Pro Eye	2019	1440 × 1600	No	110	90Hz	Yes	NA	Tethered VR
ASUS HC102	2018	1440 × 1440	No	95	90Hz	No	429	Tethered VR
HTC Vive Pro	2018	1440 × 1600	No	110	90Hz	No	1399	Tethered VR
Pimax 5K Plus	2018	2560 × 1440	No	200	90Hz	Yes	699	Tethered VR
Pimax 8K	2018	3840 × 2160	No	200	80Hz	Yes	899	Tethered VR
Acer AH101	2017	1400 × 1400	No	100	90Hz	No	399	Tethered VR
Dell Visor	2017	1440 × 1440	No	110	90Hz	No	449	Tethered VR
FOVE 0	2017	1280 × 1440	No	100	70Hz	Yes	599	Tethered VR

Samsung Odyssey	2017	1440 × 1600	No	110	90Hz	No	499	Tethered VR
HTC Vive	2016	1080 × 1200	No	110	90Hz	No	499	Tethered VR
Oculus Rift	2016	1080 × 1200	No	110	90Hz	No	399	Tethered VR
OSVR HDK2	2016	1080 × 1200	No	110	90Hz	No	399	Tethered VR
Sony Play Station VR	2016	960 × 1080	No	100	120Hz	No	399	Tethered VR
Pico G2 4K	2019	1920 × 2160	Yes	101	75Hz	No	NA	Standalone VR
HTC Vive Focus	2018	1440 × 1600	Yes	110	75Hz	No	650	Standalone VR
Lenovo Mirage Solo	2018	1280 × 1440	Yes	110	75Hz	No	399	Standalone VR
Oculus Quest	2018	1600 × 1440	Yes	101	72Hz	No	NA	Standalone VR
Pico G2	2018	1440 × 1600	Yes	101	90Hz	No	NA	Standalone VR
Oculus Go	2017	1280 × 1440	Yes	101	72Hz	No	199	Standalone VR
Google Daydream View 2	2017	Depends on phone	Yes	100	Various	No	99	Smartphone VR
Samsung Gear VR	2015	Depends on phone	Yes	101	Various	No	119	Smartphone VR

Discussion of Specs

Degrees of freedom (DoF) is one of the important VR specifications. DoF is the number of movement types that the user may experience. In VR, headsets offer either 3DoF (360° tracking) or 6DoF (positional tracking).(Noble 2018) In the investigated VR devices, all the tethered VR headsets have 6DoF, half of the standalone VR headsets have 6DoF. And for the rest, including the other half of standalone VR headsets and all smartphone VR headsets, only have 3DoF. For the VR devices with only 3DoF, it can only be played in fixed location mode, making it harder for user to have good virtual experience. For those with 6DoF, they can enable the user to move freely in certain area, but they can also be played in fixed location mode, if room size is a constraint. So 6DoF should be an essential requirement for a capable VR device.

Field of view (FoV) is another important technical parameter. FoV is the extent of the observable world that is seen by user at any given moment. In the context of human vision, the term "field of view" is typically only used in the sense of a restriction to what is visible by external apparatus, like when wearing VR headsets. The wider the field of view, the better immersive experience it can provide. For reference, the human field of view (with eye rotation) can reach to a maximum of 220 degrees. (Noble 2018). Most VR headsets can provide around 100 degrees, when using them, there will be some black areas around user’s view. So the VR deceives with smaller FoV will give the user the feeling that they are observing the surrounding world in from a small window. But bigger FoV also means bigger screen, more pixels, requiring more computing power, and eventually more cost. So manufacturers need to find a balance between the level of immersive experience, hardware complexity and the manufacturing cost. It’s worth noting that, some latest models, like Pimax 5k and 8k, have FoV of 200 degrees, that’s approaching the limit of human eyes. From users actually experience, the device with 100 degrees or higher FoV is good enough for normal applications.

Eye tracking is the new trend in VR devices, some latest devices come with eye tracking ability. Although, the technology itself is not very sophisticated, cameras that facing user eyes are often used to track the user’s gaze. In VR, users usually only have limited selection of input methods, for example, most the hand held controllers that come with the device cannot function as complex as a keyboard. In this case, the eye tracking can become a more convenient input method. In addition to the input method, eye tracking has another function called foveated rendering. It is an upcoming graphics-rendering technique which uses an eye tracker integrated with a virtual reality headset to reduce the rendering workload by greatly reducing the image quality in the peripheral vision (outside of the zone gazed by the fovea). By tracking the user's eye gaze, the VR device only need to render better sharpness and detail to the specific portion of the display that the user is looking at. This foveated rendering can both improve the performance of the VR device and save the computer's computing power. More importantly, the eye gaze data collected by the VR device's eye-tracker, which recorded users' eye attention history, can also be used in wide range of applications, for example: Attentional neuroscience, Scene perception, Aviation, Print advertising. (Duchowski 2002)Adding eye tracking function to VR devices can significantly expand the application range.

Refresh rate and screen resolution are often used together to evaluate the quality of a display. Generally speaking, 60Hz is the minimum for a good quality, solid experience from a monitor. All these VR devices have a higher refresh rate than 60Hz. For gaming and other visual effect focused purposes, then the higher the refresh rate, the better. Monitor refresh rates now go up to a whopping 240Hz, so, when compared with computer monitors, all the display refresh rate on these VR devices seem to be at the lower end of refresh rate scale. For screen resolution, all these deceives seem to be up-to-date, because they often use the same screen technologies with the smartphones, like the LCD, OLED, AMOLED. When a smaller screen have same resolution with a regular computer monitor, the pixels per inch (PPI) become the key indicator. PPI measures of the pixel density (resolution) of an electronic image device, such as a computer monitor or television display, or image digitizing device such as a camera or image scanner. The PPI of these VR headsets range from 300s to 800s. As a comparison, the PPI of a normal laptop display is about 200. It's safe to say all these VR devices have relatively good display. Basically, the display of most VR device have higher resolution and lower refresh rate than a normal computer monitor.

Base on the comparison of available VR systems. An ideal VR system should contain a powerful computer, a tethered VR headset with high resolution, refresh rate, FoV and 6DoF. And it would be better if it's also equipped with eye tracking. Consumer grade VR headsets are in the price range from a few hundred to two thousand dollars, if there are certain limits in the budget, the price need to be take into consideration.

AR device evaluation

There are 11 candidate AR devices in this review. All of them are released in the last three years, comparison is mainly focused on screen related specs. Among the most recent devices, eye tracking is also been added. As mentioned in VR part comparison, this function can be very useful in controlling the device and recording additional data.

Table 2 Comparison of AR devices

Device Name	Release Year	Screen Resolution	Wireless	Field of view	Refresh rate	Eye tracking	Price $	Device Type
DreamWorld DreamGlass	2018	Each eye 1280 × 880	No	90	60Hz	Yes	619	Tethered AR
Epson Moverio BT-300	2016	Each eye 1280 × 720	No	23	30Hz	No	699	Tethered AR
Meta 2	2017	Each eye 1280 × 1440	No	90	60Hz	No	949	Tethered AR
Microsoft HoloLens	2016	Each eye 1268 × 720	Yes	35	60Hz	No	3000	Standalone AR
Microsoft HoloLens 2	2019	Each eye 2048 × 1080	Yes	43	60Hz	Yes	3500	Standalone AR
Magic Leap One	2018	Each eye 1280 × 960	Yes	50	60Hz	Yes	2295	Standalone AR
Google Glass Enterprise Edition	2018	One screen 640x360	Yes	13	NA	No	1500	Standalone AR
Vuzix Blade	2018	NA	Yes	NA	NA	No	999	Standalone AR
Optinvent Ora-2	2018	NA	Yes	NA	NA	No	699	Standalone AR
ODG R-7	2017	Each eye 1280 × 720	Yes	30	80Hz	No	2750	Standalone AR
Smartphone with AR apps	NA	Depends on phone	Yes	Depends on phone	Various	NA	NA	Smartphone AR

Discussion of Specs

Display quality is equally important for VR and VR, but due to the inherent limitation of the transparent or projection screen, the screen resolution, refresh rate and FoV of AR devices are generally not as good as VR devices. The screen refreshing rates of these AR devices are also significantly lower than their VR counterparts. Among all these devices, the Google Glass have the longest history, its first generation can be traced back to early 2013. But after an initial burst of media glory, its popularity stalled. It was announced that the second generation, would be released in the US. But when it comes back, the consumer market has been occupied by various devices from various manufacturers. So the second generation is now the Google Glass Enterprise Edition, they are prepared for companies such as Boeing. Even now, the Google Glass' 640x360 projection display is one of the smallest in all AR devices. AR devices like DreamWorld DreamGlass and Epson Moverio BT-300, have drawbacks of tethered style and limited use cases. Other devices from less well known companies also suffer from the problems like headsets' bulkiness makes them uncomfortable to wear for extended stretches of time. Some user commented that currently there just aren't enough apps for users to justify keeping these devices on their heads.(PROSPERO 2019) It is very difficult to even find some online discussion of them due to their extremely small user population.

After examining all these devices' feature and specifications, the Microsoft HoloLens and Magic Leap One seem to be the more promising products. Especially the HoloLens, it features higher screen resolution, larger FoV and newly added eye tracking. When combined with its latest computing hardware, it can be a powerful AR device. Also due to its company background and its predecessor's reputation, the HoloLens can have a larger developer base and longer update support.

Base on the comparison of available and upcoming VR/AR systems. HTC Vive and Microsoft HoloLens should be selected for this project. In addition to these two companies' VR/AR history and reputation, these two devices also have large online community support, making it easier to develop applications on them.

Hand-on evaluation

HTC Vive

The HTC Vive is a tethered VR system, the main components consist of one head mounted display, two tracking base stations and two hand controllers. This is a typical setup of a HTC vive system, the user stand in the center of the play area, the headset and hand controllers are tracked by the wall mounted base station. The user is immersed in the virtual environmental presented by the cable connected display image and earphone audio. The image is also displayed on the computer screen for other people to see.

Figure 6 Hands-on evaluation of HTC Vive

Steam is a video game digital distribution platform developed by Valve Corporation. On the Steam platform, there are many popular VR games supported by HTC Vive, making the HTC Vive also very popular among game developers. The developers can use Unity game engine to design and build their own applications. For this study, our VR application will also be developed using the Unity game engine. Although HTC Vive is a tethered system, when it combined with a backpacked computer system, the user can still play the VR games and apps wirelessly.

As shown in the photo above, the user can put the whole computer system and VR device on the back, when properly configured, the system can provide very comfortable untethered user experience.

Microsoft HoloLens

HoloLens is developed and manufactured by Microsoft. It is a standalone AR headset that carries all its display, sensing, computing, power and storage units. By Microsoft Company's definition, it is the first head-mounted display running the Windows Mixed Reality platform under the Windows 10 computer operating system.

Since it is a standalone device, there are no peripheral equipment like tracking base stations or handheld controllers, the tracking technology used in HoloLens can trace its lineage to Kinect, the Xbox gaming console add-on device. The HoloLens have onboard accelerometer, gyroscope, and magnetometer, which work together as an inertial measurement unit (IMU). The IMU, also work in combination with other sensors like image camera, video camera, depth camera, ambient light sensor and microphone array to locate and keep track of user's head movement. In additions to normal computers' CPU, the HoloLens features a custom-made Holographic Processing Unit (HPU), a coprocessor manufactured specifically for the HoloLens by Microsoft. The HoloLens contains 2 GB of RAM and 64GB of internal storage, the internal rechargeable battery, with average life rated at 2–3 hours of active use, or 2 weeks of standby time. The HoloLens can be operated while charging. The display of HoloLens, a transparent display with a 35 degree diagonal field of view (16:9), might be its weakest part. As can be seen in previous device comparison sections, most of the VR devices' display boast of more than 100 degree diagonal field of view, which cover most of the user's visual area. But HoloLens display area is very small, the user sometimes need to move and turn around to find the right position to see, like look out of a room through a small window. As for the computing power, although the HoloLens is a pioneer in this standalone AR field, the hardware still greatly limited its application and performance. This shortcoming can be seen when running relatively large programs.

Figure 7 Hands-on evaluation of Hololens

The HoloLens is a head-mounted display unit connected to an adjustable headband. When putting on the device, the user need to loosen the headband, fits the HoloLens on their head, then use adjustment wheel on the back to tighten the band to attach it to the head. There are some room for position adjustment between the headband and the device, after securing the headband, the user can manually which can tilt and move HoloLens' position and orientation to fit the head and eyes. When it comes to the input methods, also because of the special nature of the standalone device, HoloLens mainly uses sensual and natural input methods. The methods include eye gaze, hand gesture, and user voice commands. Gaze commands, such as head-tracking, allows the user to bring application focus to the center of user's view. Just like clicking a computer mouse button in the air, the virtual buttons in the AR apps are selected using an air tap hand gesture. The tap can be held for a drag simulation to move an element, as well as voice commands for certain commands and actions.

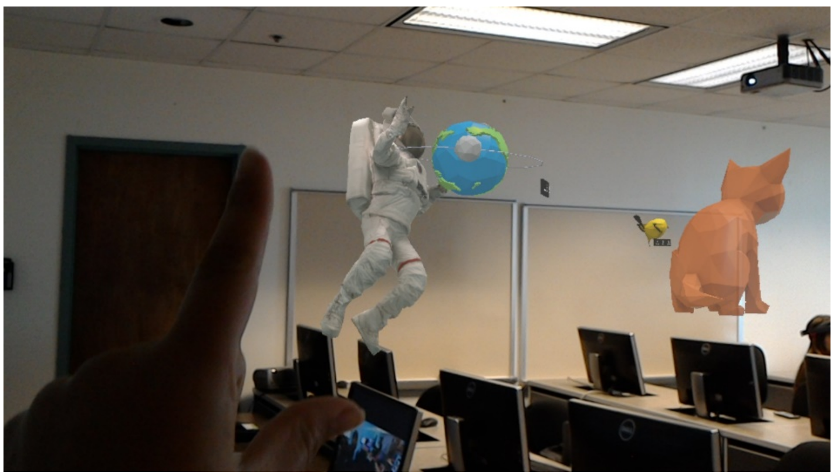

Figure 8 Superimpose of virtual objects onto real scene

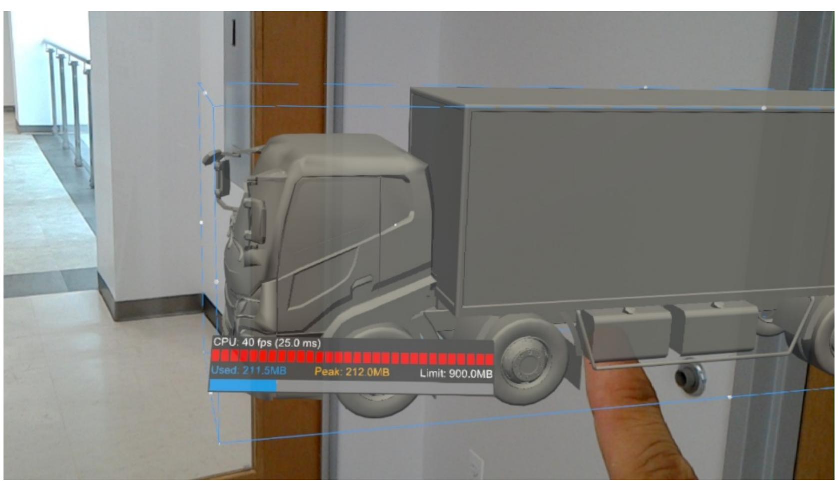

Figure 9 Object interaction through gestures

In the evaluation of the HoloLens AR system, we also have developed AR program to demonstrate the potential of the device. The program we build is a real building of Rutgers University, it is the Class of 1914 Boathouse. The building is located on the Raritan River, which separates the campuses of Cook, Douglass, and Rutgers College in New Brunswick from those of Livingston and Busch in Piscataway. The boathouse was built in 1950 and is a gift of the Class of 1914. An addition was added in 1961 and today is it houses over 20 boats.

Figure 10 Rutgers Boathouse

We used the scan-model-simulation workflow to develop this AR module. In this module, the hologram of the boathouse model is presented. The user can observe the building from various angel which is hard to achieve in real life. This can be very useful in the conceptual design of the building, if there are any new plan to make change to the original building. The designer and make the changes in hologram and present it to others. This display method makes it easier for various stakeholders to find design errors. Construction and maintenance personnel can also benefit from this program for its vivid display of model.

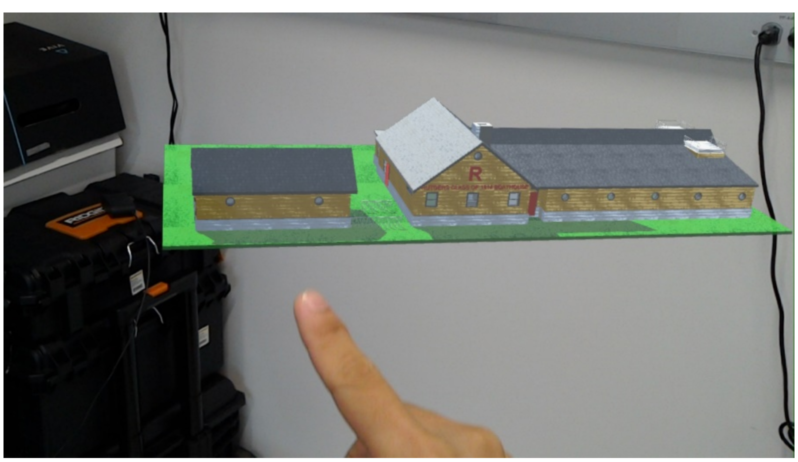

Figure 11 Hologram of the boat house

Base on the evaluation of those two previously mentioned VR and AR systems, we believe VR/AR based training is the future for transportation workforce. This project will serve as a testimony to this vision. With the increasingly available head mount VR/AR headsets which can conveniently provide immersive visualization environments, the training modules such as those developed in this project can bring a variety of benefits:

(1) It will reduce the training cost for transportation workforce while improving training effectiveness (some of stakeholders have already shared that these training modules can save the time and cost to send their workers to remote sites for training);

(2) It can reduce the mistake in marking out underground facilities such that it can reduce the environment impacts caused by leaking gas;

(3) It can foster a safe working environment which will in return reduce transportation related fatalities.

Task 4: Developing a taxonomy of use cases of AR technologies in transportation infrastructure management;

More recently, VR/AR technologies have been used extensively in various engineering activities. This research activity is to summarize the various types of use cases in transportation. During the research, it was noted that there were similarities in six distinct categories of the published works and a more detailed analysis of these papers is given later in this paper under each section of reviewed literature. In addition to the implementation method and application purpose, the taxonomy mainly focused on the required data integration and computing complexity to evaluate each use case. The research cases category covers building, infrastructure or other civil engineering areas, which in themselves may be theoretical, practical or technical. Classified according to the content or influence in transportation infrastructure management, these six categories are as follows:

1. Construction progress tracking and visualization
2. Construction simulation
3. Construction inspection
4. Training Purpose
5. Safety Improvement
6. Facility management

In the following, we illustrate various use cases in each of the above categories.

Construction progress tracking and visualization: In a BIM+AR integration study, Wang, Truijens et al. demonstrate how AR can be effectively used together with BIM to improve the way the information is accessed, and improve productivity in the application of liquefied natural gas industry construction. (Wang, Truijens et al. 2014) Their BIM + AR systems are capable of identifying the interdependence, as well as the complexity of tasks derived from different roles that mainly focus on their individual tasks in the current construction practice. BIM + AR systems can also make the interdependencies between work tasks more explicit, making the existing interdependency and complexity more visible and manageable. The systems integrating AR with BIM provided an immersive view combined with the real environments, where the participants stay, visualize the as planned model onto the as built environment simultaneously. The system required data integration included paper drawings and BIM models, the linking part uses some barcode. Computing complexity included model visualization and sequence simulation. Using AR-based animation, installation sequence can be seen in the real scale and right in the real context as well. This can streamline the construction progress by providing the workers with location, angle, orientation, dimension, shape, geometry, materials, texture, assembly sequence, assembly path, assembly safety instructions.

In an unmanned aerial vehicles imagery based construction AR applications study, Zollmann, Stefanie, et al. describe how to use AR to support monitoring and documentation of construction site progress.(Zollmann, Hoppe et al. 2014) Construction progress monitoring usually requires fast and comprehensible access to progress information to enable comparison to the as-built status as well as to as planned data. Instead of tediously searching and mapping related information to the actual construction site environment, the AR system combining aerial vision with a mobile AR interface and thus allows relevant information to be accessed directly on construction site. This is achieved by superimposing progress as well as as-planned information onto the user's view of the physical environment. Data integration of this study mainly use 3D reconstruction model from aerial imagery, and BIM models. Computing complexity mainly included 3D reconstruction of the as-built model and visualization of the BIM model. For the registration purpose, they implemented different techniques that either use additional sensors, such as GPS and IMU, or are purely vision based. Having the data and the registration available, the progress information for documentation and monitoring are visualized on site.

Construction simulation: VR/AR simulation have been used in both building construction and bridge construction. Visual simulation has emerged as a key planning tool for an intended built environment because it enables architects, engineers and project managers to visualize the evolution of a construction process before a project starts. In a construction operation simulation study, authors use VR/AR operational visualization and simulation to enable efficient construction, reducing time and cost through planning and controlling resources, machines and materials.(Rohani, Fan et al. 2014) Construction industry has evolved from traditional on-site building to offsite modern methods of construction. Highly efficient and effective onsite planning and management processes are urgently needed. And this require implementing visual techniques to provide a powerful management platform for planning and controlling projects. 4D-CAD data has been integrated for simulation of construction operation, superimposed to video taken by fix tablets. AR scenes of project process can be introduced in planning stage to implement decision making for various built environments required. Computing complexity mainly included visual presentation of building model at different stage for the construction process simulation. The VR/AR simulation can enable higher degree of air-tightness in buildings necessary for energy-efficient passive homes and would minimize waste generation, thus contributing to a sustainable development.

In civil engineering, VR visualization and simulation are emerging topics that not only relate to the buildings, but can also be applied to other forms of construction, including bridges. The bridge construction process involves multiple complex equipment and plant, virtual reality technology can benefit the all parties of construction practice. In a bridge construction simulation study, authors described the relationship between temporary building platforms, equipment and the proposed bridge model during the planning phase. And they use Virtual Prototyping Simulation (VPS) to simulate different construction scenarios to help planners in finding the optimal construction plan. (Li, Chan et al. 2012). A case study demonstrated the use of VPS integrated different combination of temporary platform design and plant and equipment-resource. VPS in the construction process is to assist project planners to better understand the relationships among temporary platforms, plant and equipment resources and proposed-built models in construction planning. Data integration contains building the virtual model of terrain contours, existing viaduct and proposed widening of viaduct structures. The research team used topographical survey data of the project site and terrain contours and details of the existing structure to build the 3D model. The proposed widening of the viaduct structure was modeled from the 2D drawings. The computing complexity is collision analysis to detect and highlight any potential collisions between the construction plant and equipment and the virtual environment in the simulation and between the activities of construction plant and equipment respectively.

Construction inspection: VR/AR base inspection methods have been applied in bridge and tunnel constructions. Recent research has revealed that the nondestructive evaluation technique used most often to assess the physical condition of a bridge is visual inspection. The observations and measurements information that made during a routine visual inspection, are recorded by means of field sketches, written descriptions, and site photographs. This information is ultimately entered into a bridge management system where it is maintained and used to make decisions regarding future maintenance, rehabilitation, or replacement of the bridge. (Jáuregui, White et al. 2005) Recognizing the importance of such documentation, the study reports on the use of QuickTime Virtual Reality (QTVR) for recording and managing information normally collected during a routine inspection. With QTVR system, bridge inspection projects can be documented in an interactive, virtual reality format and supplement customary inspection reports. The data integration included creating and rendering panoramic images into a virtual environment. The five basic steps in the QTVR development process were: planning of site visit and photographs, taking of photographs, creation of panoramic images, 4 movie creation incorporating hot spots, and management of QTVR files. The computing complexity concluded that the QTVR technology has the potential to supplement existing methods for bridge inspection data recording.

For tunnel construction, (Zhou, Luo et al. 2017) discusses the feasibility of using AR to rapidly inspect segment displacement during construction of tunnel. Their AR technology allow on-site quality inspectors to retrieve the virtual quality control baseline model established according to the quality standard, and overlay it model onto the real tunnel segment displacement in AR. Therefore, the structural safety can be automatically evaluated by measuring the differences between the baseline model and the real construction site view. The benefits of the inspection using a prototype AR system over a conventional method have been evaluated in the case study. The result shows that all inspections and analyses can be conducted on-site, in real-time, and at a very low cost. The data integration included live onsite scene captured by video camera, and the global coordinate and virtual camera coordinate acquired by tracking device. A virtual baseline model (3D CAD drawing) was superimposed over an onsite image in real time, and then, the combined scenes were presented to the end users by a display. The computing complexity is that the AR can be applied in on-site inspections more practically and effectively.

Training Purpose: VR/AR have been used for training purposes in both building and transportation construction projects. The virtual training applications range from small scaffolding to big cranes. Cranes are usually involved in the transporting equipment and material on construction job site. In order to improve the efficiency of the construction process, a smooth crane movement plan is needed. This planning is of great importance, especially in transportation related projects, as space and time are greatly limited by the heavy traffic on the highway. The moving time and moving distance of a crane from the equipment storage area to the workspace need to be minimized. To explore the use of construction simulation in facilitating people's understanding of construction processes, searchers(Mastli and Zhang 2017) presented a crane movement simulation from the site equipment storage area near the highway to the beam erection location on a highway construction site. This VR simulation was modeled in the Unity 3D game engine and visualized in a projection based VR environment. The VR use projectors to show different view of the 3D scene on different walls of a space, providing the users with immersive experience. The data integration included the modelling of 3D job site from 2D plans. The computing complexity is the VR simulation can help people to plan crane routes before the actual moving of equipment, so they can minimize crane movement distance and movement time in the planning phase to minimize interruptions to the road traffic, reduce construction costs, and making the construction operations more sustainable.

BIM facilitates information sharing between architecture, engineering, and construction (AEC) professionals via purpose-built 3D model, 4D design, analysis, evaluation, and simulation. But due to the fact that the remote collaboration in civil engineering like offshore outsourcing are growing continuously, the communication of such 3D data-rich models are often fragmented and typically limits real time communication and interaction because of users are geographically dispersed, or the users lack the modeling and analyses skills to interact with these models. In order to deal with these emerging practice changes, AEC education needs to find new ways. In their search,(Ku and Mahabaleshwarkar 2011)used the Second Life game platform as the virtual reality environment to help users to address the communication issues and complement traditional teaching. And they take the further step to integrate VR with BIM to enhance construction education. One of the existing obstacles is the data integration requires the workflow from BIM to VR. Another challenge is adding the interactive par, which is Building interactive Modeling (BiM) . The VR training system demonstrate the concept of BiM which complements the capabilities of BIM with social interaction to enhance collaborative information and knowledge sharing. And computing complexity is the role-playing scenarios can be used for different training purpose like scaffolding and crane operation.

Safety Improvement: Safety is a critical issue for the highway construction industry. There are literature argues that human error contributes to more than half of occupational incidents and could be directly impacted by effective training programs. In their research, (Zhao and Lucas 2015) reviewed the current safety training status in the US construction industry and identified the gap between the status and industry expectation on safety. They demonstrated the development and utilization of a training program that is based on VR simulation to narrow the gap. The data integration of the VR simulation included 3D modelling and simulation. The modelling process includes two separate parts: the 3D object modelling and 3D environment modelling. The 3D objects include buildings, machines, equipment, tools, materials, electrical components, background settings, and worker actors. Most of these models, such as a mobile crane and electricity transmission tower, were created using Autodesk's 3ds Max. 3D environment modelling includes designs of area terrain, sky clouds, sun point, wind, rain, light layout, landscape, as well as relative sounds. This modelling process was implemented in Garage Games' Torque 3D engine v2.0. The computing complexity, which is the simulation part, included safety scenarios from electricity basics, working around electricity, working with electricity, and safe emergency response procedures. In the virtual safety training environment, users can effectively rehearse tasks with electrical hazards and ultimately promote their abilities for electrical hazard cognition and intervention. Its visualization and simulation can also remove the training barriers caused by electricity's features of invisibility and dangerousness.

Safety education is important in promoting a safe and healthy working environment in construction. The construction industry is a complicated environment where high accident rates are still encountered. In order to provide students with realistic and practical safety training experiences, framework for using mobile based VR and AR for experiential construction safety education was established.(Le, Pedro et al. 2015). Researchers proposed framework consists of three modules: Safety Knowledge Dissemination, Safety Knowledge Reflection, and Safety Knowledge Assessment. The prototype was developed and evaluated with different scenarios to identify the system's benefits and limitations derived from real accident cases and safety regulations was developed. The data integration included Revit and Blender model data. The Xcode, iOS Software Development Kit, and MySQLSever were used to develop and manage the mobile application and link with database respectively. For the computing complexity, the scenarios included accident types of fall into elevator opening, fall from height to below, fall from stair, fall into stair opening, and fall from scaffold to below. The results concluded that using mobile based VR+AR would improve construction safety & health effectively.

The ability of construction workers to identify and assess onsite risks is acquired through safety training is among the key factors that affect their onsite behavior and determine their safety condition. In a research, (Sacks, Perlman et al. 2013) tested the VR construction site safety training and compared to conventional safety training method in feasibility and effectiveness. The researchers focused on workers' learning and recall ability of safety risks, and compared the VR training to the conventional method equivalent. The research participants were provided with construction safety training, and their knowledge ability were tested three times to evaluate the quality of VR training methods. The VR system is a 3D immersive VR power-wall, it is a three-sided wall that uses 3D stereo projection with active glasses. For the data integration, three software tools were used to generate the VR contents. The construction site 3D building was modelled by Revit, other 3D objects were modelled by 3D Studio MAX, and the VR scenarios were generated by EON Studio. For computing complexity, there are three chapters of the training course: The part of general site safety, including vehicle and worker movement on site, working under cranes, falls from heights and personal protective equipment. The part of safety in cast-in-situ concrete, including work at heights, working with tools. The part of safety during stone cladding work on facades, including work on scaffolding, working with electrical tools and winches. The results showed that VR training for stone cladding work and for cast-in-situ concrete work have significant advantages. VR training was more effective in terms of maintaining trainees' attention and concentration, and VR training was more effective over time. Based on the need for improving safety training and the advantages of VR training, more VR applications in construction safety training should be encouraged.

Facility management: Currently, in the architectural, engineering, construction and facility management (AEC/FM) area, there are many context-aware techniques for project information transferring purpose, they usually detect and analyze users' surrounding environment intelligently, and deliver corresponding project information such as digital drawings or models to on-site users. But, as those aforementioned techniques primarily rely on location tracking technologies that primarily rely on external signal source (e.g.,GPS or WLAN). So they typically do not provide sufficient precision in congested construction sites or require additional hardware and custom mobile devices. In their research, (Bae, Golparvar-Fard et al. 2013)presented a new vision-based mobile augmented reality system that allows onsite users to query and access 3D cyber-information by just taking conventional mobile device photos. The user's location and orientation are purely derived by comparing images from the user's mobile device to a 3D point cloud model generated from a set of pre-collected site photographs. Thus, their system does not require any location tracking device, external hardware, or optical markers. The experimental results show that 1) the underlying 3D reconstruction module of the system generates complete 3D point cloud models of target scene, and is up to 35 times faster than other state-of-the-art Structure-from-Motion (SfM) algorithms, 2) the localization time takes at most few seconds in actual construction site. The data integration included 3D reconstruction from photos, and generate 3D point cloud, then, using the point cloud, the system can accurately localize and augment new photographs captured on a mobile device. The computing complexity is upon successful localization of a new photograph, a field engineer can easily perform the facility management work like creating and adding a new 3D BIM element on the device. The localization speed and empirical accuracy of the system provides the ability to use the system on real-world construction sites for facility management purposes.

User case taxonomy conclusion

VR/AR have shown great potential in civil engineering and made valuable contributions to transportation infrastructure related engineering area. Literatures have shown researchers and engineers are already using these new technologies in various creative ways, but the great potential of the VR/AR still need to be fully utilized. Derived from current research cases from around the world, this taxonomy have indicated that there are several areas of potential research and development including construction progress tracking and visualization, construction simulation, construction inspection, training purpose, safety improvement, and facility management. The taxonomy was developed to indicate not only categories of current VR/AR research and application but also to demonstrate where that work is concentrated. This can help us in evaluating the feasibility of the above VR/AR technologies in supporting various selected set of use cases in transportation infrastructure management.

Task 5: Evaluating the feasibility of the above AR technologies in supporting a selected set of use cases in transportation infrastructure management.

& Task 6: Conducting additional development on the most promising platform to explore the deep integration of AR technologies with project data in supporting real-time interactive computing and simulation in VR/AR environment

We conducted these two research tasks in an integrated manner. Two VR training modules/software packages were developed as part of these two tasks to provide a variety of innovative infrastructure related training. The first VR training module is a full-scale VR cable stayed bridge. The second VR training module is a facility that manages storm water to keep roads from inundated. This type of facility represents an exemplar case of training in critical facilities.

Bridge VR module

The bridge VR model was modeled after the Stan Musial Veterans Memorial Bridge. The Stan Musial Veterans Memorial Bridge (known as the New Mississippi River Bridge until its formal naming in 2013[8] and informally known as the "Stan Span"[9]) is a bridge across the Mississippi River between St. Clair County, Illinois, and the city of St. Louis, Missouri. Built between April 19, 2010, and July 2013, the bridge opened on February 9, 2014. The cable-stayed bridge has a main span of 1,500 feet. The final cost of constructing the bridge was $695 million.

Figure 12 The Stan Musial Veterans Memorial Bridge

The bridge model was developed in Sketchup based on bridge drawings. The Sketchup model was then imported into Unity to further develop the VR simulation capabilities (Figure 13). The VR bridge environment is designed to provide mechanisms for users to simulate a variety of tasks. Among all the tasks, the most important purpose of this VR environment is to simulate work zones on a bridge. The simulation of work zones focuses on immersive experience for construction workers, various setups of work zones, and training on work zone setup. Training workers to work safely in highway construction zones is a challenging and critical task. Before VR based training, such training often takes place in the context of table-top exercises, which are very difficult to give workers realistic experiences. One innovation of this VR module is a fully parametrized environment that can be reconfigured on the fly to reflect various traffic scenarios and various work zone setups. For example, the bridge environment can be populated with a mix of traffics such as sedans and trucks (Figure 14), and can be adjusted to reflect various weather conditions such as fog, rain, and snow (Figure 15). The environment can also be varied by visibility so as to simulate night-time construction.

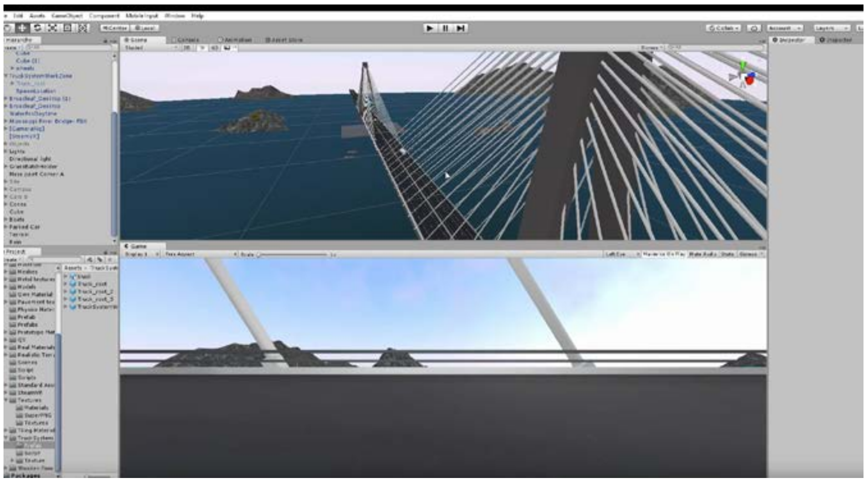

Figure 13 The Bridge VR model in Unity

Figure 14 Mixed Traffic Example

Figure 15 Fogy Conditions

Once the environment is set up, users can immerse themselves in the VR environment to explore the bridge. One benefit of this type of the visualization is that users can quickly familiarize themselves with the site. They may experience what it feels like performing inspection activities on the top of the mast. More advanced use of this VR environment is for work zone setup. The users can interact with the work zone objects in the scene, such as picking up cones and replace them at different places. The users also can perform flag man tasks such as alternating stop and slow signs to control traffic. These traffic control objects give the users the tools to virtually set up work zones for training purpose. Within the environment, obstacle avoidance behaviors are designed for vehicles such that they act intelligently in the presence of construction cones and other obstacles. The vehicles are also programmed to observe traffic signals and signs. With these capabilities, a realistic work zone scenario can be designed and placed rapidly.

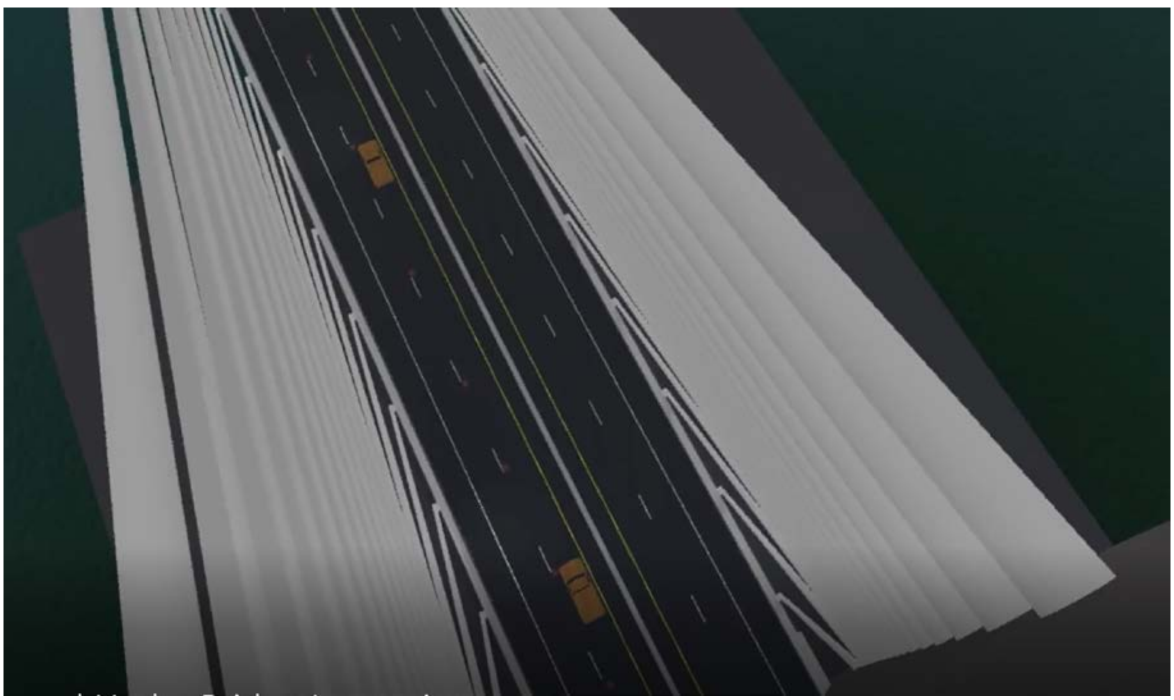

Figure 16 Exploration in the VR environment

Figure 17 Work zone objects for user interaction

One unique capability of our bridge VR module is the simulation of placement of construction cones from a moving platform. Placing construction cones from a moving platform is a common method for work zone setup, but it is a dangerous one if the workers do not have rich experience. In fact, this capability was developed at the request of a highway construction union. Training workers to set up a work zone safely and quickly is one of the primary goals for highway construction unions. The cone placement module in this bridge VR environment provides a unique training environment for highway workers without putting them into the harm's way.

Critical facility VR module

The second VR training module is a full-scale critical facility modeled after an in-service pump station. This is a century-old sewerage infrastructure that have never been digitized in computer model before. We used the scan-model-simulation workflow to develop this VR module. The lidar scan data of this station is shown in Figure 18. The scan data was converted into a building information model (Figure 19). The BIM model was then imported into Unity to develop various training modules. In the training module, various accident scenarios such as equipment fire (Figure 21) and pipe leaks (Figure 22) can be simulated in the model. The model can be used for confined space training, for training response to gas leaks, and for training the utility mark out procedures.

Figure 18 Point cloud model of the pump station

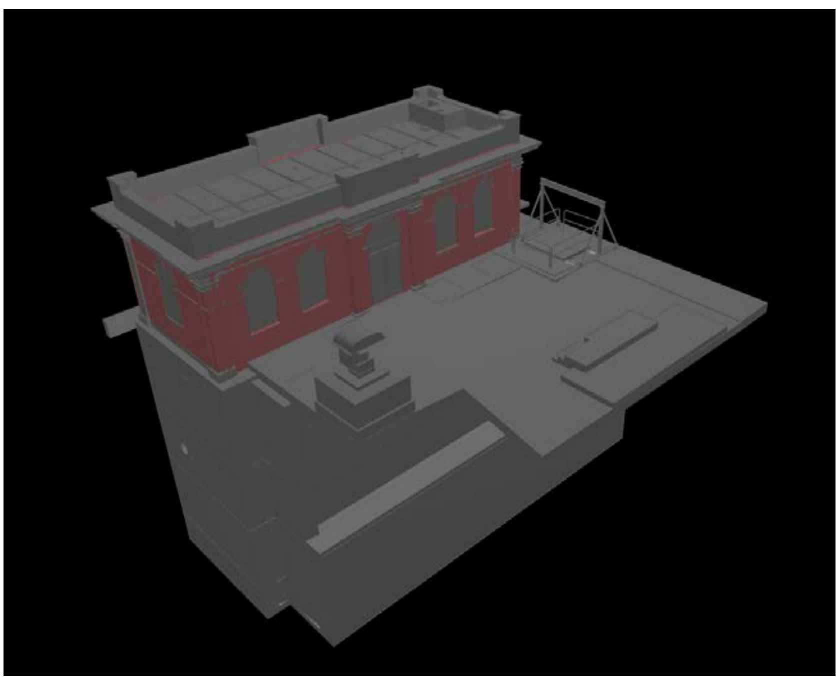
Figure 19 BIM model of the pump station

Figure 20 Simulation of fire accidents

Figure 21 Simulation of fire fighting

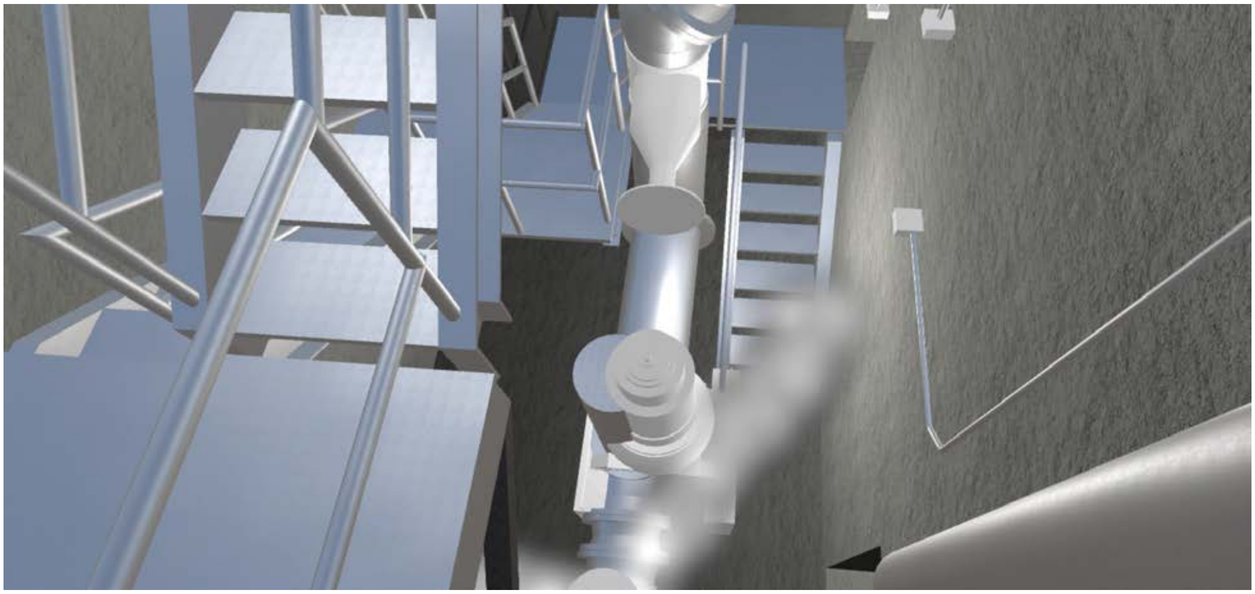

Figure 22 Gas leak in a confined space

Task 7: Conducting demonstration sessions with stakeholders to evaluate project products and findings.

We have conducted many demonstration sessions with stakeholders and potential customers after the development of the above two VR modules (Figure 23). The attendees of these demonstration sessions include Port Authority of New York and New Jersey, NJ Board of Public Utilities, local natural gas companies, highway construction unions, and visitors from Federal Highway Administration. During the process of technology demonstration, many users have expressed that they have sense of reality of virtual environment. Especially when they are standing on the top of the bridge tower or walking on a cable, some of them even said the VR have triggered their acrophobia.

In general, the consensus is that the two VR training modules have produced new ways of providing training to transportation and infrastructure workforces. These virtual environments are modeled after two real facilities. The virtual training environments can greatly improve the efficiency and effectiveness of training for transportation and infrastructure workforce. For example, construction crews can use the bridge VR environment to simulate the setup of work zones (i.e. placing cones and controlling traffics with flagman) and experience the resulted traffic flow in a fully immersive environment. Such training can greatly enhance the safety of construction crews and the traveling public. The facility VR environment can be used for confined space training. Several private companies and labor unions have expressed interests to fund the further development of these modules for their own training needs.

We expect collaboration with labor unions (which have already expressed interests in collaboration) can transform the current training requirements. In the near future, construction repair work on highways, in particular on critical nodes, will require crews trained in simulated environment. Just like airplane pilots need to log certain amount of simulator training time.

Figure 23 Demonstration sessions with stakeholders

CONCLUSIONS AND RECOMMENDATIONS

The following provides a quick summary of the project.

(1) What was accomplished?

The research team have reviewed available VR/AR technologies and produced a technical summary on how these technologies can be used in various infrastructure use cases. We have developed two VR training modules/software packages to provide a variety of innovative infrastructure related training. The first VR training module is a full-scale cable stayed bridge which was modeled after the Stan Musial Veterans Memorial Bridge. This bridge VR module can be used for training work zone setup and for training bridge inspection activities. The module provides mechanisms to interact with work zone objects such as construction cones and traffic signals. The second VR training module is a full-scale critical facility modeled after an in-service pump station. Various accident scenarios such as fire and leaks can be simulated in the model. The model can be used for confined space training, for training response to gas leaks, and for training the utility mark out procedures. Several private companies and labor unions have expressed interests to fund the further development of these modules for their own training needs.

(2) Outputs such as any new or improved process, practice, technology, software, training aid, or other tangible product resulting from research and development activities. They are used to improve the efficiency, effectiveness and safety of transportation systems.

The project produced new ways of providing training to transportation workforces. More specifically, two full-immersive virtual environments featuring bridges and critical facilities have been developed. These virtual environments are modeled after two real facilities. The virtual training environments can greatly improve the efficiency and effectiveness of training for transportation workforce. For example, construction crews can use the bridge VR environment to simulate the setup of work zones (i.e. placing cones and controlling traffics with flagman) and experience the resulted traffic flow in a fully immersive environment. Such training can greatly enhance the safety of construction crews and the traveling public. The facility VR environment can be used for confined space training.

(3) Outcomes?

Collaboration with labor unions (which have already expressed interests in collaboration) is on the way to transform the current training requirements. In the near future, construction repair work on highways, in particular on critical nodes, will require crews trained in simulated environment. Just like airplane pilots need to log certain amount of simulator training time

(4) Impacts?

We believe VR/AR based training is the future for transportation workforce. This project will serve as a testimony to this vision. With the increasingly available head mount VR/AR headsets which can conveniently provide immersive visualization environments, the training modules such as those developed in this project can bring a variety of benefits: (1) it will reduce the training cost for transportation workforce while improving training effectiveness (some of stakeholders have already shared that these training modules can save the time and cost to send their workers to remote sites for training); (2) it can reduce the mistake in marking out underground facilities such that it can reduce the environment impacts caused by leaking gas; and (3) it can foster a safe working environment which will in return reduce transportation related fatalities.

(5) Products and Data Sets

The project produced two fully functional VR training packages that can be used in particular for safety training. The full VR packages are available to download at the CAIT website.

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