

Augmented Reality for Indoor Navigation and Task Guidance

by
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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored (refer to [Statement of Contribution](#)). This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTION

Manuscripts from Part III of this research are in preparation. The following manuscripts have been incorporated in Part II of this research.:

- Rehman, U., & Cao, S. (2015). Augmented Reality-Based Indoor Navigation Using Google Glass as a Wearable Head-Mounted Display. In Systems, Man, and Cybernetics (SMC), 2015 IEEE International Conference on (pp. 1452–1457). IEEE.

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ABSTRACT

Modern augmented reality systems are becoming increasingly popular in different industrial sectors as augmented reality based applications can improve performance and reduce workload during operations. The efficacy of such systems, however, has not been comprehensively investigated from human factors and performance standpoints. This research explores the design, development and evaluation of augmented reality based prototype applications for two discrete domain areas which include indoor navigation (Part II) and procedural task support in nuclear power plants (Part III).

AUGMENTED REALITY-BASED INDOOR NAVIGATION

In the study, we introduced an augmented reality-based indoor navigation application that utilizes pre-scanned environmental features and markerless tracking technology to assist people to navigate in indoor environments. The application can be implemented on electronic devices such as a smartphone or a head-mounted display, providing both visual and auditory instructions. In particular, we examined google glass as a wearable head-mounted device in comparison to hand-held navigation aids including a smartphone and a paper map. We conducted both a technical assessment study and a human factors study to comprehensively evaluate the system. The technical assessment established the feasibility and reliability of the system. The human factors study evaluated human-machine system performance measures including perceived accuracy, navigation time, subjective comfort, subjective workload, and route memory retention. The results showed that the wearable device was perceived to be more accurate, but other performance and workload results indicated that the wearable device was not significantly different from the hand-held smartphone. We also found that both digital navigation aids were better than the paper map in terms of shorter navigation time and lower workload, but digital navigation aids resulted in worse route retention. These results could provide empirical evidence supporting future designs of indoor navigation systems. Implications and future research were also discussed.

AUGMENTED REALITY-BASED TASK ASSISTANCE IN NUCLEAR POWER PLANTS

This research illustrates the design, development and human factors evaluation of an augmented reality based procedural task guidance system, implemented on a hand-held tablet device (ipad), in order to support nuclear power plant operators with main control room operations. After conducting an extensive literature review, we detail the development stages of our new application prototype that employs marker based tracking to superimpose computer generated instructions in the live view of the operators control panel. We had hypothesized that the augmented reality-based procedures would perform better than the traditional methods currently used in nuclear power plants that include computer-based procedures and paper-based procedures . A research study was devised and carried out that compared the three methods of procedural instructions. The performance evaluation and human factors study revealed that the augmented reality based prototype solution reduced operators workload, increased operators situation awareness, made processes efficient and less prone to errors and reduced inquiry communication. The results also led us

to conclude that augmented reality based procedural assistance poorly supports memory retention and skill learning amongst operators.

*Believe in yourself and in your plan.
Say not-I cannot but I can.
The prizes of life we fail to win,
because we doubt the power within.*

[— Catherine Pulsifer]

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Ohana means family.
Family means nobody gets left behind, or forgotten.
— Lilo & Stitch

Dedicated to the loving memory of Tasneem Akhtar.
1943–2016

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LIST OF ACRONYMS

ABP	Augmented Reality-Based Procedures
AR	Augmented Reality
ARO	Assistant Reactor Operator
CAD	Computer Aided Design
CBP	Computer-Based Procedures
EOP	Emergency Operating Procedures
EP	Electronic Procedures
FOV	Field of View
GPS	Global Positioning System
HMD	Head Mounted Displays
HMS	Human Machine Systems
MCR	Main Control Room
NPP	Nuclear Power Plants
PBP	Paper-Based Procedures
QR	Quick Response
RO	Reactor Operator
SA	Situation Awareness
SC	Step Complexity
SDK	Software Development Kit
SLAM	Simultaneous Localization and Mapping
SOP	Standard Operating Procedures
SS	Shift Supervisor
UI	User Interface
VDU	Visual Display Unit
VR	Virtual Reality

Part I

INTRODUCTION

1 INTRODUCTION TO AUGMENTED REALITY

1.1 DEFINITION OF AUGMENTED REALITY

AR is defined as technology that can interactively and in real time overlay layers of computer generated virtual content in the user's natural Field of View (**FOV**) (Azuma, 1997; Glockner, Jannek, Mahn, & Theis, 2014). **AR** therefore differs from Virtual Reality (**VR**) as **VR** is a complete immersion in the digital world whereas **AR** combines the digital and the physical environments. Hence **AR** can enhance the physical reality with supplementary information that can be presented to the user in a meaningful way. Virtual content overlaid on real feed in **AR** applications would mostly consist of visual information (text, graphics etc.) however recent applications have also tested other sensory outputs such as audio, haptics and even smell (Glockner et al., 2014). Different types of **AR** based tracking technologies, application areas, user interfaces, display devices and interaction techniques have been introduced and discussed in prior research studies (Zhou, Duh, & Billinghurst, 2008).¹

1.2 AUGMENTED REALITY TRACKING

The majority of **AR** tracking has been geared towards computer vision techniques (Figure 1.1) that employ image processing to estimate camera poses relative to the physical environment. Initial work in this domain illustrated the development of marker based tracking approach (Stricker, Klinker, & Reiners, 1999) and improvements in algorithms that reduced position error and made tracking more accurate (Comport, Marchand, & Chaumette, 2003; Ribo, Pinz, & Fuhrmann, 2001). A range of generic square markers (Kanbara & Yokoya, 2002), circular fiducial markers and barcode based fiducial systems were investigated (Kato & Billinghurst, 1999). Fiducial markers performed better than other alternatives as they offered high information density and sub-pixel accuracy (Zhou et al., 2008).

Research has also shown that camera pose could be calculated from naturally occurring features such as points, lines, edges or textures (Neumann & You, 1999). Unlike marker based tracking, feature tracking² provided constant estimation of pose as naturally occurring features could be extended within the environment as potential trackables (Comport et al., 2003). Rietmayr & Drummund (2006), have also shown that model-based tracking methods can apply **AR** information overlays to track homogeneous features within a 2D model (e.g. Computer Aided Design (**CAD**) model).

Sensor based **AR** tracking is another alternative that mostly utilizes inertial sensors however research has also investigated other techniques that employ magnetic, acoustic, optical, and mechanical sensors for tracking (Zhou et al., 2008). Modern applications rely on hybrid tracking that utilizes several different technologies such as a combination of inertial sensor tracking approach and a particular computer vision method. Hybrid tracking is considered highly reliable as this approach can re-estimate camera poses and therefore overlay steady virtual imagery even during rapid motions (You, Neumann, & Azuma, 1999).

¹ A complete review of ten years of **AR** research published in International Symposium on Mixed and Augmented Reality is available as a review (Zhou, Duh, & Billinghurst, 2008) at <http://goo.gl/gGU42L>.

² Feature tracking was employed when developing **AR** based indoor navigation prototype. Refer to Chapter 10 for more details.



Figure 1.1.: This figure represents the different trackables that can be utilized to overlay virtual imagery. The trackable include fiducial ID markers, barcodes, QR codes, image based markers, borderless marker, 3D point map, and CAD edge model (Koch, Neges, König, & Abramovici, 2014). Source: 88.

1.3 AUGMENTED REALITY INTERFACES

Certain AR interfaces are tailored for a particular class of applications and these interfaces entail specific interaction techniques. Tangible AR (Figure 1.2a) is a novel class of user interfaces that would allow objects in the physical environment to be used as AR interface components. Physical objects can hence be used by the user to communicate with the displayed virtual content (Lee, Nelles, Billingham, & Kim, 2004). Users can generally interact with the physical objects via specific hand gestures or voice commands therefore these interfaces are also categorized as multimodal interfaces. Collaborative AR (Figure 1.2b) can enhance multi-user communication and improve performance when humans undertake shared activities. These activities could be performed remotely or in collocated workspaces (Billingham & Kato, 2002). Hybrid AR applications (Figure 1.2c) would combine complementary interfaces and allow users to utilize a variety of interaction techniques and multiple devices in efforts to provide a more seamless and intuitive experience to the user (Feiner, Macintyre, & Seligmann, 1993).³

³ Refer to a comprehensive review on AR interfaces and design by Haller, (2006) at <https://goo.gl/sUCoey>.

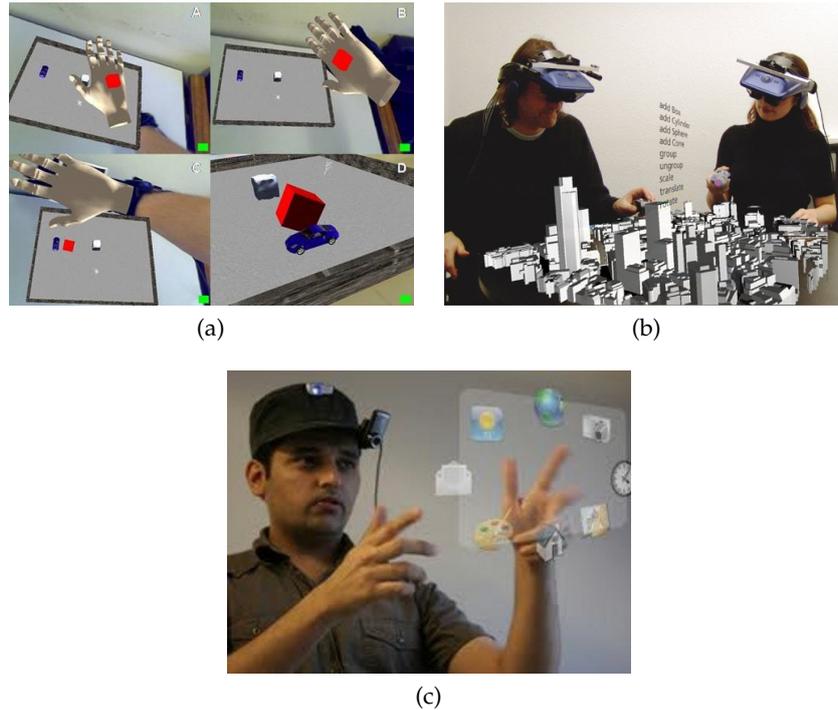


Figure 1.2.: This figure illustrates the different types of AR interfaces. Figure 1.2a depicts a user interacting with augmented virtual content using multimodal/tangible interactions. Figure 1.2b represents users interacting collaboratively with virtual imagery on a tabletop. Figure 1.2c represents Pranav Mistry's sixth sense using multitouch devices and an assortment of interaction techniques (Mistry & Maes, 2009). Source:88.

1.4 AUGMENTED REALITY DEVICES

Many different categories of devices have been introduced to implement AR applications. Modern hand-held devices (tablets, smartphones etc.) are best suited for mobile AR applications as these devices are equipped with features such as high definition displays, top quality cameras, robust processing speeds and multitude of sensors that can support accurate tracking. Hand-held devices (Figure 1.3a) however carry an ergonomic limitation as they cannot provide a hands-free experience during operations (Wagner & Schmalstieg, 2003). Stationary AR systems (Figure 1.3b), mostly used in commercial activities, are essentially large motionless display screens with advanced camera systems showing realistic overlay of virtual information (Chang, Li, Chen, Feng, & Chien, 2013). Spatial AR systems (Figure 1.3c) differ as they are designed to turn any suitable environment into an interactive display with the help of large optical elements and video-projectors. The augmented information displayed on the physical environment is therefore in original proportions and can be observed by multiple viewers simultaneously. Spatial AR systems are also mostly motionless in nature however with the availability of mini projectors that can be attached to smart hand-held devices, these systems can also be configured to become portable (Bimber & Raskar, 2005).

From a user experience perspective Head Mounted Displays (HMD) are ideal for AR applications as most modern HMD (Figure 1.3d) allow users to view virtual content in synchrony with their head movements. Two major types of HMD include optical see-through HMD and

video see-through **HMD**. Optical see-through devices are less intrusive and have minimal parallax error whereas video see-through devices can better manage occlusion issues in display (Kato & Billinghurst, 1999). Commercially available **HMD** are categorized as smart glasses and these **AR** devices carry high quality cameras and all the major sensors found in modern smartphones. Research is also being conducted on smart contact lenses as the ultimate future wearable device to support **AR** applications (Glockner et al., 2014).

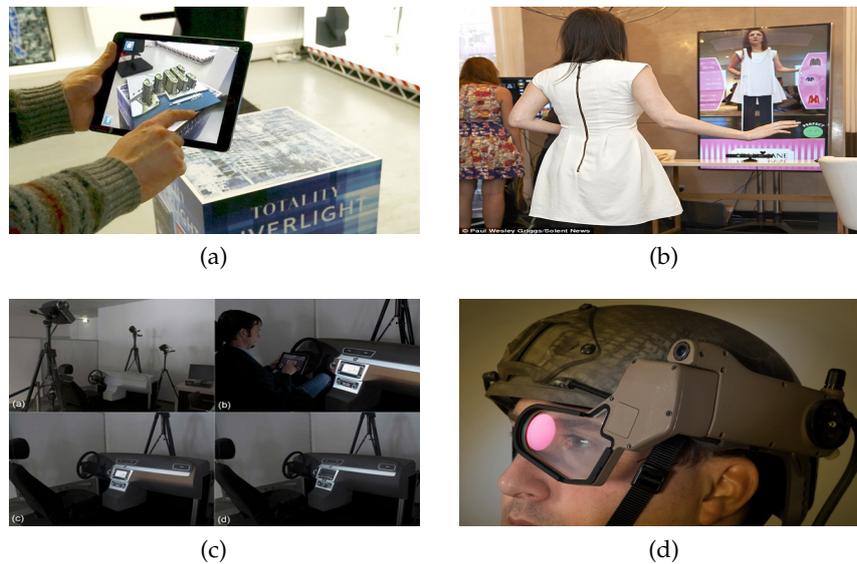


Figure 1.3.: This figure illustrates the different types of **AR** devices. Figure 1.3a depicts a user interacting with a hand-held tablet device. Figure 1.3b represents a user interacting with a stationary **AR** system. Figure 1.3c represents a user interacting with spatial **AR** systems. Figure 1.3d represents a design of modern **HMD** designed to assist soldiers through augmented cues. Source:88.

1.5 AUGMENTED REALITY APPLICATIONS

AR uses can be categorized based on the nature and complexity of the different applications. **AR** applications that just provide users with situation specific contextual information (Oh, Woo, & others, 2009) are classified as context-sensitive **AR** applications (Figure 1.4a). The second category would encompass those **AR** applications that can enhance human sensing capabilities (Glockner et al., 2014) as shown Figure 1.4b. Applications that allow users to adjust and modify virtual content in the physical environment are called mixed reality solutions (Benford & Giannachi, 2011), an example shown in Figure 1.4c. The most interactive group of applications are those which allows the user to communicate with the superimposed virtual content using specified interaction techniques (Figure 1.4d) in order to control physical objects or trigger action in the real world (Mistry & Maes, 2009).

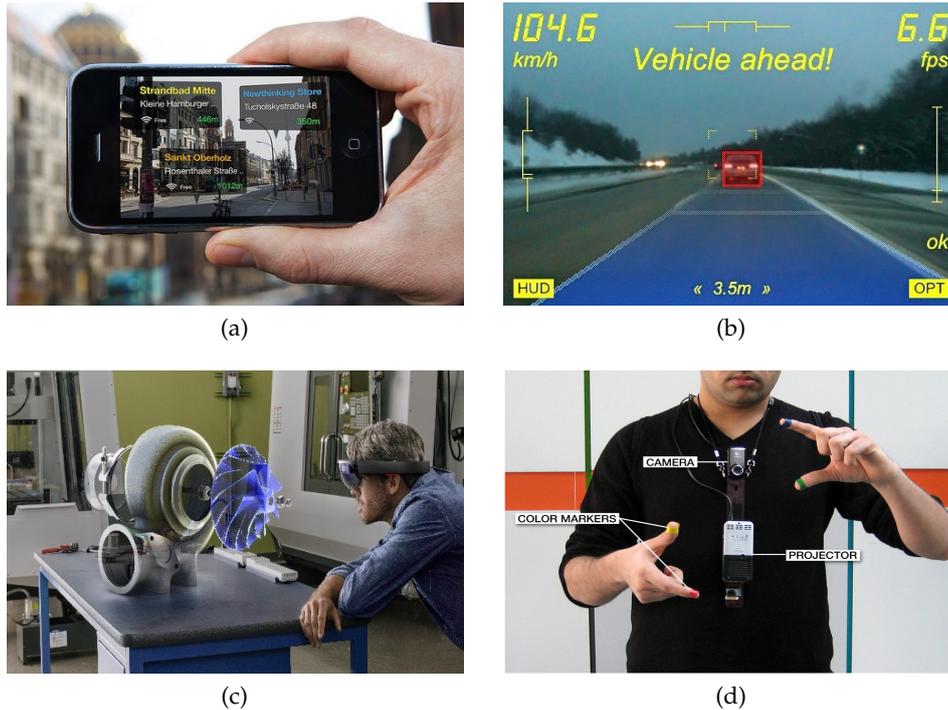


Figure 1.4.: This figure illustrates the different types of AR best practices. In Figure 1.4a, an AR application informs the user of the different commercial places that are located in the surroundings. Figure 1.4b represents an AR application enhancing human driving capability using visual cues to alert vehicle distance. Figure 1.4c illustrates a mechanic interacting with virtual content. Figure 1.4d represents Pranav Mistry’s sixth sense using multitouch devices and an assortment of AR interaction techniques (Mistry & Maes, 2009). Source:88.

1.6 RESEARCH OUTLINE

The design, development, and evaluation of AR based prototype systems in two discrete domain areas which include indoor navigation and procedural task support in NPP are discussed within this research. The tracking technology, interface design, display devices, and interaction techniques employed to develop the two applications differ as each solution is optimized for its particular domain. The overarching research problem, focused throughout this thesis, relates to analyzing the benefits and drawbacks of using the AR based prototypes in comparison to traditional solutions. The following questions were initially shortlisted:

1. We want to analyze the practicability of the application and how the development of the AR software could be implemented across commercially available devices for it to work optimally in that particular domain. This research question would primarily deal with the development aspect and would take into consideration the different design measures, user interface elements and previously tested heuristics that had been applied towards the development of user centered AR applications.
2. We want to focus on understanding how a particular category of device (wearable, handheld etc.), running the AR application, would impact operator performance in that domain. We therefore plan to take into account the hardware specifications and

biomechanics of the device to investigate usability performance. We also would be interested in addressing issues concerning the impact of computer vision algorithms on battery life of the device and the extensive processing capabilities needed to analyze heaps of real time camera feed.

3. Our prime interest would be investigating the performance of the AR applications from human factors standpoints. We would investigate human error, mental workload, situation awareness and communication in efforts to analyze the utility of the application within their respective domain. User studies would be carefully designed and conducted in order to collect empirical data which could be then analyzed to formulate insights.
4. Impact of AR application on operators learning and retention would also be explored as degradation of skill could be unsafe when automation aids (such as AR applications) become unavailable due to technical issues. It is therefore always preferred to use those automation aids that could complement operator's memory and skill learning alongside providing a safe and intuitive user experience.

These research questions were further refined with supporting theoretical basis and established in the preliminary chapters of the two studies⁴. Focussing on these research problems, this thesis provides an extensive review of the literature, details the application development processes, illustrates the design decisions, performance tests, human factor experiments, and comprehensive discussions, all of which are geared to holistically scrutinize the newly developed AR based prototypes and provide a deeper understanding of its relative use to the application domain.

⁴ Part I research questions are detailed in Section 2.2 and Part II are research questions are detailed in Section 8.2 of this thesis.

Part II

AUGMENTED REALITY-BASED INDOOR NAVIGATION: A COMPARATIVE ANALYSIS OF HAND-HELD DEVICES AGAINST GOOGLE GLASS AS A WEARABLE HEAD-MOUNTED DISPLAY

In this study, we introduce the design, development and human factors evaluation of an augmented reality-based indoor navigation application that utilizes pre-scanned environmental features and markerless tracking technology to assist people navigate in indoor environments. The application was implemented on Google Glass™ and on an Android smartphone.

2 INTRODUCTION TO INDOOR NAVIGATION STUDY

2.1 OVERVIEW

Modern navigation systems use electronic devices to determine user's location, find appropriate routes, and in some cases also autonomously supervise vehicles to the destination. Currently, most navigation systems use satellite signals from Global Positioning System (GPS), which works in outdoor environments but has difficulty indoors due to reduced signal strength. Alternative technologies such as Wi-Fi-based and image-based methods have been proposed for indoor navigation; however, a definite solution for the industry has not been established. As the prevalence of smart mobile devices and location-aware applications increases (Coelho, Aguiar, & Lopes, 2011; Tony Costa et al., 2013), indoor navigation systems become highly valuable for both personal use and in industries (Jeong, Choi, Han, Suh, & Yeo, 2011) such as retail, entertainment, healthcare, and manufacturing (Tony Costa et al., 2013).

On the machine side of indoor navigation systems, the most important goal is to achieve accurate localization. Compared with outdoor cases, indoor navigation faces a lot of technical challenges such as non line of sight conditions, high attenuation and signal scattering, greater concentration of physical impediments, transitory environment changes, and higher demand for accuracy. To address these challenges, different technologies have been introduced with various levels of accuracy, cost, and scalability. In order to find a suitable navigation technology for a particular application, designers need to align the performance parameters to the requirements of the users (Mautz, Rainer, 2012).

On the human side of indoor navigation systems, few studies have examined the human factors and usability issues. Part of the reason is that the technology itself is still being developed. In contrast, human factors regarding outdoor navigation devices and interfaces have been investigated in many previous studies. However, since the technologies (such as sensors) used in indoor navigation devices are very different and currently less reliable than outdoor navigation devices (Pahlavan, Li, & Makela, 2002), findings pertaining to outdoor navigation cannot be directly applied to indoor environments. As a result, there is a strong need to test and evaluate the human factors of indoor navigation technologies and devices (Brown & Pinchin, 2013).

The focus of the current study is on HMD and AR interfaces. Wearable devices such as HMD¹ have been extensively investigated in research laboratories, and they now have a rapidly growing global market (Moustafa, Kenn, Sayrafian, Scanlon, & Zhang, 2015). HMD can be worn on the head as a spectacle or as a part of a helmet. They essentially contain a display optic unit in front of one (monocular HMD) or both eyes (binocular HMD) (Emmitt & Ruikar, 2013). Some HMD only show computer-generated virtual scenarios, whereas other HMD can superimpose images on real-world views or camera feed. Systems combining HMD and head movement tracking technologies could be highly valuable for navigation applications (Jeong et al., 2011; Mautz, Rainer, 2012), because such technologies can directly show the route in front of the user's eyes and allow hands to perform other activities. Previous studies using HMD (Joseph et al., 2013; Kalkusch et al., 2002; J. Kim & Jun, 2008;

¹ One of the first patents that illustrates an operational HMD in detail at <https://www.google.com/patents/US3923370>.

J. B. Kim, 2003) were often conducted in controlled laboratory environments (Kasprzak, Komninou, & Barrie, 2013) due to the large size of the devices and their wired connections. Recently, however, companies such as Google and Microsoft have released their prototype versions of **HMD** (Moustafa et al., 2015), which allow researchers to conduct more practical studies in natural environments. In a **HMD**, sensor data is utilized to automatically track head orientation and position, whereas with a hand-held device, users need to hold the device in a particular orientation and position for proper navigation view. Therefore a hand-held device entails more cognitive and physical demands. We therefore believe that there is a strong need to conduct comparative studies on **HMD** and hand-held devices in order to investigate the systems from cognitive ergonomics and human performance standpoints as most previous studies related to indoor navigation have focused on analyzing or improving localization techniques rather than human factors issues such as workload, comfort, and memory retention (Mulloni, Seichter, & Schmalstieg, 2011).

An imperative aspect of an indoor navigation system is the user interface design. With the traditional interface used in most electronic navigation systems, users had to mentally match the directions shown in the display to directions in the real world. With **AR**, this mental effort is reduced, because an **AR** interface can directly superimpose directions on a real-world view, therefore improving awareness and making the directions easier to perceive (Huey, Sebastian, & Drieberg, 2011; J. Kim & Jun, 2008; J. B. Kim, 2003). Many **AR**-based applications have been developed for a wide range of work domains including healthcare, defense, intelligence, and transportation (J. Kim & Jun, 2008). **AR** interfaces for indoor navigation have been implemented on hand-held devices and evaluated in previous studies (Mulloni et al., 2011; Möller et al., 2014). These studies found that **AR** could support accurate localization and improved user experience (Bhanage & Zhong, 2014); however, for hand-held devices, users need to hold the devices in an appropriate manner (specific orientation and position) for the applications to work properly (Möller et al., 2014). This requirement may influence usability, navigation accuracy, and user satisfaction.

2.2 RESEARCH QUESTIONS

The overall research focus of the current study and our previous work (Rehman & Cao, 2015a, 2015b) was on the design, development, and evaluation of an advanced and intuitive indoor navigation system. We concentrated our efforts towards developing a workable prototype, which could be used to investigate complexities confronting both the human and machine sides of indoor navigation research. The following research questions were investigated in this study.

1. Is it possible to build a feasible **AR** indoor navigation solution that could be implemented on both wearable devices (**HMD**) and traditional hand-held cell phones?
2. Is it possible to achieve the above **AR** solution using methods that do not require physical infrastructure installation during pre-deployment stage (e.g. Bluetooth beacons, Wi-Fi routers, and fiducial markers)?
3. Can the above solution pass technical assessments to ensure that it is workable and does not cause many glitches and fluctuations during usual walking scenarios?
4. Will the implementation on a wearable device result in better performance, lower workload, and better route retention than the hand-held implementation and paper maps in an indoor navigation task?

2.3 CONTRIBUTIONS

The technical solution developed in the current study was a novel design of an indoor navigation systems that utilized advanced feature tracking² and AR approaches towards navigation. The system used a pre-scanned 3D map to track environmental features. These features contained directional information so that instructions could be superimposed on the live visual feed at appropriate places. During navigation, directional information was presented to the user via both the visual channel (arrow and icons) and the auditory channel (speeches).

After developing the technical solution, we comprehensively tested the application in two studies, a technical assessment study and a human factors experiment. The technical assessment focused on the efficiency and feasibility of the technology in normal and fast walking scenarios. A real office environment was used to test the feature tracking technology.

The same prototype was then deployed on both a hand-held device (Samsung Galaxy S4 smartphone) and a wearable device (google glass). The human factors experiment focused on performance, workload, and memory retention. Diagnostic, summative, and formative tests were all performed in order to ensure a comprehensive analysis. It was very important to ascertain how accurate the users perceived the devices to be (i.e., perceived accuracy) and how much contextual information they retained after using the navigation aid. Specifically, by analyzing the data from the user study, we examined the AR indoor navigation prototype implemented on a wearable device (Condition 1) vs. a hand-held device (Condition 2), with a paper map as a baseline in comparison (Condition 3). We assessed these indoor navigation aids on the basis of perceived accuracy, comfort, subjective workload, efficiency (traversal time), and route retention error. The test of route retention was important because it reflected the extent to which users overly relied on the navigational aids. It could also reflect the performance of how users would act if the assistance devices were removed. It is necessary to consider such situations, especially for users in extreme environment such as firefighting and combating. Previous studies have identified some negative effects of too much navigational aid on route retention (Holmquist, 2005). Therefore, route retention error was included in the current study.

² Natural feature tracking (Neumann & You, 1999) is better elaborated in this study at <http://goo.gl/Rhs0Z8>.

3 BACKGROUND OF TECHNOLOGY

Technologies used for indoor positioning can be generally categorized into two groups, wireless transmission methods and computer vision methods. Wireless transmission methods use technologies such as ultra-wide band, wireless local area networks, and radio frequency identification to localize a device. These technologies often require physical infrastructures, such as Wi-Fi routers and Bluetooth beacons, to be deployed and installed in the indoor environment (Mautz, Rainer, 2012). Most of these solutions are not very accurate and contain substantial localization errors, though these errors could be reduced by incorporating inertial sensor based positioning approaches and probabilistic techniques such as particle filtering (Plamen Levchev, Michael N Krishnan, Chaoran Yu, Joseph Menke, & Avidesh Zakhor, 2014). Some technology solutions such as Bluetooth and infrared methods also have high latency during the detection phase (Liang, Corso, Turner, & Zakhor, 2013). Although these technologies are popular localization solutions, they have difficulties in estimating the user's orientation, and therefore are not ideal for AR applications (JZ Liang, E Turner, A Zakhor, & N Corso, 2015). In contrast, computer vision techniques are more suitable for AR-based applications, and previous studies have found computer vision technologies to be more accurate in comparison to Wi-Fi based fingerprinting (Liang et al., 2013).

Many techniques have been developed to provide localization and navigation using computer vision. Simultaneous Localization and Mapping (SLAM)¹ is one popular technique that stemmed out of the robotics community for autonomous vehicles (Gerstweiler, Vonach, & Kaufmann, 2015). The SLAM mapping process attempts to obtain spatial data (e.g., Received Signal Strength and 3D Point Clouds) of the environment in order to build a global reference map while simultaneously tracking the position of the subject (Bailey & Durrant-Whyte, 2006). There are many different SLAM algorithms that pertain to different technologies such as Wi-Fi, Bluetooth, feature tracking, and image recognition (Bailey & Durrant-Whyte, 2006; Gerstweiler et al., 2015). All these data types may be utilized for SLAM. However, the focus of the current study is on navigation situations such as in hospitals and office buildings where environment mapping can be done in advance. As a result, we did not use SLAM methods. Instead, the 3D maps were built offline before the navigation tasks.

A commonly studied vision-based indoor positioning approach involves image recognition of the real environment through live camera feed. These images are referenced against a pre-collected sequential database of orthographic images of the same environment. The pre-collected images are annotated with their locations, and the inertial sensors of the device can help deliver orientation (Lakhani, 2013). This technique can therefore be used to deliver successful AR-based directional instructions as well as user localization. An issue with this technique, however, is that it requires extensive computational power because a large database of images is being utilized, which may cause delays during navigation (Kasprzak et al., 2013).

Another computer vision based approach, widely studied before (Chawathe, 2007; Delail, Weruaga, & Zemerly, 2012; Huey et al., 2011; Kalkusch et al., 2002; Kasprzak et al., 2013; J. Kim & Jun, 2008), uses physical markers for optical tracking as discussed in Chapter 1. Physical markers such as ID markers, barcodes, and QR codes use fiducial tracking (Amin & Govilkar, 2015) for detection. These markers are easily recognizable due to their unique

¹ Refer to this study to completely understand SLAM (Bailey & Durrant-Whyte, 2006) at <http://goo.gl/VDPgYZ>.

geometric shape and/or high contrast. Other physical markers such as picture markers need to have enough unique visual content to be distinctly recognizable. Physical markers often need to be positioned strategically to cover the entire indoor environment. In some cases, distinct features within the environment such as furniture and signs could also be used as picture markers. An issue with most physical markers is that they have to be physically placed in the environment so that they are all visible during navigation. For vision-based localization methods in general, there is a risk that the visual scenes might get changed, which could impair navigation performance (Koch, Neges, König, & Abramovici, 2014).

Recent studies have also examined 3D markerless tracking approaches as an advanced form of optical tracking (Koch et al., 2014). 3D maps are created by scanning the area of interest. Once adequate visual information of trackables (i.e., 3D point clouds at different camera angles) are collected, they could be used for AR information overlay. This approach is not very computationally exhaustive for mobile devices and also has some degree of resilience against changes in the environment. Identifying distinct point cloud patterns in an indoor area is easier than identifying a specific picture marker. A picture marker is difficult to see clearly from farther away. In contrast, point cloud patterns can cover a large area and are easier to detect from relatively farther distances. Directional information can then be overlaid on the trackables using AR technologies, which can produce a very accurate navigational experience. Therefore in the current study, we utilized 3D point cloud tracking technology on a wearable HMD with an AR interface to assist users in indoor navigation.

4 PROPOSED SYSTEM

4.1 SYSTEM DESIGN

The major function of the system is to assist people to navigate in indoor environments using environment tracking technology and AR instructions (both visual and auditory). The system design is developed to achieve optimal performance for a mobile device or a HMD. The HMD used is Google Glass™ (Figure 4.1). It is suitable for AR application in this study because it has sensors (gyroscope, accelerometer, and magnetometer) that can facilitate the identification of device orientation. Algorithms based on sensor readings can help maintain the required position for the visual overlay to be displayed properly. This delivers a very rich experience where the virtual contents can be seamlessly integrated with the real environment. Developing applications on Google Glass™ is straightforward as Glass Development Kit is an add-on to the Android Software Development Kit (SDK); thus the Android platform is used. The development of 3D point cloud localization requires a pre-deployment stage, where the indoor environment has to be 3D scanned (Figure 4.2). We developed our indoor navigation application using Metaio SDK (“Metaio SDK,” 2013)¹ that provides a multilayered environment to build AR applications on android platform.

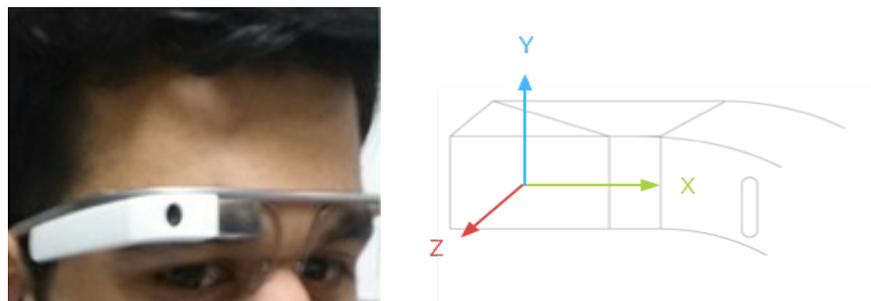


Figure 4.1.: The Google Glass™ sensor coordinate system is shown above relative to its display. The accelerometer, gyroscope, and magnetometer are located on the optics pod of the device (“Google Developers,” n.d.).

¹ Metaio GmbH got acquired by Apple Inc. and therefore the company website and products are inaccessible to general public now.

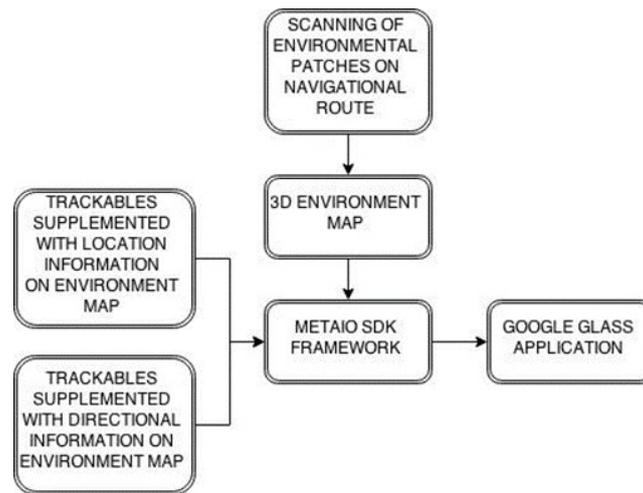


Figure 4.2.: Framework for the pre-deployment stage (Rehman & Cao, 2015a).

4.2 SYSTEM OVERVIEW

The pre-deployment data were collected and configured in Metaio [SDK](#). The scanned environment that consists of visual features (3D point clouds) is stored as trackables. In a database, these trackables are associated with their corresponding locations and navigation related information, which can be superimposed on visual feed during the navigation aid process. The camera and inertial sensors of the device are used to track the 3D point clouds and device orientation. Based on the trackables identified from the camera feed, the current location and orientation of the user is determined. Then the route is calculated. The potential routes in this study, supplemented with directional instructions in a chronological order, are pre-stored in the application. The routes covered a floor of a mid-size office building. We kept the routes within a manageable size because the wearable device (Google Glass™) has limited battery resources. The application presents [AR](#)-based navigation instructions including both visual and auditory cues, leading the user to the destination. As the user moves, location and navigation aids are updated in real time. Using gravity measurement from inertial sensors for pose estimation, the application positions the visual instructions at suitable screen locations, preventing any incongruity that could create confusion between augmented and real world environments. The system architecture is shown in [Figure 4.3](#) below.

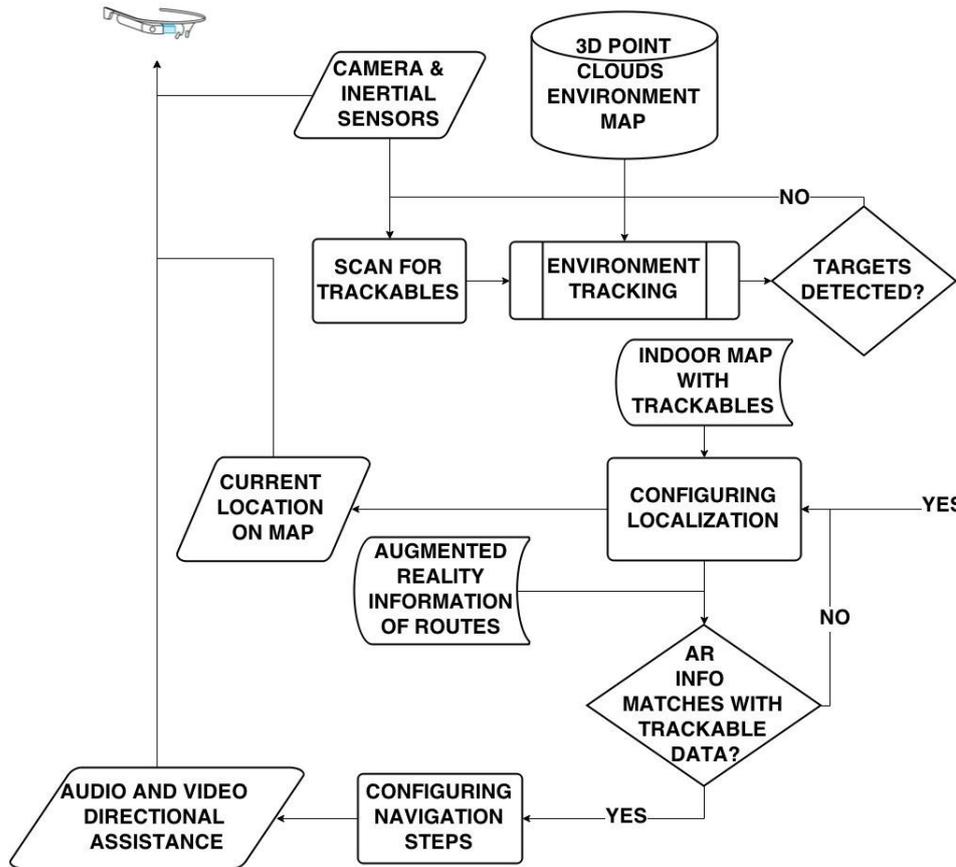


Figure 4.3.: Overall system architecture (Rehman & Cao, 2015a).

4.3 3D ENVIRONMENT SCANNING

The location chosen for the experiment was the Games Institute at University of Waterloo². Nine different areas on each route were scanned using Metaio Toolbox (“Metaio Toolbox,” 2012) to develop the environment map. Crucial objects were shortlisted for potential tracking. We did not intend to scan the entire environment because that would have created a lot of data to process, which would have been highly strenuous on the battery of Google Glass™. We established that the minimum area to be scanned would be 2 m in length (Figure 4.4a) so that trackables from far away could also be easily detected during the navigation aid process. This design choice would ensure that no discrepancy occurs when AR-based positional information is overlaid. Although all distinguishable surfaces within the environment were taken into consideration, highly textured surfaces were preferred in order to maximize the number of visual features (3D point clouds) within a scanned area. Environmental objects such as tables, chairs, bulletin boards, and signs were scanned from different angles. We also established that the minimum number of features to be scanned within an area would be 1500 so that the environment map could get adequately populated with trackables (Figure 4.4b). Areas where a potential turn was expected were more comprehensively scanned for higher accuracy. All areas, once scanned with trackables, were gravity-aligned

² <https://uwaterloo.ca/games-institute/>

using the inertial sensors of the device. The process concluded once sufficient features on a route had been scanned.

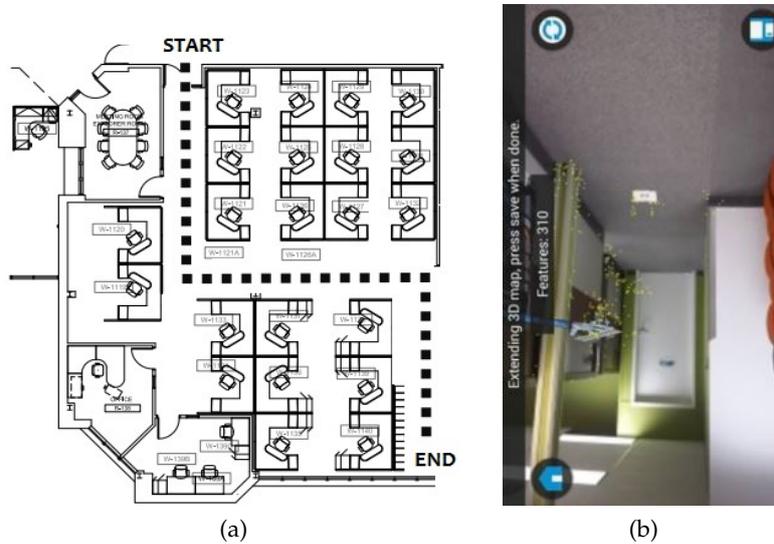


Figure 4.4.: Figure 4.4a depicts a map with a route which was used during the scanning process and Figure 4.4b shows a 3D scanning process underway. Various areas (approximately 2 m in length) on this route were 3D scanned for environmental features. The features scanned at the time were 310 however these features were increased to 1500 to ensure that the area has been adequately populated with features for future tracking.

4.4 INFORMATION OVERLAY AND TRACKING

After the routes were fully scanned, the images were exported to Metaio SDK for AR information overlay. The 3D scans of all areas were placed in a sequential order to develop a movie-like timeline progressing from the start to the end of each route. The next step was to add directional instructions on the trackables (e.g., shown in Figure 4.5). Three forms of assistive information were overlaid on the scanned areas. Visual arrows were the first information added. The arrows were superimposed as augmented information on the camera feed, which was then shown to the user via the display devices (for both smartphone and glass cases). In the glass condition, it was not implemented as a see-through display. We used giant, glossy, and green-colored arrows in order to achieve high visual salience on small displays. Three forms of auditory instructions—“turn right, go straight, and turn left”—were also added to the scenario on appropriate places. Finally, text-based visual instructions (same contents as the auditory instructions) was also superimposed on the trackables, providing additional assistance. Other forms of augmentation, such as haptics that could better support people with either hearing or vision impairments, could also be considered in the future; however, the current study was geared towards the normal population. The trackables were properly translated, rotated, and scaled to ensure that AR information was correctly positioned.

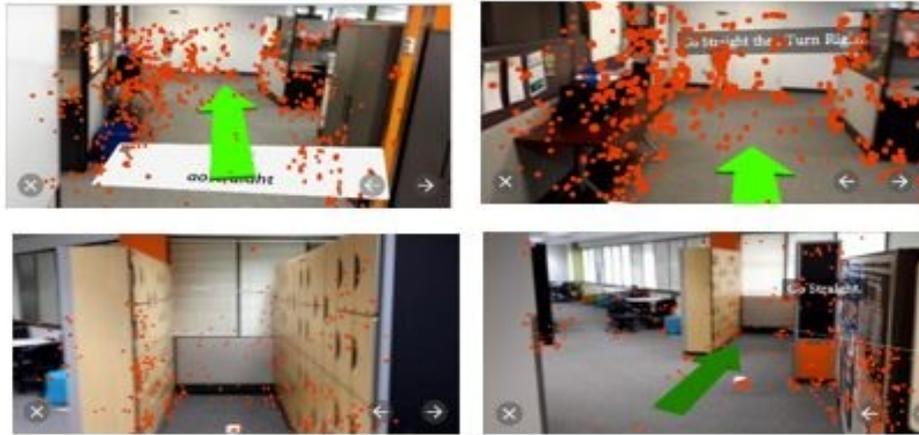


Figure 4.5.: Information overlaid to the scanned 3D point clouds of different areas within the test environment (Rehman & Cao, 2015a). The point clouds were only displayed in the development stage for testing but not shown to the users in the human factors experiment.

The design decisions were made following general guidelines and previous designs in this research field (Mulloni et al., 2011; Billingham, Grasset, & Looser, 2005). Based on these studies we concluded that the major elements for an AR interface in this application should have the following characteristics.

1. Elements should be easy to discern.
2. Voice augmentation should be added to complement visual instructions.
3. All major areas should have adequate information to prevent navigation errors.
4. Virtual content should be meaningful, simple, commonly used, and context aware.
5. The most suitable tracking method should be utilized.

Our application used elements which were easily discernible, turn by turn voice augmentation was also added. Navigation instructions were comprehensively distributed on the route, the virtual content such as arrows and audio instructions were: meaningful, simple, commonly used, and context aware and we utilized 3D point cloud tracking as that seemed to be the most appropriate option for indoor navigation scenarios.

When the application was tested on the testing site using both google glass (HMD) and Samsung Galaxy S4 (hand-held), the interface updated navigational cues in real time as the user moved through the areas (Figure 4.6). The trackables were quickly detected, and the application processing was swift. The auditory augmentation was helpful and made the application more intuitive. Visual 3D arrows properly showed the directions and moved accordingly as the user walked around.

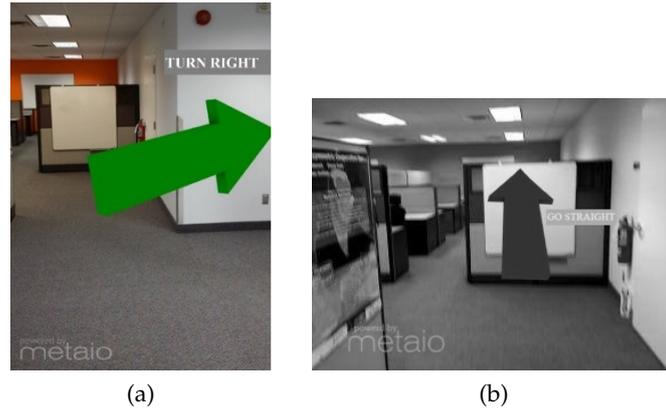


Figure 4.6.: Figure 4.6a shows application implemented on Samsung Galaxy S4. Figure 4.6b shows application implemented on google glass. Visual information aids (arrows and words) were superimposed onto the camera feed, which was then shown to the user via the display devices.

5 TECHNICAL ASSESSMENT RESULTS AND DISCUSSION

Technical performance assessment was conducted to evaluate the technology in terms of its feasibility and efficiency. We carefully measured the time needed for successful feature detection, processing of those features, and the subsequent display of auditory and visual instructions (specific results mention in Table 5.2 on page 25). Since we needed to quantify very short durations of time, a separate software program was developed to record important time stamps. Feasibility was determined by analyzing the application’s ability to detect the percentage of features in a walking-speed controlled scenario as well as analyzing the walking speed threshold. The technical assessment was conducted on nine evenly distributed areas of a route as shown in Figure 5.1. The height of users and the height where they held the phone camera were not considered as independent variables in this study. Participants generally held the phone around the shoulder or neck level. Participants’ variation in heights also represented the same fact from the general user population.

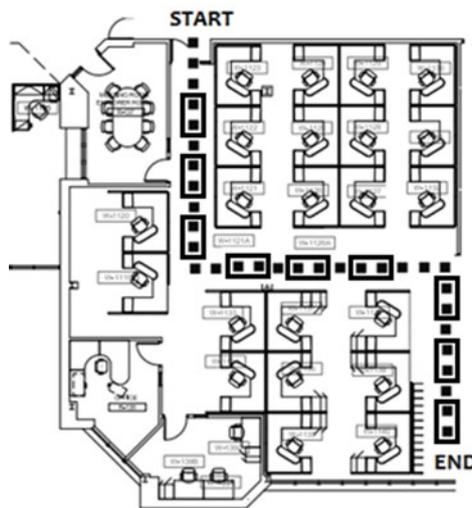


Figure 5.1.: Nine areas on the route that were chosen for the technical assessment.

A critical factor determining localization accuracy is how many features (rather than pixels) can be recognized in each camera view (Rusu, Marton, Blodow, Dolha, & Beetz, 2008; Irschara, Zach, Frahm, & Bischof, 2009). Ideally, a considerable number of features should be tracked in a minimal amount of time so that AR information could be accurately overlaid without any noticeable delay. However, there are concerns with specific usage scenarios. For example, if a user is walking very fast and expected to take a turn, but the system still needs more time to identify sufficient features, a delay in information delivery could happen, which could negatively affect overall performance and user experience. In some possible but rare situations, if a user passes a target location way too swiftly, there will not be enough time for the camera to adequately capture the trackables, preventing the system from working properly. We used the percentage of recognized features as the measure

because it allows results to be compared across different locations and camera views. System time responses were also measured.

In the current study, as the first step towards testing AR-based indoor navigation systems, we scanned the testing area with visual features in nine areas that were uniformly distributed along the route. All technical experimentation was done in these nine areas where each area was roughly equal to 2 m in length. For experimental purposes, feature detection and AR overlay processes would only initiate after the user was physically present in the area. A total of four different assessments were conducted on the testing route. The assessments were conducted first on google glass, which is the focus device of this study, and then on a smartphone.

In the first assessment, we wanted to figure out the minimum percentage of features that are needed to initiate AR overlay processing for the application. In this assessment, the user started from a fast walking pace and gradually reduced the speed until there was enough time to collect the minimum number of features. The first study was repeated four times and we programmed a separate internal script that could record the number of tracked features. The results (Figure 5.2) showed that on average, the minimum feature percentage needed was approximately 45%, with some variation across different areas. Regarding the corresponding actual number of features, that was on average about one feature in each 2.3 degree horizontal by 2.3 degree vertical visual field of view. Not all directional information was successfully overlaid on the trackables but adequate information was conveyed to the user, leading the user to the destination successfully. Overall, the speed threshold (i.e., the fastest pace that the user can walk without causing system localization failures) was found to be around 6.4 km/h to 7.6 km/h. Previous studies found that the general walking speed is around 3.4 km/h to 5.5 km/h (Fitzpatrick, Brewer, & Turner, 2006), which is below the threshold speed. As a result, we could expect our system to be feasible for practical use at normal walking speed.

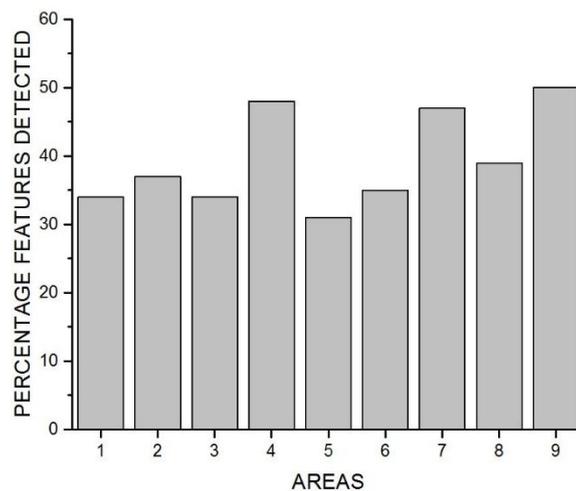


Figure 5.2.: Minimum percentage of features needed to initiate AR overlay processing.

In the second assessment, we wanted to test the feasibility of the application in a fast walking scenario. For this assessment, our test user maintained an average walking speed of 6.4 km/h, which is much faster than the normal walking speed (about 30% more). We

conducted four trials with this speed on the route and found out that the user was spending on average 0.7 s per area. Therefore, we wanted to test the percentage of features the application could successfully detect in 0.7 s. The results (Figure 5.3) indicated that on average 50.6% of features were successfully detected, allowing navigation aids to be displayed correctly and promptly without any major issue. The results validated the application’s effectiveness at a faster walking pace.

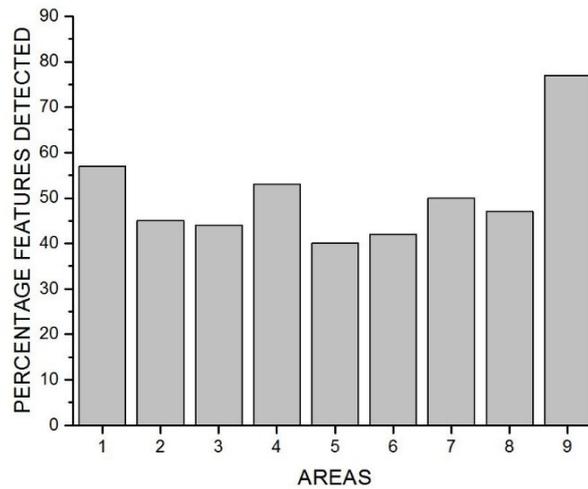


Figure 5.3.: Percentage of features detected in a 0.7 s time limit for each area.

The third assessment was conducted to figure out the average speed and maximum time the application would require to work ideally. The ideal condition is when 95% of the features are detected at a particular position because 95% of features could seamlessly communicate all navigational instructions as well as process future instructions. This assessment was repeated six times and the maximum time for the system to identify 95% of features was mostly under 1 s at all areas while walking at an average speed around 4.3 km/h and nothing going below 3.8 km/h. The average speed of 4.3 km/h was within the general walking speed range, so it validated that this application could operate ideally with maximum efficiency at a slower walking pace. In particular, this result showed that the user travelled 1.2 m on average before the system detected 95% of the features. Refer to Figure 5.4 for more details.

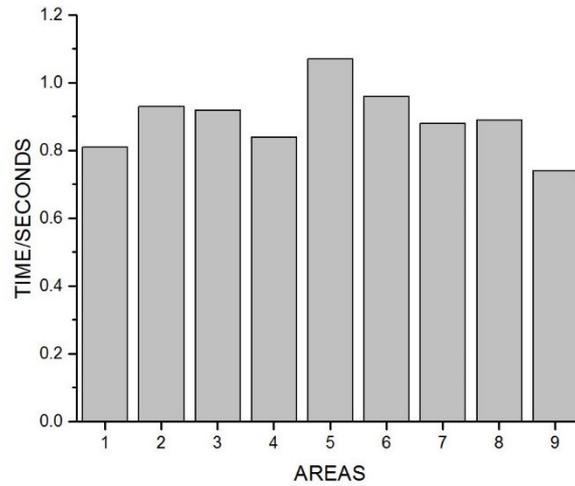


Figure 5.4.: Time taken to detect 95% of features.

Analyzing the time needed for each type of AR display was also crucial to determine the efficiency of the technology. As previously introduced, the two types of navigational assistance include visual direction (arrows and texts) and auditory direction (speech). We developed a testing program that could estimate the time for processing each kind of navigational assistance. This assessment was trialed five times and overall, the average time for google glass to produce audio augmentation was 0.18 s, and for visual direction arrows and texts, it was 0.14 s. The average distance travelled was less than 0.5 m during this time period (Figure 5.5).

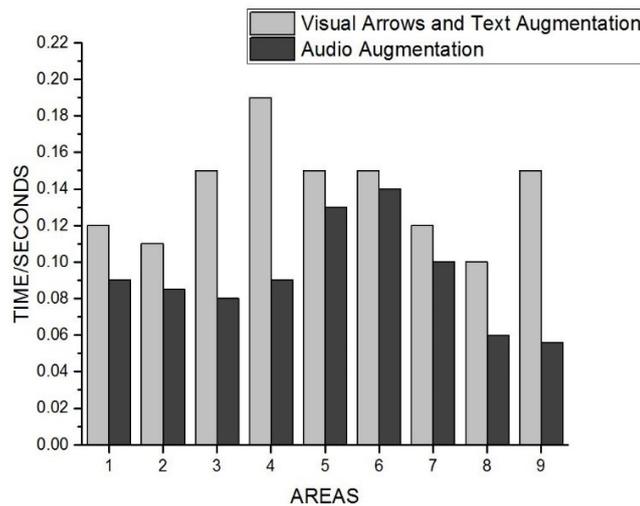


Figure 5.5.: Time needed to generate each type of navigational information.

After examining the application on Google Glass™, we also wanted to examine the same application’s performance on a hand-held smartphone/cell phone. A Samsung S4 Galaxy

cell phone was used in the test. Below we listed the specifications of the two devices (Table:5.1). The comparative performance results were listed in Table 5.2, which shows similar results from both devices.

Specifications	Google Glass	Samsung S4 Galaxy
Form-Factor	Monocular	Slate
Weight (grams)	50 g	130 g
Processing Unit	OMAP 4430 SoC, dual-core	Soc Exynos 5 Octa 5410, 1.6 GHz quad-core Cortex-A15
Operating System	KitKat for Glass	Android 4.2.2 "Jelly Bean"
Storage	16 GB flash memory total (12 GB of usable memory)	32 GB (8 GB used by the system) and 64 GB microSDXC
Memory	2 GB RAM	2 GB LPDDR3 RAM
Power	570 mAh Internal lithium-ion battery	2600 mAh External lithium-ion battery
Display	Prism projector, 640x360 pixels, covering $13^{\circ} \times 7.3^{\circ}$ of the visual field	Super AMOLED, 1920x1080 pixels
Sound	Bone conduction transducer	Qualcomm DAC
Camera	5 MP Camera, f/2.48 aperture, focal length of 2.8mm, FoV ($75.7^{\circ} \times 58.3^{\circ}$) with 2528 x 1856 pixel resolution. During video recording, image gets encoded to 1280 x 720 pixels at 30fps (720p)	13 MP Camera, f/2.2 aperture, focal length of 4.2mm, FoV ($69^{\circ} \times 49.6^{\circ}$) with 1920 x 1080 pixels at 30fps (1080p HD)

Table 5.1.: Hardware Specification of Devices

	Google Glass	Samsung S4 Galaxy
Minimum percentage of features needed to initiate AR overlay processing.	45.0% (34%, 37%, 34%, 49%, 53%, 35%, 46%, 67%, 50%) on average for the nine locations with the speed between 6.4 km/h to 7.6 km/h.	42.7% (31%, 32%, 22%, 36%, 47%, 33%, 46%, 72%, 66%) on average for the nine locations with the speed between 6.0 km/h to 7.9 km/h.
Percentage of features detected at a fast walking pace.	50.6% (57%, 45%, 44%, 53%, 40%, 42%, 50%, 47%, 77%) on average for the nine locations with an average speed of 6.4 km/h and minimum speed of 5.5 km/h.	44.3% (36%, 38%, 40%, 24%, 55%, 63%, 48%, 41%, 54%) on average for the nine locations with an average speed of 6.5 km/h and minimum speed of 5.3 km/h.
Time taken to detect 95% of features.	95% of features detected under 1 s (0.81 s, 0.93 s, 0.92 s, 0.84 s, 1.07 s, 0.96 s, 0.88 s, 0.89 s, 0.74 s) for all nine areas with an average speed of around 4.3 km/h.	95% of features detected under 1 s (0.76 s, 0.74 s, 1.01 s, 0.85 s, 0.92 s, 0.99 s, 0.93 s, 0.9 s, 0.82 s) for all nine areas with an average speed of around 3.9 km/h.
Time needed to generate each type of navigational information.	0.18 s (0.17 s, 0.25 s, 0.2 s, 0.19 s, 0.13 s, 0.14 s, 0.2 s, 0.19 s, 0.16 s) on average for all nine locations to generate audio augmentation; 0.14 s (0.12 s, 0.11 s, 0.15 s, 0.19 s, 0.17 s, 0.15 s, 0.12 s, 0.1 s, 0.15 s) on average for all nine locations to generate visual direction arrows and texts.	0.22 s (0.2 s, 0.27 s, 0.18 s, 0.23 s, 0.15 s, 0.24 s, 0.23 s, 0.26 s, 0.24 s) on average for all nine locations to generate audio augmentation; 0.13 s (0.09 s, 0.16 s, 0.13 s, 0.11 s, 0.1 s, 0.12 s, 0.1 s, 0.2 s, 0.17 s) on average for all nine locations to generate visual direction arrows and texts.

Table 5.2.: Comparative analysis of technical performance assessments conducted on google glass and on android cell phone using the same AR-based navigation technology.

6 HUMAN FACTORS STUDY

The overall goal of the human factors study was to test and evaluate the human performance and workload of using the AR-based indoor navigation system, by comparing the results across the three types of navigational aids including AR navigation implemented on google glass, AR navigation implemented on a smartphone, and a traditional paper map. The paper map was included as a baseline condition. The digital navigation devices (google glass and cell phone) use an egocentric perspective whereas the paper map uses an exocentric perspective (Wickens, Liang, Prevett, & Olmos, 1994). Participants were recruited to navigate an indoor environment using the three aids in a within-subject design. The human factors measures included traversal time, perceived accuracy, subjective workload, and route retention error.

To navigate successfully, people rely on spatial knowledge and cognitive abilities that can build and use such knowledge. Human spatial knowledge in topographic contexts includes three levels – landmark knowledge, route knowledge, and configurational knowledge (Raubal & Egenhofer, 1998). As people navigate, they tend to build spatial knowledge about the area into cognitive maps that represent the real world area (Kuipers, 1982). When more cognitive resources and attention efforts are used to process spatial information and build the cognitive maps, the results often leave a stronger and keener trace in memory.

Digital navigation aids (Google Glass™ and cell phone conditions in the current study) provide turn by turn guidance and use an egocentric perspective, which is similar to the perspective of mental route knowledge represented as a sequence of egocentric visual images of landmarks with directions (Gillner & Mallot, 1998). Users cognitive maps formed while using digital navigation aids are often limited because of the ease to use the same egocentric perspective and the lower level of cognitive processing involved in passively following directions. In contrast, using a paper map involves much more cognitive processing and effort. It requires spatial information to be mentally converted from the exocentric to the egocentric perspective. This helps the user develop comprehensive spatial cognitive maps (Filimon, 2015). While navigating with a exocentric map, users often need more cognitive processes such as mental rotation and zooming to establish correspondence between the map and the real world view (Harwood & Wickens, 1991). This is why navigation with the exocentric perspective is often more difficult and time consuming than egocentric navigation (Harwood & Wickens, 1991; Lee & Cheng, 2008). However, active and deeper mental processing helps the learning and retention of cognitive maps (Bakdash, Linkenauger, & Proffitt, 2008).

Based on the theories and previous research findings, we expected that digital navigation aids would require less mental workload and time and would be perceived as more accurate when compared against the paper map; however when using the paper map, participants would retain more spatial knowledge and hence would have less route retention error. Due to the natural characteristics of HMD, we expected that google glass would be better at conveying AR directional information than the hand-held cell phone.

6.1 METHOD

6.1.1 *Participants*

Thirty nine adults (24 males and 15 females), all of whom were students from University of Waterloo, participated in this study. None of them had any previous experience with mobile navigational aids in indoor environments; however, all were well aware of mobile navigational aids and had experienced them in outdoor environments. The majority of the participants stated that they were confident in navigating in indoor environments with or without navigation aids. All had normal or corrected-to-normal visual and auditory acuities. The participants had various levels of familiarity with the testing environment. Some of them were very familiar with the environment, whereas others had never been there before. This individual difference should not affect the results because a within-subject design was used.

6.1.2 *Tasks and Materials*

Three different routes (Figure 6.1a) were formulated and optimized for the experiment to ensure that navigational instructions were added at the most appropriate places. Once the user interface was properly designed, it was deployed on both the hand-held device (Samsung Galaxy S4-Android Cell Phone) and a wearable device (Google Glass™). The third navigational aid was a paper map, which was a CAD version of the entire floor plan.

The tasks required the participants to navigate through the test location and find specific books located on different shelves using different types of aids. Such tasks are typical representations of indoor navigation. When the participants approached the shelf using AR based digital aids, the audio channel informed the participant the target shelf number, and the visual channel pointed an arrow at that shelf alongside the text showing the shelf number. While using the paper map the user read the shelf number from the paper and visually searched for it. In the map retention test after the completion of the experiment (completing all three routes), participants were given a similar but not identical version of the floor plan to re-draw the routes (Figure 6.1b) as they remembered.

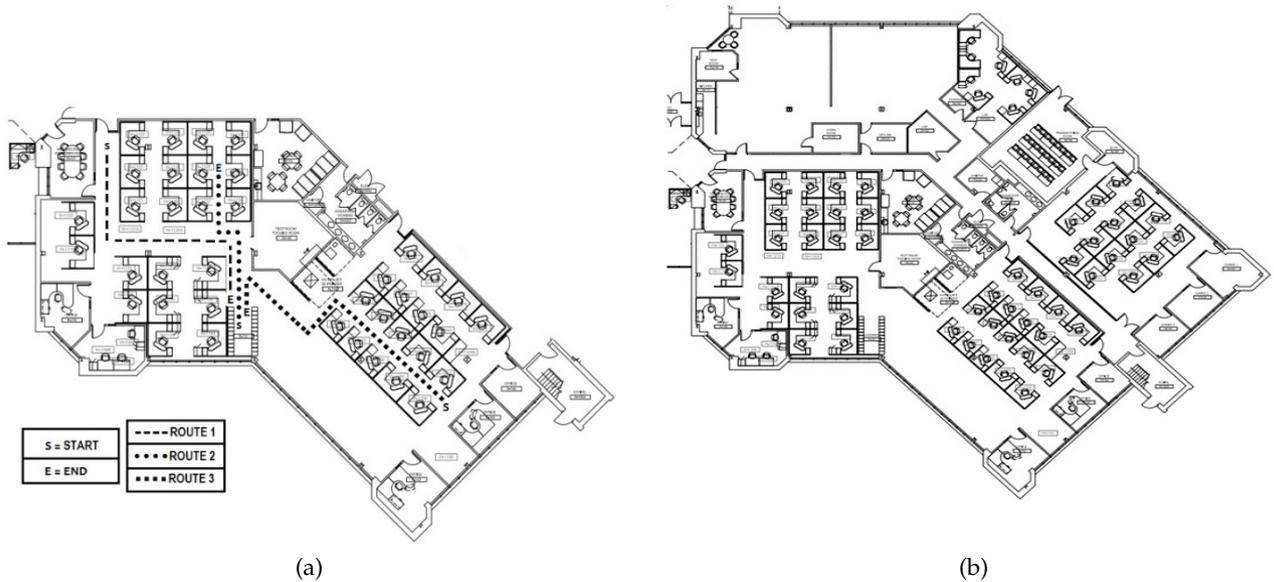


Figure 6.1.: Figure 6.1a shows the three different routes used in the experiment. In the paper map condition, this map was given without the start points and the routes. Only the end points were shown. Figure 6.1b shows the version of map that was used in the map retention test. No start point, end point, or any route was shown.

6.1.3 Experimental Design and Measures

The experiment used a within-subject design. The independent variable was the type of navigation aids, including three conditions that include paper map, cell phone (hand-held) and google glass (wearable). The order of experiencing the three navigational aids was balanced across subjects using a Latin square design. In addition, each navigational aid was equally tested on the three unique routes. The dependent variables included subjective workload ratings using NASA-TLX (raw overall score), perceived accuracy, contextual retention error, and efficiency (i.e., traversal time/task completion time). Each dependent variable was individually measured for the three navigational aid conditions. With the hand-held cell phone, the application would automatically re-orient the display in landscape or portrait based on user preference. Majority of the participants used it in portrait. The google glass view was landscape.

In order to measure unprepared route memory retention performance, the participants were asked to re-draw all the three trajectories only after completing all the three routes. Since the order of experiencing the three aids were balanced, the carryover effects should be controlled. Distance errors resulting from participants' map drawing were used to quantify the route retention error. The three target routes (Figure 6.1) had the shortest distance to their destinations, and therefore any extra distance drawn by the participants meant error. We compared the target routes on the map with the routes drawn by the participants, by superimposing both of them on a single map. The additional distance drawn by the participants was recorded as map retention distance error. In order to measure efficiency performance, we recorded the time taken by each subject to complete a single route (traversal time) for each device and calculated the average value for each aid condition. In addition, perceived accuracy was obtained through a questionnaire (5-point Likert scale) conducted after the experiment. Perceived accuracy here refers to how accurate the users perceived

the navigational aids to be. It is not about the accuracy of 3D feature tracking algorithms used in this study. We used 3D feature tracking as an established method. Regarding the measurement and verification of 3D feature tracking accuracy, previous studies have documented the technical details, for example, benchmarking with corresponding ground truth poses or benchmarking with device data including inertial sensor data (e.g., gravity, acceleration, and rotation rate), camera properties (e.g., shutter time, gain, and focus), and time stamps (Kurz & Ben Himane, 2011; Kurz, Lieberknecht, Benhimane, & others, 2011; Kurz, Olszamowski, & Benhimane, 2012; Lieberknecht, Benhimane, Meier, & Navab, 2009; Pentenrieder, Meier, Klinker, & others, 2006). We did not cover the details here due to limited space in this paper. The questionnaire in the current study also included other subjective evaluation questions for wearability comfort, usability control comfort, display comfort ratings, and subjective workload (raw NASA-TLX, without the weighting procedure).

6.1.4 Procedure

First, the participants read the information letter that described the details of the experiment, and then they filled the consent form and the pre-experiment questionnaire. Short practice for about 5 minutes was provided for them to get familiar with the devices. Most participants had not used google glass before, so we gave them adequate time to practice with the navigational technology until they felt fully confident to initiate the formal experiment. In each of the three trials, each participant was instructed to navigate using one of the three aids (wearable, hand-held phone, and paper map) from the start location to the end location, taking the shortest route. Each end location was a locker at the test location. They were instructed to arrive at the destination as quickly as possible with a reasonable and safe walking speed in the same way for all three navigation conditions. Although different individuals may have different baseline walking speed, it should not affect our results because we used a repeated measures design. The experimenter shadowed and timed the participants. Once the participants completed testing the three aids, they were asked to fill the post-experiment questionnaires. Finally, they were given a blank floor map (Figure 6.1b) and were requested to draw the three routes as they remembered during the experiment. The participants drew all the three maps at the end after they had finished navigating all the routes and spent a few minutes filling the post experiment questionnaire.

6.2 RESULTS

Initially, repeated measures multivariate analysis of variance was conducted using SPSS (Version 22) to determine the effect of navigational aid type on the dependent variables, which included traversal time (task completion time), perceived accuracy, NASA-TLX (workload score), map retention distance error, and subjective evaluation scores (wearability comfort, display comfort, and usability control comfort).

Preliminary assumption checking revealed that there was no univariate or multivariate outlier, as assessed by boxplot and Mahalanobis distance, respectively; there were linear relationships, as assessed by scatterplot; no multicollinearity was present as assessed by Pearson correlation. The data was not normally distributed, as assessed by Shapiro-Wilk's and Kolmogorov-Smirnov's test ($p < 0.001$). The assumption for homogeneity of variance/covariances, as assessed by Box's test of equality of covariance ($p < 0.001$), was also not met. However, multivariate analysis of variance are robust to violations of multivariate normality and violations of homogeneity of variance/covariance, if groups are of nearly equal

size (Finch, 2005; Leech, Barrett, & Morgan, 2015; “One-way MANOVA in SPSS Statistics | Laerd Statistics Premium,” n.d.). Since our groups were indeed of an equal size, we continued with the analysis. The MANOVA result showed that the effect on the dependent variables combined was significant, $F(12, 220) = 9.735$, $p < 0.001$; Pillai’s Trace = 0.694; partial $\eta^2 = 0.347$.

Then we followed it up with repeated measures analysis of variance using SPSS (Version 22); pairwise comparisons were conducted (with Bonferroni correction) to compare the three types of aids. One-way repeated measures analysis of variance is also considered to be very robust against the violation of normality; Greenhouse-Geisser correction was consulted when the sphericity assumption was violated (Howell, 2012; Norman, 2010; “One-way repeated measures ANOVA using SPSS Statistics | Laerd Statistics Premium,” n.d.).

The effect of aid type on perceived accuracy was significant, $F(2, 76) = 29.622$, $p < 0.001$, $\eta^2 = 0.438$ as shown in Figure 6.2a. The wearable aid (4.46) was perceived to be more accurate than both cell phone (3.67) and paper map (3.00) conditions (p values < 0.001); difference of perceived accuracy found between the cell phone and paper map conditions was also significant ($p = 0.011$).

The effect of aid type on map retention distance error was also significant, $F(2, 76) = 11.056$, $p < 0.001$, $\eta^2 = 0.225$. No significant difference was found between the wearable (1.67 m) and cell phone (1.54 m) conditions ($p = 1.000$), but both conditions had significantly larger retention error than the paper map (0.63 m) condition (p values ≤ 0.001) as shown in Figure 6.2b.

Similarly, the effect of aid type on NASA-TLX overall workload score was significant, $F(2, 76) = 40.239$, $p < 0.001$, $\eta^2 = 0.514$. No significant difference was found between the wearable (21.52) and cell phone (28.53) conditions ($p = 0.059$), but both of them had significantly smaller overall workload than the paper map (52.39) condition (p values < 0.001), shown in Figure 6.2c.

The effect of aid type on traversal time (task completion time) was significant, $F(1.371, 52.116) = 10.515$, $p = 0.001$, $\eta^2 = 0.217$, using the Greenhouse-Geisser correction $\epsilon = 0.686$, because Mauchly’s Test showed that the sphericity assumption was violated, $p < 0.001$. No significant difference was found between the wearable (111.26 s) and cell phone (118.03 s) conditions ($p = 1.000$), but both of them had significantly shorter completion time than the paper map (219.21 s) condition (p values ≤ 0.008) as shown in Figure 6.2d.

No significant effect was found on the wearability comfort ($p = 0.162$, $\eta^2 = 0.047$) between the wearable (3.46), cell phone (4.05), and paper map condition (3.64). Similarly no significant effect was found on usability control comfort ($p = 0.224$, $\eta^2 = 0.078$) between the wearable (3.97), cell phone (3.74), and paper map condition (3.58). Also no significant effect was found on display comfort ratings ($p = 0.221$, $\eta^2 = 0.039$) between the wearable (3.36), cell phone (3.79), and paper map condition (3.69).

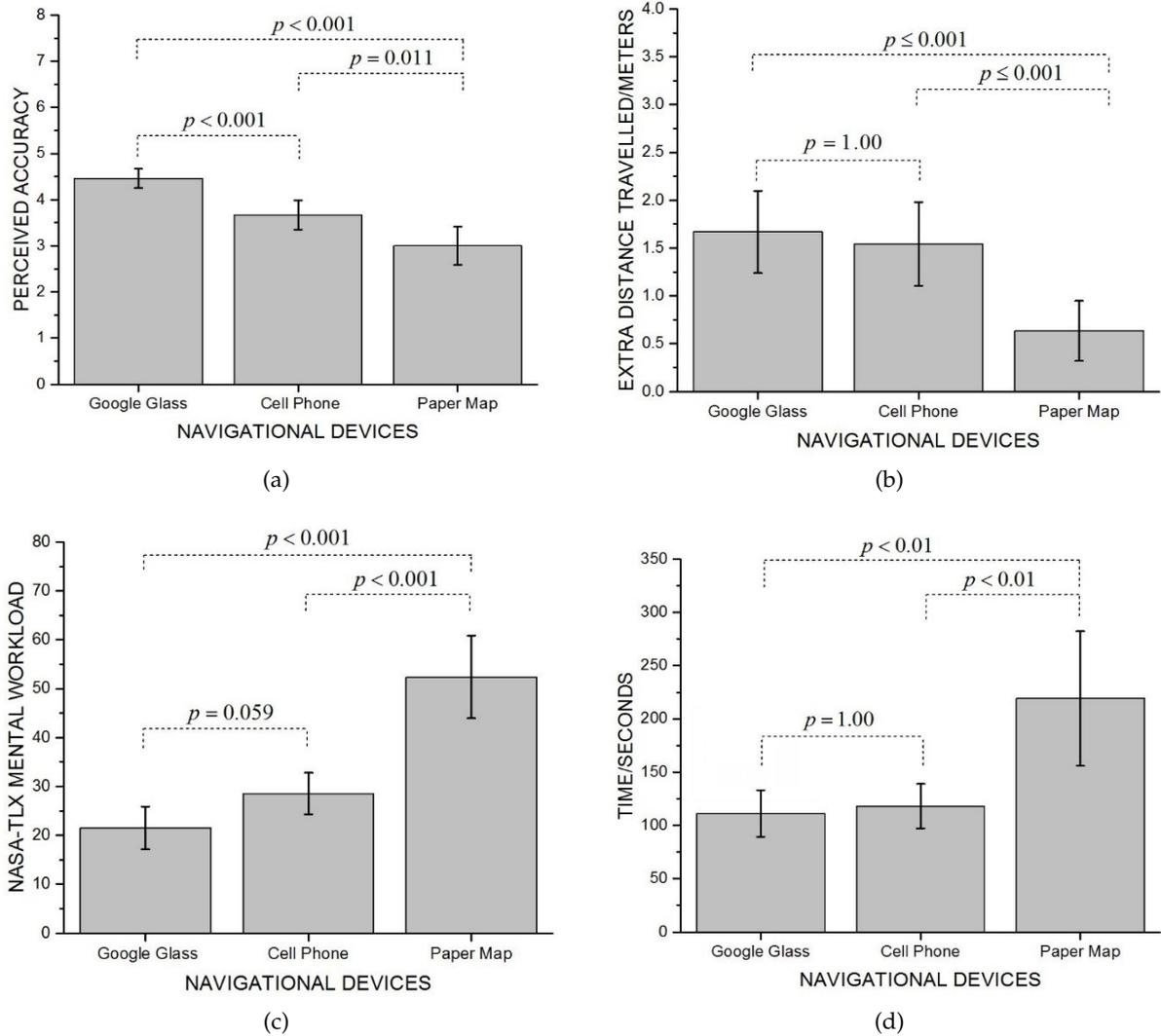


Figure 6.2.: Figure 6.2a shows effects of navigation aid type on perceived accuracy. Figure 6.2b shows effects of navigation aid type on retention error. Figure 6.2c shows effects of navigation aid type on NASA-TLX overall workload rating. Figure 6.2d shows effects of navigation aid type on route traversal time. Error bars represent 95% confidence interval.

6.3 HUMAN FACTORS STUDY DISCUSSION

In this human factors experiment, the wearable device (Google Glass™) was perceived to have the best accuracy. A potential explanation for this would be that the camera of the wearable device was located at a higher position than the hand-held cell phone; the high position gave it a wider view for feature tracking, and it was also a more natural viewing angle. The camera of the cell phone was usually held at the mid-body level that is different from the normal viewing angle, and therefore it may be perceived as unnatural and less accurate. Also the HMD on the wearable device made the AR experience more intuitive. The virtual representation of directional instructions on the camera feed was directly concentrated on the pupil of the eye, and the camera also adjusted naturally with head movement.

This feature enhanced the navigational experience of the wearable device as its interface became more focused and adaptive.

A disadvantage of the cell phone condition is that it has to be held in an upright position, which made users tired. The way users held the cell phone while navigation is not an ergonomic posture to maintain while walking. In contrast, HMD (such as google glass) does not have this issue. The results from the current study, however, did not show this disadvantage of the cell phone, probably because the route and test time were not long enough. Future studies need to test and compare the devices in longer routes with longer test duration to investigate this issue.

The traversal time was not significantly different between the wearable and the cell phone conditions. The traditional paper map, however, was a very slow medium for directional assistance. It took participants almost twice as much time as the two electronic device conditions. An explanation is that when using the paper map, users have to mentally understand and rotate the map and then translate it to the contextual environment. This is same as our expectation based on previous study findings.

No significant difference was found on subjective comfort ratings (wearability comfort, usability control comfort, and display comfort) across the three aid types. This is possibly because each individual device had certain drawbacks that influenced the participants' experience. The cellphone had to be kept at a certain position and orientation in front of the head for the augmented information to match the real-world perspective. Glass has a display resolution smaller than the smartphone, and the display contrast may be low due to background glare. For the paper map condition, the floor plan was not easily explicable because the paper map had excessive information that made discerning the area of interest challenging.

The NASA-TLX results showed that navigation using the paper map caused the highest workload. The participants had to analyze where they were on the map with respect to the environment and also identify their target location; then they had to constantly analyze the surrounding for potential clues. All this yielded a heavy toll on the time taken to complete the experiment and raised participant dissatisfaction. The workload values in the wearable and cell phone conditions were lower since neither was a cognitively strenuous exercise.

Another key aspect we wanted to evaluate was route retention in case the user had to navigate the same routes without the navigational aids. We concluded that the wearable device and the cell phone performed poorly in this test as the retention errors were larger than the paper map condition. In the map retention test, we used a paper map similar (but not identical) to the one used in the navigation condition. Alternatively, a blank piece of paper could be used. The advantage of using a blank paper is that it would not provide any reminder of the paper map used in the navigation test. However, the disadvantage of using a blank paper is that it would be very difficult to quantify map retention error without the necessary spatial and distance references (e.g., walls and corridors). As a result, we chose to use a similar paper map in the retention tests with design considerations to minimize its potential disadvantages. The navigation activity using the paper map was for a relatively short period of time (several minutes). There was a time delay from using the map as a navigation aid to the map retention test (at least 10 minutes). The participants were asked to complete other survey and workload questionnaires before finally asked to complete the memory retention test, minimizing any trace of the navigation map in the working memory. Participants were not told that there would be a map retention test until after all the navigation tests, so they should not have strong motivation to memorize the map. The navigation map did not contain start points or the shortest route information. Moreover, previous studies that administered a similar sketching question, on a blank paper, also reported results

indicating that users of digital navigation devices had poorer understanding of the routes as compared to those who used paper maps (Ishikawa, Fujiwara, Imai, & Okabe, 2008). Nevertheless, it is a potential limitation that the retention test paper map looks similar to the navigation aid paper map. An improvement in future studies could be adding the use of a blank paper as the first step of retention test, followed by the second step using a map with necessary spatial information. Combining the two methods may give a more comprehensive evaluation of map retention.

7 CONCLUSION AND FUTURE WORKS

In summary, we conducted both a technical assessment study and a human factors study to comprehensively evaluate the developed novel AR-based indoor navigation systems. In the first technical assessment, the results showed that on average, the minimum average feature percentage needed to conduct appropriate navigation on the route was approximately 45%. In the second assessment, walking on the route at a faster speed than the general walking speed, we found that 50.6% of features were successfully detected on average, therefore detecting more features than the minimum needed. Both the first and second assessments found that the general walking speed to be lower than the threshold speed that was maintained during experimentation, therefore indicating that our developed system was feasible for practical use at moderately fast walking speeds. The third assessment was conducted to figure out the average speed and maximum time the application would entail to work ideally (detect 95% of features). The maximum time for the system to identify 95% of features was under 1 s at all areas with an average speed of around 4.34 km/h, which validated the fact that this application could operate ideally with maximum efficiency at normal walking speeds. In the last assessment, we measured the average time it took google glass to produce audio augmentation and visual direction information, which was 0.18 s and 0.14 s respectively. This result confirmed that the application was highly efficient and able to quickly process and display the directional information.

In the human factors experiment, the wearable device (google glass) was perceived to have the best accuracy. The traversal time was not significantly different between the wearable and the cell phone conditions; however, the paper map condition was comparatively time consuming. No significant difference was found on subjective comfort ratings (wearability comfort, usability control comfort, and display comfort) across the three aids. The NASA-TLX results showed that navigation using the paper map caused the highest workload. We concluded that the wearable device and the cell phone performed poorly in the memory retention test as their errors were much larger than the paper map condition. The wearable device was perceived to be more accurate, but objective performance and subjective workload results indicated that the wearable device condition was not significantly different from the hand-held cell phone condition. This result might be explained by the fact that the current experiment was conducted in a simple indoor environment and used relatively shorter routes. We also faced technical difficulties as the google glass had limited battery life, and 3D scanning during the pre-deployment stages was time consuming and complicated, which hampered our ability to conduct large scale tests. Based on the current results, we concluded that AR indoor navigation implemented on the wearable device was neither worse nor better than the cell phone implementation. However, we still expect that the wearable implementation would be preferred if the task was performed for longer duration in a more complex environment. The current study, however, would form the basis for future research that could aim to use technologically superior wearable devices with better battery life and higher computational powers. Computer vision technologies provide an effective alternative to other sensor-based localization and navigation methods especially for indoor navigation purposes. While many of them had been extensively investigated before, 3D point cloud based environment tracking has not been thoroughly studied. In this study,

we detailed an implementation of this tracking technology on google glass. The empirical results could inform future developers designing indoor navigation systems.

Various aspects of this study could be potentially pursued for future research. Firstly, a dynamic localization module within the application could be developed in order to accomplish a comprehensive position-error analysis so that this technology could be quantitatively compared to other positioning technologies such as Wi-Fi and Bluetooth. In the current experiment, we investigated 3D point cloud tracking for AR information overlay; however other markerless techniques, such as edge model tracking, could also be explored. The impact of environmental features, such as lighting and visual contents of objects, should be examined in order to determine their bearing on the tracking capacity of the system. Future applications of this technology, as well as wearable devices equipped with other sensors, could be individually studied in different industrial settings such as healthcare, gaming, and manufacturing.

Part III

AUGMENTED REALITY-BASED PROCEDURAL TASK ASSISTANCE TO SUPPORT MAIN CONTROL ROOM OPERATIONS IN NUCLEAR POWER PLANTS

This research illustrates the design, development and human factors evaluation of an augmented reality based procedural task guidance system, implemented on a hand-held tablet device (ipad), in order to support nuclear power plant operators with main control room operations.

8.1 OVERVIEW

Task operating procedures are a certain set of activities implemented in accordance with predetermined specifications to obtain desired outcomes. Task operating procedures could vary in complexity therefore it is imperative that human cognitive resources are utilized appropriately. Over the years, different automated and non-automated forms of procedural task assistance have been introduced in order to assist personnel with operational duties. In **NPP** operators utilize standardized procedural tasks to manage Main Control Room (**MCR**) operations. Operators are expected to carry additional teamwork and communication skills alongside the necessary domain knowledge for them to excel in managing **MCR** operations. It is therefore important that the method of procedural instruction utilized should considerably improve overall operator performance. This research introduces a novel procedural task guidance system geared towards the **NPP** industry where task operating procedures are rendered using **AR** cues to **NPP** operators on small handheld tablet devices. It is hypothesized that **AR** based guidance system would improve operator performance, reduce human error and enhance team communication.

8.1.1 *Procedural tasks*

With recent advances in technology, many new systems have been developed that carry the capacity to effectively assist human operators in performing procedural tasks. Procedural tasks by definition are series of activities carried out to achieve a particular goal. A person performs these progressive activities while interacting with objects in the external environment (S. J. Henderson, 2011). Gagne (1977) first stated the term procedural tasks which he defined as the tasks that would entail both motor and cognitive skills. Procedural tasks could be undertaken by a single person or by a team and these tasks would usually vary with regards to the amount of required planning, number of steps, amount of decision points, nature of procedural complexity, flexibility of activity ordering, and type of goal (Ellis, Whitehill, & Irick, 1996). Procedures could be utilized through various practices since some domains would require the user to learn the procedure ahead of time and be prepared while executing it in an actual scenario. Such tasks would entail expert knowledge and a bit of improvisation during actual execution. There are other approaches where the user could be accompanied with certain aids such as checklists or instruction manuals during actual execution of the task. A considerable amount of literature is available that details how people employ procedural tasks for assistance (Eiriksdottir & Catrambone, 2011; Ellis et al., 1996; Humphreys, Bain, & Pike, 1989; Konoske & Ellis, 1991; Robertson, Pascual-Leone, & Miall, 2004). Unlike learning a theory or a model, procedures are clearly defined so that each activity is explicit to the operator. Procedures can be either extremely simple with minimal decision points or overly complex requiring extensive human decision making. Some literary work covers classification of procedural tasks. These classifications have been either domain specific, task focused or geared towards user centricity. Fleishman, Quaintance, & Broedling (1984) conducted prominent research in the area by outlining a comprehensive taxonomy of human abilities and matching them with work requirements.

8.1.1.1 Task Guidance Systems

Various technological systems have been put in place for the development and use of procedures especially after small and inexpensive computer technology came into practice which gave birth to what we call task guidance systems (J. Ockerman & Pritchett, 2000) . Task guidance systems can comprise of different kinds of technologies that provide assistance to operators during task operations. These are interactive guidance systems which can replace the need for paper documentation as shown in Figure 8.1. Operators can harness the power and memory of the devices (mobile, wearable, portable computers etc.) that run these guidance systems to not only experience richer instructional content but also benefit from a number of other features such as menus, hyperlinked media, search technology etc. While approaches for rendering procedural assistance to workers span over a wide range of automated technologies, a technique less frequently studied in this category is the use of AR for task assistance. AR can overlay instructional content virtually on user's physical view of the environment, combining real and virtual elements interactively (Azuma et al., 2001; S. J. Henderson, 2011). AR can hence enhance real world environments and assist users with procedural tasks through overlaid instructions, real-time visualization of hidden objects, superimposed feedback and operational cuing etc.

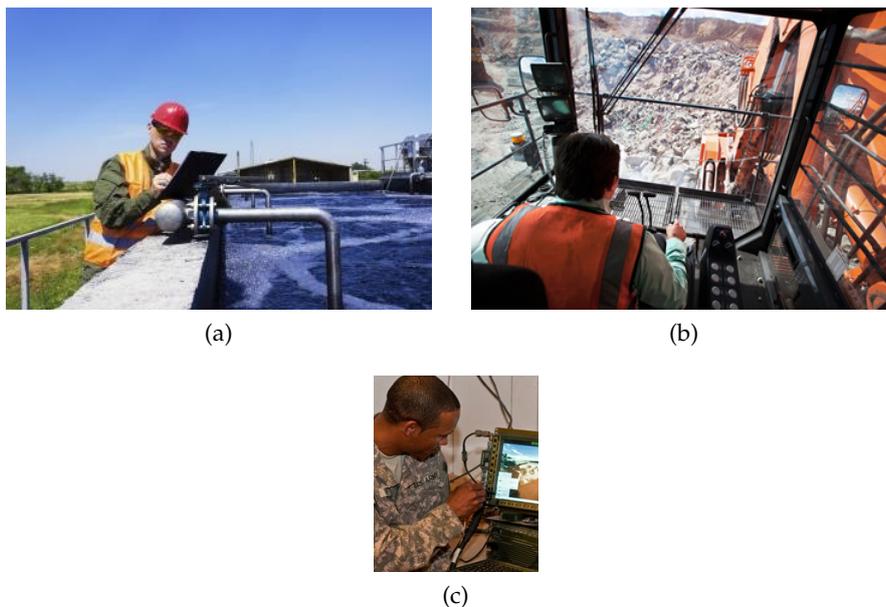


Figure 8.1.: This figure illustrates the different applications of task guidance systems in the industry. Figure 8.1a depicts an operator monitoring meters, and gauges using a tablet based task guidance system in a water treatment facility. Figure 8.1b represents a mine supervisor using an automated machine guidance system attached on the left panel of his vehicle that provides centimetre-level accuracy for all digging, contouring, and data collection operations. Figure 8.1c represents a military mechanic operating a systems repairer to perform sustainment level maintenance and repair of field artillery digital devices. Source:88.

8.1.1.2 Teaching and Learning

Procedural task instructions have been used as a training tool in many industries but mainly to assist operators during task execution. In most cases however the same procedural meth-

ods are used in training which are later utilized during onsite scenarios (Chalupsky & Kopf, 1967). Instrumental research was conducted by Fitts & Posner (1967), who developed the three phase model, that consisted of a cognitive phase, an associative phase and an autonomous phase, to describe teaching and learning of procedural instructions. Later Gagne & Rohwer Jr. (1969), researched into the pedagogy of procedural tasks which drew great anticipation from the academic community as they provided a comprehensive review on instructional psychology discussing in detail “those variables and conditions that appear to have fairly direct applicability to the design of instruction”. Similarly Bloom (1976) emphasized the significance of rehearsal and reappraisal in procedural task instructions. Vineberg (1975) and Schendel & others (1978) provided research that explained how subjects would disremember the procedural task instructions that were taught to them during training. Their research was advanced by Wetzell, Konoske, & Montague (1983) who discussed the reasons behind the lack of memory retention and degradation of acoustic analysis skills during actual task execution.

8.1.1.3 *Design*

Many cognitive psychology and human factor studies have been conducted in past that aim to improve quality instructional design documentation. Researchers, alongside have also explored ways that illustrate how procedural task assistance could be more effectively leveraged using modern technology (automated procedures). The existing research has led to the development of many practical design frameworks, most of them either focused towards a particular industrial domain or are general guidelines that deal with the design of computerized procedures. The current research continues to build on the established principles of instructional design in efforts to develop more effective, structured and consistent forms of procedural task assistance methods. Moore & Fitz (1993) worked towards introducing Gestalt theory to document design. Prominent research towards highlighting user-centered approaches to instructional design was conducted by Van der Meij (1995) who recommended a series of interactive design principles. Wright (1977, 1981) developed a comprehensive set of suggestions that could enhance procedural text and assist users better understand technical prose. Smith & Goodman (1984) conducted experiments to gather empirical data to show the significance of an explanatory schema adjacent to the task that described the structure of the task. Booher (1975) concluded that graphics help could be more efficient during task execution yet text based instruction insured more accuracy. Ellis et al., (1996) extended these findings and concluded that pictures were excellent for pedagogical purposes but did not serve much purpose once the user had mastered the task itself.

8.1.1.4 *Non-Automated Forms of Assistance*

The major non-automated forms of procedural task assistance methods include workcards (Figure 8.2a), checklists and manuals (Figure 8.2b). Workcards, usually used in aviation domain (Patel, Drury, & Lofgren, 1994), are portable paper documents that categorically list the steps of a procedural tasks. They not only assist the user in executing the task but also provide official record of the work that has been achieved as these cards are usually archived once operations come to an end (Drury, 1994). Checklists are very similar to workcards as checklists are portable as well however checklists are not collected as a formal record and mostly reused every time (S. J. Henderson, 2011). Manuals are documents which are comprehensive in detail and would usually embody all the necessary information including diagrams, schematics, conceptual processes, and checklists, which are all critically needed for

task operations. Other less frequently utilized forms of assistance include printed posters, charts, and stickers that are placed in major areas where task operations are performed (Rodriguez & Polson, 2004). These forms of assistance are normally used to assist multiple operators working towards a common task in the field.

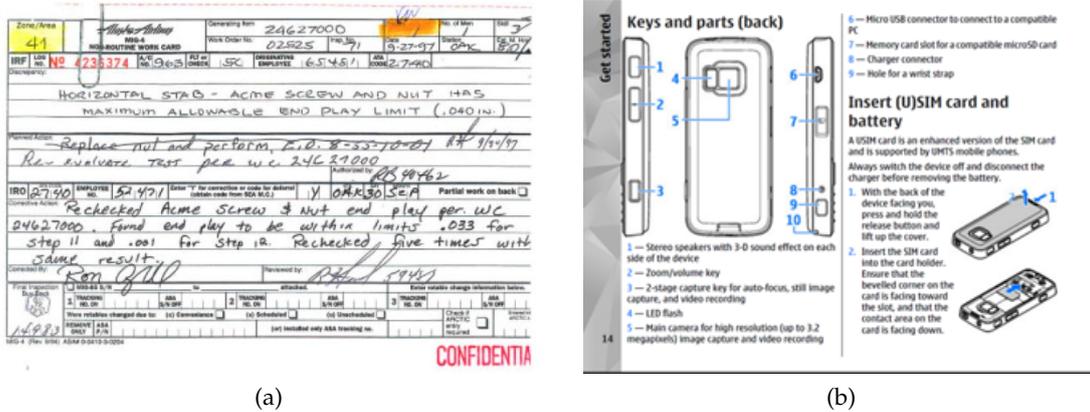


Figure 8.2.: Figure 8.2a shows a nonroutine work card of MiG 4 aircraft filled by a day-shift mechanic and an inspector. Figure 8.2b shows a user manual of a cellphone (Nokia N78). Source:88.

8.1.1.5 Automated Forms of Assistance

The use of automation to leverage assistance during task operations has been a massive area for research. The many benefits of utilizing automated forms of assistance have been continually reported in prior studies that have been conducted across various domains primarily aviation shown in Figure 8.3 (Mosier, Skitka, Heers, & Burdick, 1998; Palmer & Degani, 1991), maintenance (J. J. Ockerman & Pritchett, 2004), process control facilities (Jamieson, 2007), manufacturing (Paquet & Lin, 2002) etc. Earliest forms of procedural automation merely included Electronic Procedures (EP). EP are essentially just mock-ups of PBP, digitally displayed on a Visual Display Unit (VDU), with some additional functionality such as hyperlinks and navigation (Yang, Yang, Cheng, Jou, & Chiou, 2012). Later Computer-Based Procedures (CBP) were introduced that contained functionalities like automatic retrieval and display of precise information, controls to perform a particular step, automatic processing of step logic, automatic checking of preconditions, and efficient display of alerts and warnings (Fink, Killian, Hanes, & Naser, 2009; O'Hara, Higgins, & Stubler, 2000).



Figure 8.3.: Figure 8.3 shows United Airlines pilots using a light weight tablet device in order to replace 38 pounds of operating manuals, navigation charts, reference handbooks, flight checklists, logbooks and weather information found in pilot bag. Source: 88.

8.1.1.6 *Augmented Reality-Based Automation for Procedural Tasks*

AR interfaces for procedural tasks have been used as a pedagogical platform and a medium for operational assistance, primarily in the following domains:

1. Guiding workers with maintenance (Figure 8.4a), repair, inspection, manufacturing (Figure 8.4b) and assembly of equipment (S. J. Henderson & Feiner, 2007).
2. Assisting doctors (Figure 8.4c) performing surgical operations with image guidance (Schulz, Waldeck, & Mauer, 2012).
3. Using AR based cockpit checklists to support pilot tasks (Elder & Vakaloudis, 2015).
4. Supporting field construction workers as shown in Figure 8.4d (Reiners, Stricker, Klinker, & Müller, 1998).
5. Providing movement training to patients suffering from diseases like Parkinsons etc. (Espay et al., 2010).

Studies conducted in the above listed domains confirm certain key characteristics regarding the use of AR interfaces for procedural tasks. AR interfaces significantly reduce head and eye movement which leads to more ‘eye on the workspace’ (Haines, Fischer, & Price, 1980; Steven Henderson & Feiner, 2011). This reduces time for searching information and hence enhances operator performance by making it more efficient and accurate.

AR is believed to reduce the cost of attention switching as the task focus does not get considerably divided between the instructional medium and the workspace. Moreover prior studies have found AR based instructions to improve human cognitive processes and attention guidance (Neumann & Majoros, 1998).

AR is also found to be highly effective for training purposes since most humans tend to learn better when they have a frame of reference in mind as many theories in cognitive science confirm a relationship between spatial location and working memory. Therefore AR based instructional guides carry the ability to bring better task focus through blended

computer graphics, tactically applied to real world view to support cognition and memory (Biocca et al., 2001; Kirsh, 1995) however empirical evidence is essential in support of this notion.

Most current systems for procedural assistance, such as CBP, are hard to integrate with existing displays, panels and other tools whereas AR supports human-machine collaboration and is easy to incorporate in existing infrastructure. In research studies, AR interfaces are usually considered to be the preferred method for procedural instructions as AR interfaces employ ambient cues and multimodal augmentation which makes the overall procedure appear more intuitive and easy to follow (Tang, Owen, Biocca, & Mou, 2003).



Figure 8.4.: This figure illustrates the different industrial applications of AR to support procedural tasks. Figure 8.4a depicts a construction worker using an AR app and a building information modelling software. Together these two applications can enable operators to see the finished structure before it's even built reducing early stage construction errors. Figure 8.4b shows a mechanic wearing a HMD performing a maintenance task on an aircraft engine (S. J. Henderson, 2011). Figure 8.4c illustrates AR being used in a manufacturing facility for a study being conducted to observe how AR impacts operator learning and development. Figure 8.4d depicts a mock surgery with the help of an AR application that overlays complex vascular systems during operations. Source:88.

8.1.2 Task Operating Procedures in Nuclear Power Plants

Modern NPP have been upgraded with digitized control panels rather than old analogue panels and operators can access majority of the information from their personal working

space (Carvalho, dos Santos, Gomes, Borges, & Guerlain, 2008; E. M. Roth, Mumaw, Vicente, & Burns, 1997). A lot of research is taking place to ensure that such automated and digitized systems work in synchrony with operational requirements and human capabilities. The challenge is to maintain effective human-human and human-system interaction therefore different parameters are taken into account before machine interface design (Nachreiner, Nickel, & Meyer, 2006). The principles adopted in the design of the operator control panel must conform to cognitive ergonomic concepts as prior accidents have been attributed to issues arising from poor design approach resulting in weak human-machine cooperation (Kletz, 1998). It is extremely important that the design of a control panel must facilitate adherence to task operating procedures however this might be impractical as it would entail extensive amount of time, expenses and effort in re-designing existing facilities so that they could comply with newly researched ergonomic concepts.

The processes in **NPP** are characterized as 99 % boredom and 1 % panic (Carvalho, dos Santos, Gomes, & Borges, 2008). 99 % boredom during Standard Operating Procedures (**SOP**) which requires uninterrupted monitoring and the 1 % panic is usually during emergency situations which requires effective adherence to Emergency Operating Procedures (**EOP**). Considering the importance of operating procedures in such task critical environments, a lot of safety standards and regulatory codes and practices are placed under deliberation when devising **NPP** procedures. The goal is to develop procedures that are technical correct, efficient, easily comprehensible and accurately executable (Carvalho et al., 2008; Kozinsky, 1982). Environments like **NPP**, where most human operations have been successfully automated, would still require the operators to be conversant with the workings of the system in order to efficiently manage emergency scenarios.

Operator's performance can considerably diminish due to two major issues concerning procedure design and usage. The first issue deals with the fact that a procedure can only be drafted for predictable human events and despite the highest quality procedure design, unforeseen events cannot be entirely prevented (Oxstrand & Le Blanc, 2012). The other major issue deals with how humans tend to deviate from procedural instructions, intentionally or unintentionally, which results in major catastrophes. This concern however can be addressed after analyzing limitations in current procedural support methods. Non adherence to procedures usually occurs due to an inherent weaknesses present in procedure design and delivery. Research related to operating procedures in **NPP** came into limelight after the Three-Mile Island accident (Rogovin, 1979) which was attributed to inferior quality of **EOP** design. Procedural issues have been cited approximately 69 % of the times to be the contributing factor for events leading to unsafe conditions in **NPP** (Paradies, Unger, & Ramey-Smith, 1991; West, Eckenrode, & Goodman, 1991) alongside sensors and feedback to the operators. Operating procedures do get periodically updated and revised, as they have to reflect the changes that take place in the **MCR**, in terms of technology automation, staffing, safety protocols etc. however procedures rarely reflect changes in structure as the same format of delivery is mostly utilized and therefore most plants depict lack of improvement in this area (Niwa, Hollnagel, & Green, 1996).

8.1.2.1 Paper-Based Procedures in Nuclear Power Plants

Many **NPP** accidents occur due to poor structuring and design of **PBP** therefore the US Nuclear Research Council recommended that all **NPP** operating procedures must be appropriately revised and improved based on the set regulatory standards (Lapinsky, 1988). Researchers have also been contemplating on phasing out **PBP** in **NPP** facilities (example shown in Figure 8.5a & 8.5b) and introducing some sort of automated procedures as a re-

placement (Fink et al., 2009). A major drawback in the use of **PBP** deals with the fact that the operators have to spend a significant amount of time searching the required information as **PBP** are extraneously documented, comprising of all possible scenarios that could occur at the facility. Such superfluous detail can be highly counterproductive and risky. Many complex operations would require operators to perform multiple tasks simultaneously which leads to task switching. In task switching scenarios, **PBP** become an impediment to safe and efficient execution of tasks since searching, understanding and navigating within the same procedure or in between multiple procedures becomes a nuisance (Converse & others, 1995; Foerdestroemmen & Haugset, 1991; E. Roth & O'Hara, 2002). Maintaining awareness during task execution also becomes exhaustive for operators as **PBP** contribute to increased mental load and fatigue (O'Hara et al., 2000). In time critical situations, these factors could certainly escalate the likelihood of human error.



Figure 8.5.: Figure 8.5a shows **NPP** operator using **PBP** to train in simulator environments to manage unforeseen emergency events. Figure 8.5b shows operators at Sendai **NPP** checking the enhanced **PBP**, introduced by Nuclear Regulation Authority, at a simulator setting in Satsumasendai, Kagoshima, Japan. Source:88.

8.1.2.2 Automated Procedures in Nuclear Power Plants

Although automated procedures have been in the realm of industrial research for a while (Lipner & Kerch, 1994; Reynes & Beltranda, 1990), their implementation in real **NPP** settings have been rare mainly due to obstacles such as varying level of automation, hidden logic, recurrent context switching and complications in procedure interpretation (Jung, Shin, & Park, 2000a). Introducing automated procedures is a major transition and it requires serious effort and expenditure to upgrade existential systems, train employees accordingly, develop security and safety protocols etc. Due to these issues, safety critical industry sectors such as **NPP** industry has been impervious to change (Niwa et al., 1996). Most automated procedures in **NPP** settings are essentially **EP**, not significantly different from **PBP**, carrying additional functionality such as searching capability, interactive animations etc. Popular **CBP** (Figure 8.6 shows operators using **CBP** during operations) include COPMA (Handelsby, Ness, & Teigen, 1992), COMPRO (Lipner & Kerch, 1994), N4 Procedure (Reynes & Beltranda, 1990), and DIAM (Forzano & Castagna, 1997) etc. These **CBP** systems support features such as “automatic display of process information relevant to a procedure step, automatic processing of procedure step logic and display of results and lastly the ability of the machine to carry out multiple steps on demand from operator” (Lin, Hsieh, Yang, & Huang, 2016).

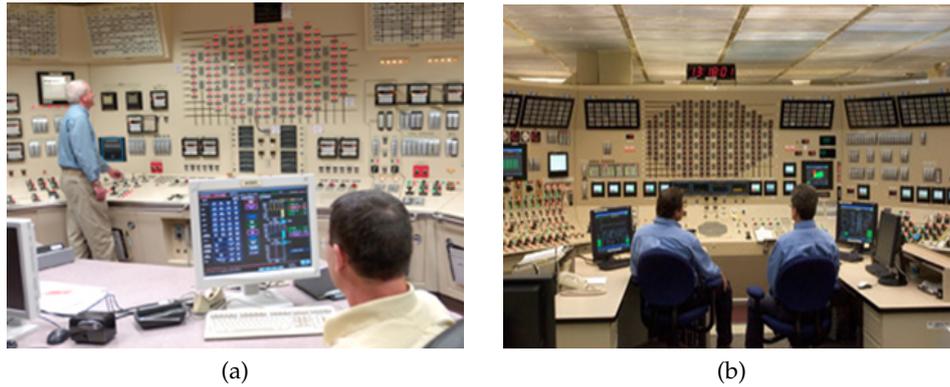


Figure 8.6.: Figure 8.6a depicts a SS interacting with CBP and a RO interacting with the control panel elements. Figure 8.6b shows operators using CBP in a control room at Browns Ferry Nuclear Plant in Athens, Ala., on June 21, 2007. Source:88.

8.1.2.3 Augmented Reality-Based Automation for Procedural Tasks in Nuclear Power Plants

Despite the utility of AR devices in many domains, existing literature demonstrates that AR interfaces have not yet been adequately explored in efforts to assist operators in performing MCR operations in NPP neither have the pedagogic benefits of AR explored in training of operators in such facilities. Many reasons are attributed to the lack of adoption, primarily the fact that AR interfaces are a recent development and lack the technical validity to be used in high risk areas. Moreover AR interfaces are mostly implemented on mobile or wearable devices whereas NPP facilities are still not accustomed to such digital transformation. This however is gradually transitioning as certain research studies in NPP show field operators using mobile and wearable devices as well as utilizing the benefits of AR for maintenance and repair purposes (Ishii et al., 2007; Klinker et al., 2001).

Hypothetically AR based procedural instructions could decrease human error, decrease task completion time, improve SA and reduce mental workload. Operators face divided attention scenarios in NPP where they would be receiving instructions from a secondary display unit or through paper manuals but they would be required to implement those instructions at an entirely different location within the task environment. Undertaking complex and time sensitive tasks in such situations can be challenging for operators. The solution would be to provide a procedural assistance method that could improve task focus and ease procedural task navigation. An operator control panel cannot support detailed description of all the elements (buttons, switches, knobs etc.) which is often required by operators to understand procedural functionality however an augmented display can provide information and multimedia superimposed on that very element. This could reduce the time operators spend on secondary display units or going through manuals. An AR application tailored for NPP operations could effectively overlay attention guidance cues, virtual instructions, context-sensitive description of control panel elements and procedural directives through a collaborative interface that could not only track control panel elements but alongside keep the control room operators updated and informed.

8.2 RESEARCH QUESTIONS

The purpose of this research is to design, develop and evaluate a novel procedural task assistance method that could improve operator performance and be evaluated as a better alternative than the current automated and non-automated forms of task guidance systems used in the **NPP** industry. Based on our analysis, we believe that **AR** technology could be affectively leveraged to better support operators with procedural tasks in **NPP**. The following research questions were therefore established towards substantiating the above stated proposition:

1. We have to initially analyze if it is actually practical to build an Augmented Reality-Based Procedures (**ABP**) system for the **NPP** industry. We then have to explore and narrow down the essential User Interface (**UI**) elements for this system that could significantly improve the performance of the operators. We must also establish the **AR** design guidelines implemented towards the development of the prototype as adopting such standards would further enhance the reliability of our application. We then have to investigate what devices and which **AR** technology would be most feasible for developing the prototype.
2. It would also be necessary to design and develop **AR** based user interaction support techniques for operators in order for them to efficiently interact with control panel elements.
3. A preliminary study, comparing **AR** based solution with other methods of procedural instructions used in the industry, would be indispensable in justifying the use of **AR** based prototype. From our literature review, we concluded the following essential dependent variables to be considered for the comparative study: mental workload, **SA**, team communication, task execution efficiency and number of errors.
4. **AR** assisted automation to help **NPP** operators might improve initial task performance but result in degradation of skill when automated support is unavailable. This could be a serious threat to control room safety as the unavailability of procedural aid is always a possibility and it is therefore recommended that the operators remain proficient and well trained with or without procedural aids. We would therefore measure an additional dependent variable termed as memory retention which would give us a picture of how well acquainted the operators are with the operating task and the interacted control panel elements, once the procedural task support system is unavailable.
5. It would be fundamental to analyze whether our prototype performs equally well under both procedural conditions that include **EOP** and **SOP** because an industry wide solution would require the product to perform optimally under all possible scenarios.
6. Lastly, we must explore the results to ascertain the benefits of using **AR** based task guidance system in this domain. The empirical data should also provide an illustration of how our results would compare to previous studies in the domain, where automated forms of assistance were proven to be a more viable option. We must also deduce the limitations of the **AR** based solution so that in future studies we could address these drawbacks and work towards a more feasible solution.

8.3 CONTRIBUTION

We at first analyzed the feasibility of an all encompassing AR based prototype solution and after validating the prospects of such a solution, we proposed the important user interaction support techniques for operators that would facilitate operations. We detail the development of the new application prototype that employs marker based (QR codes) AR technology to superimpose computer generated instructions on the live view of the operators control panel. Operators also received guided audio instructions during task execution. We had hypothesized that the ABP would perform better than both the traditional methods (CBP and PBP). To test this hypothesis, a preliminary research study was devised and carried out that compared the three methods of procedural instructions. The AR based method required operators to use ipad as the secondary device. The hand-held ipad mini was chosen over a range of other wearable and hand-held devices due to its many benefits as discussed in Section 10.1. The ABP when compared against CBP and PBP enhanced SA, yielded lesser mental workload and caused fewer errors however they did decrease the amount of communication between operators and provided poor memory retention results.

9

RELATED WORK IN NUCLEAR POWER PLANTS

9.1 USER STUDIES

Converse & others (1995) conducted a comparative study to analyze the performance and mental workload when operators separately used **CBP** and **PBP**. They found out that in accident scenarios, **CBP** caused lesser errors however operators required more time to initiate the procedure which resulted in a speed-accuracy trade-off. In normal operating conditions no change was observed in the difference in time to initiate a procedure, or in the number of errors committed by the operators. They also found no considerable difference in the mental workload of the operators in both the scenarios. They believe that unlike **CBP**, **PBP** allowed operators to preview future steps which could have led the operators to inadvertently diverge from the defined procedural pathway. Deviation from the procedural pathway was considered as an error in the study since most actual errors are credited to operators not adhering to defined procedures.

Jeffroy & Charron (1997) presented work in progress, without a synopsis of results, detailing how a data driven analyses would be conducted to analyze **CBP** in **NPP** operations from primarily a safety assessment perspective. Their investigation included a guided expert observation of videos that compared **CBP** against **PBP**. The principles adopted in analyzing **CBP** were focused towards contextually analyzing operator activity taking into account the situated nature of cognition and the independent interaction of the operator with the task guidance system. They found out on some occasions it was difficult for the operator to adhere to the procedures as the procedures were in discourse with the operators thought process. Poorly structured **CBP** made operations even worse therefore highlighting the importance of procedural method and design in **NPP**.

E. Roth & O'Hara (2002) conducted an observational study coupled with interviews, where they inspected the effect of introducing advanced human system interfaces, which included **CBP** as well, in a traditional **NPP** control room. They studied the usability of **CBP**, the ability of the operator to switch back and forth from **CBP** to **PBP** and also explored operator communication when they were using **CBP**. They concluded that **CBP** were user friendly and allowed the operators to easily switch back and forth making these procedures versatile as well. They however did notice a considerable breakdown in communication when operators were using **CBP**. This was considered to be a drawback as communication generally improves decision making and reduces likelihood of errors.

Chung, Min, & Kim (2002) conducted observational studies on the **MCR** of a **NPP** where the possible effects of using **CBP** during **EOP** were analyzed. They concluded that **CBP** caused issues in team communication and suggested that a new approach to **CBP** should be adopted to ensure better communication.

Lee, Hwang, & Wang (2005) found out that **CBP** with embedded controls/parameters performed better than normal **CBP** with separate controls/parameters in terms of performance time and ease of use. However, the embedded design restricted operator's opportunity to gather information whereas the design of separate controls/parameters was comparatively less efficient but helped the operator better understand the arrangement of the system. The impact of navigation on **CBP** did not affect any performance measure since the duration of

the study was small however they did receive a strong disposition for the inclusion of that feature from the operators.

E. M. Roth & Patterson (2005) observational study discovered that the introduction of **CBP** in **MCR** environment of a **NPP** decreased the level of communication between shift supervisor and the board operator. This provided the operators with adequate time to concentrate and work on their own individual operations henceforth their personal **SA**, speed and accuracy improved but team **SA** as a whole decreased. They further stated that communication issues with **CBP** could be addressed to an extent if specific training is provided to the operators.

Xu et al., (2008) conducted a study in which they explored the effects presentation style, task complexity, and training level on the performance of operators when they used **CBP** during emergency scenarios. They concluded that complexity, presentation style, and training level all can significantly influence the error rate. Task complexity and training level can significantly influence operation time however training level can significantly influence the subjective workload.

Huang & Hwang (2009) conducted two experiments to investigate the effects of **CBP** and team size on operating performance and concluded that using the **CBP** resulted in better team performance and increased operational efficiency.

9.2 THEORETICAL MODELS & STEP COMPLEXITY MEASURES

Jung, Shin, & Park (2000) formulated an incremental objective achievement model for execution of computerized procedures in **NPP** and they indicated how the procedures implemented using that model would enhance operator control and situation awareness since the model would improve translation, printout and maintenance of procedures.

Park, Jung, & Ha (2001) devised a method that could quantitatively measure the complexity of an **EOP** using entropy measures. It could measure Step Complexity (**SC**) from various perspectives such as the amount of information in a step, operator's action needed in a step, the complexity of the logic structure of a step etc. To confirm validity of the **SC** measure, estimated **SC** values were compared with subjective task load scores obtained from the NASA-TLX (task load index) method and step performance time obtained from the simulator.

Jung, Seong, & Kim (2004) developed a model for plant operating procedure based on flowchart, process information and success logic tree. A **CBP** conforming to the model was evaluated and the model was found to improve understanding of procedures, minimize context switching and maximize the usage of computers.

Park, Jeong, & Jung (2005), following up their previous Park, Jung, & Ha (2001) study, discovered two additional complexity factors for consideration in the **SC** measure after drawing comparisons between operator's behaviour and their performance data (measured in the form of step performance time).

Park & Jung (2007) developed a method for measuring the complexity of tasks in **EOP** of **NPP**. The score they determined after employing their method was correlated against performance time data to prove validity.

After evaluating a series of theoretical models and **SC** measures, it was evident that a complexity of a procedure would be dependent on many factors and the complexity would influence other major human factor concepts as well such as **SA**, mental workload, performance time etc. This was the reason why the above mentioned studies compared their results with the human factor concepts to prove construct validity and reliability.

9.3 RESEARCH PROVIDING GUIDELINES AND CAVEATS

Wieringa & Farkas (1991) conducted one of the first review studies concentrated towards procedure writing across the NPP domain. They highlighted some crucial issues that procedure writers could face in this domain area such as complex operations, problematic interfaces, severe consequences of errors, team driven operations etc. They then suggested guidelines that writers could adopt to better frame operating procedures. They also detailed two formats: flowcharts and action-details method that would allow procedures to be more optimally delivered to the operators.

O'Hara, Higgins, & Stubler (2000) presented review guidelines for EOP in CBP systems to aid the design process and ease potential implementation. They accentuated the fact that all the procedures should be appropriately represented (procedure number, date, revision number etc.) with the necessary information such that the operators could easily understand the procedure in minimal amount of time. They then provided the four categories of procedure functions (monitoring and detection, situation assessment, response planning, and response implementation) and described how these categories should be appropriately applied to the different levels of automation (manual, advisory, shared, and automated). Lastly, the authors specified that the CBP systems should have an interface that is user friendly, supports human system interaction, gets integrated with other Human Machine Systems (HMS) components and is easy to manage, maintain and control. They also detail future research areas that include investigating the role of plant personnel in procedure management and understanding the effect of CBP on team performance, SA, and levels of automation.

Niwa, Hollnagel, & Green (1996) discussed the human factors guidelines for computerized display of EOP and outlined elements such as navigation, formatting, progress monitoring, help and explanations, process linking and adaptation as the fundamentals that would depict a fully automated, computerized procedure presentation system.

Fink et al., (2009) provided us with an overview of the types of procedures, their design and implementation guidelines and the benefit of moving towards automated and digitized procedure systems.

Oxstrand & Le Blanc (2012) determined the challenges with current PBP, identified requirements for the use of CBP, developed a prototype CBP system based on the requirements previously identified, evaluated the CBP prototype, and defined an industry-wide vision and a path forward for future deployment.

The main review studies, detailed above, later contributed to the many guidance documents that were standardized by organizations to assist designers develop procedural instructions for NPP (Duke Energy Corporation NSD 129, 2011; Duke Energy Corporation NSD 703, 2011; Duke Energy Corporation NSD 704, 2011; Duke Energy Corporation OSG, 2011; EPRI 1011851, 2005; EPRI 1015313, 2007; IAEA-TECDOC-341, 1985; IEEE Power & Energy Society, 2011; INPO 09-004, 2009; Procedure Professionals Association PPA AP-907-001, 2011; Procedure Professionals Association PPA AP-907-005, 2011; U.S. Department of Energy DOE-STD-1029-92, 1991; U.S. Nuclear Regulatory Commission NUREG-0799, 1982)

10 PROPOSED SYSTEM

10.1 SYSTEM OVERVIEW

The major function of the system is to assist **NPP** operators with instructions (both visual and auditory) superimposed directly on the operators control panel. The system design is developed to achieve optimal performance on a hand-held tablet device. The device used for this application is the Apple ipad mini. Ipad mini renders strong graphics and carries all the necessary sensors required to identify device orientation in order for the **AR** application to precisely position virtual objects on affordances within the control panel. Ipad mini is also a comparatively smaller tablet that has a reasonable screen size and robust specifications to meet the criteria for such an application. The most suitable device type for this experiment would have been an advanced **HMD** supported with the basic device sensors such as accelerometer, gyroscope, magnetic field sensor etc. The physical constraint of holding a tablet at an upright position is a major drawback where as an **HMD** that could track head orientation would be physically less challenging and would render a deeper proprioceptive experience to the operators. However the **SDK** development challenges and the limited battery life, especially during computer vision applications, convinced us to look into other alternative devices. Occlusion and parallax errors are other drawbacks associated with **HMD**. We introduced the device specifications of the ipad mini (Table 10.1) and the necessary software architecture (Figure 10.1) needed to develop this application.

The initial prototype of the application was tested using the application called Zappar¹. The detailed application was later designed on their Zapwork Studio platform . Interactive content can be developed using this platform and Zappar is one of the leading platforms for **AR** application development. There are many advantages of using Zappar such as cross platform device integration, easy software development, strong online technology support etc. Zappar provides specialized markers that are used for **AR** tracking. The data flow diagram shown (Figure 10.1) demonstrates the system architecture in detail. All **EOP**, **SOP**, monitoring information and control panel manual was stored in the database management system using MySQL whereas data conveyed from management system to simulator display was undertaken by PHP and XML.

¹ <https://www.zappar.com/>

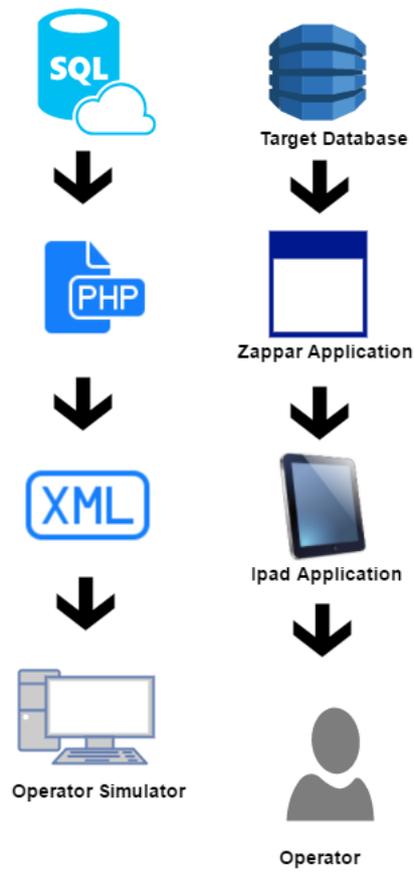


Figure 10.1.: Figure 10.1 shows data flow diagram that describes the system architecture to operate this application.

Body	Dimensions	203.2 x 134.8 x 6.1 mm (8.0 x 5.31 x 0.24 in)
	Weight	299 g (Wi-Fi) / 304 g (3G/LTE) (10.55 oz)
Display	Type	LED-backlit IPS LCD, capacitive touchscreen, 16M colors
	Size	7.9 inches (~70.6% screen-to-body ratio)
	Resolution	1536 x 2048 pixels (~324 ppi pixel density)
	Multitouch	Yes
Platform	Operating System	iOS 9, upgradable to iOS 9.3.2, planned upgrade to iOS 10
	Chipset	Apple A8
	Processing Unit	Dual-core 1.5 GHz Typhoon
	Graphics	PowerVR GX6450 (quad-core graphics)
Memory	Internal	16/64/128 GB, 2 GB RAM
Camera	Primary	8 MP, f/2.4, 32mm, autofocus
	Features	1.12µm pixel size, geo-tagging, touch focus, face/smile detection, high definition resolution (photo/panorama)
	Video	1080p at 30fps, 720p at 120fps, HDR, stereo sound rec.
	Secondary	1.2 MP, 720p 30fps, face detection, HDR, FaceTime over Wi-Fi or Cellular
Features	Sensors	Fingerprint, accelerometer, gyroscope, compass, barometer
Power	Battery	Non-removable Li-Ion 5124 mAh battery (19.1 Wh)

Table 10.1.: Specifications of Ipad Mini

10.2 DESIGN GUIDELINES

Many previous guidelines² were referred to finalize the design used for developing this AR application (Adams & Pew, 1990; Billinghamurst, Grasset, & Looser, 2005; Dünser, Grasset, Seichter, & Billinghamurst, 2007; Joe L. Gabbard & Swan II, 2008; Joseph L. Gabbard, Swan, Hix, Kim, & Fitch, 2007; Ganapathy, 2013; Gavish, Gutierrez, Webel, Rodriguez, & Tecchia, 2011;

² Mark Billinghamurst presents an interesting presentation on AR design guidelines which was also consulted during the application development phase. URL <http://www.slideshare.net/marknb00/2013-lecture-6-ar-user-interface-design-guidelines>.

Michael, 2006; R. Wetzel, McCall, Braun, & Broll, 2008). The interface design is a very important component of the overall application and it is therefore necessary to ensure that the application is interactive and supports adherence to task operating procedures. We made sure that the text we added was clear, precise and easy to read. The visual overlay of virtual components had adequate contrast to be differentiated from the background control panel. It was ensured that the visual overlay was systematized when perceived on the iPad's display. Another key process was confirming that none of the virtual objects obscured any item on the control panel. The areas that needed responsiveness were clearly marked with attention directing graphics and voice augmentation such that operators could easily identify these regions. Different icons, apart from text based instruction, were shortlisted for different purposes that included labels on control panel elements, virtual scenes for future tasks, 2D attention direction arrows etc. The distance and visibility of these virtual objects including buttons were strategically maintained such that operators could easily perceive, interact and navigate between procedures. We ensured that the virtual elements that were being added were simple, meaningful, responsive and accurately positioned. We also made certain that affordances were tactfully utilized so that operator's physical effort and cognitive load during interaction with virtual elements could be minimized.

10.3 ADAPTABLE MULTIFUNCTIONAL CONTROLS FOR NUCLEAR POWER PLANTS

In this section, we introduce a virtual class of user interaction support tools developed to assist operators carry informed decisions. These controls allow gesturing on and receiving a response from virtual objects projected via secondary device (tablet, cell phone, HMD) on otherwise unused areas already present within the task environment. This concept was derived from opportunistic controls introduced by Henderson & Feiner, (2010)³ that were focused towards biomechanical or psychomotor tasks and in domains which required extensive head, eye and hand movement. Opportunistic control were proven to be highly useful as they reduced task error and improved task completion time. We aim to provide NPP operators with tracked iPads and gestural touch sensing that could support create channels of communication through passive haptic feedback. Self-created virtual objects (3D interface widgets in AR) augmented on unused affordances within the control panel are utilized as important interface components and as ways to improve human-machine interaction within the facility. We define them as the six tuple, where:

1. τ depicts the many control panel regions where the user can interact through physical manipulation of control panel objects such as dials, switches, sliders etc. τ also carries naturally occurring affordances that would function as a tangible area of interest when viewed through the secondary device (iPad) where a 3D widget would be superimposed for touch based interaction.
2. ψ represents a 3D Widget which is essentially a reusable element within the AR interface that could either be a button, control panel handbook or operating task instruction shown as virtual object on the secondary device. The virtual model of the widget has a distinct geometric figure and is positioned to convey a particular behavior to the operator.

³ Opportunistic controls (<http://graphics.cs.columbia.edu/projects/oc/>) were designed for an immersive tangible interface without the need of the secondary device however our controls require an additional device to display virtual content and process procedural information.

3. α represents the function that ψ would perform when the operator interacts with it and $\hat{\alpha}$ represents the function τ would perform when operator interacts with it. The function can yield different effects to the visual output ζ such as changes in NPP control panel (τ) readings or changes in ψ such as a different virtual element.
4. Γ represents the gestural touch sensing that is recognized by the secondary device when the user interacts with ψ and $\hat{\Gamma}$ represents the physical interaction of the operator with τ . Both Γ and $\hat{\Gamma}$ can yield different effects to the visual output (ζ) such as changes in NPP control panel (τ) readings or changes in ψ such as a different virtual element.
5. ζ depicts the resulting output response based on what α , Γ or $\hat{\Gamma}$ would render collectively or individually on either both ψ and τ or on one of them. The result of ζ would be shown on all devices within the facility therefore the operator, assistant operator or supervisor would all be updated when an interaction with any of the virtual or physical elements has taken place within the plant.
6. ζ is a subcomponent of α and is a functional process responsible to bridge the virtual elements ψ and the physical elements τ together. ζ ensures that a proper corresponding action takes place in τ if the user interacts with ψ or vice versa.

These control allow operators to interact effectively with different interface elements while collaborating with operators within the facility. It is a multiuser interaction system that encourages useful communication, ensuring that the operators remain well-versed with the task operating procedures within the facility. All operator actions are tracked and time stamped which reduces unnecessary inquires and leads to increased workspace awareness.

Team communication in a **NPP** control room is extremely important as operators interact with various control panel elements as well as amongst themselves in order to effectively achieve desired goals. Operators therefore must have excellent team skills in order to manage operations and should be competent enough to accomplish objectives with understanding and awareness of the ever changing situations in the control room. According to Lin, Hsieh, Yang, & Huang (2016) communication in a **MCR** would be defined as the different information exchanges amongst operators. The importance of team communication in assisting users with task implementation has been identified in many studies in the past (Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995; Ford & Schmidt, 2000; Glickman, Zimmer, Montero, Guerette, & Campbell, 1987; Pinto & Pinto, 1991; Scholtes, 1988). We are interested in understanding how the different procedural methods would impact team communication in a **NPP** control room. Previous studies that tested automated and non-automated forms of procedural methods have reported that automated procedural systems reduce team communication (Lin et al., 2016).

Waller, Gupta, & Giambatista, (2004) proved that high performing **NPP** control crew participated in adaptive behavior especially during emergency scenarios when mental workload was expectedly high. They further discovered that low performing teams engaged more in information collection activities. We therefore need to analyze which procedural method would better facilitate information collection as it is necessary that operators have easy and quick access to the required information from the procedures.

The performance of a **NPP** control room team gets defined by how accurately and efficiently are tasks being implemented. The content of the procedures might not change for the different methods however substantial differences would be present in how operator would interact with the procedures and how the procedures would be delivered and perceived by the operators. These differences would influence efficiency and accuracy therefore it is necessary to determine these variables to properly understand how a particular procedural method would affect operator's performance.

Mental workload and **SA** would also vary based on the procedural method being utilized. Mental workload would depend on how extensively the cognitive resources are being utilized during task implementation. Procedural methods that would allow faster information acquisition would yield lower workload in operators. Similarly procedural methods should be capable of effectively directing operator attention to the necessary control panel elements as this would enhance operators **SA** and would contribute to efficient task execution.

PBP alongside having many other limitations that impact user performance, also curtail the amount of information conveyed to the operators. **CBP** are relatively less complex however they are ineffective in guiding operator attention to the many fragmented components of the control panel as these components require immediate responsiveness in time critical scenarios. **ABP** are hypothesized to improve operator performance, reduce workload and increase **SA** however empirical data is required to validate such an assumption. Therefore the overall goal of this preliminary user study is to confirm the practicality of using **ABP** in comparison to traditional methods. We developed an **AR** based prototype solution and also implemented the essential **UI** elements that could effectively support procedural adherence. **AR** assisted automation might result in degradation of skill therefore we are measuring

memory retention as an additional variable. Memory retention would assist us uncover potential areas of improvement so that future AR based solutions could be equipped to support skill learning and retention as well as help improve user performance.

11.1 METHOD

11.1.1 *Participants*

Twenty Four (13 males and 11 females) University of Waterloo students were recruited to participate in this study. All participants stated that they were confident in using the respective task guidance systems as methods of procedural assistance. All had normal or corrected-to-normal visual and auditory acuities. None of the participants had participated in a similar study before and all participants were interacting with the NPP simulator for the first time.

11.1.2 *Tasks and Materials*

The participants were trained for a total time period of roughly 15 minutes. At first the participants were requested to get conversant with the NPP simulator therefore they interacted with the different control panel elements and understood the functionality behind the major components of the system. The participants were then introduced to the three different procedural methods used in this experiment (PBP, CBP and ABP). The participants experienced each method individually in order to effectively prepare for the actual experiment.

The participants recruited for similar studies, in the past, were either NPP operators functioning in actual simulator rooms or individuals provided with extensive training experience in handling NPP operations. Since this was a preliminary study conducted just to analyze the feasibility of the AR based prototype; it was conducted in an ordinary experiment room with university students as subjects. NPP operations are team managed and a potential team has three major roles that include the role of a RO, Assistant Reactor Operator (ARO) and a SS. In this experiment, the simulator was operated by the RO and ARO whereas SS was positioned behind the two as illustrated in Figure 11.1. Since the participants were not actual NPP operators and had undergone minimal training therefore the role of SS was accomplished by the research investigator administering the experiment. All task operating procedures were actually implemented by the RO and ARO whereas specific guidance was given by the SS to RO and ARO only when necessary or enquired.

The simulator used for this study was a modified web version of PCTTRAN (Jing-qi, 2007)¹. The control panel for the simulator was configured and projected via two high-definition graphics monitors (1920 x 1080 pixels) operating on Lenovo T540 P laptop that used Intel® Core™ i7-4900MQ (Up to 3.80 GHz, 8MB, L3 1600 MHz) processor. Traditional mouse and keyboards were used as devices to interact with the control panel whereas operator's utilized touch based sensing on ipad for interaction with virtual objects.

PCTTRAN software was originally developed to train NPP operators in Taiwan and carried the capacity to simulate many different accident scenarios. PCTTRAN displayed all major parameters, needed in real-time to run a simulator, such as water levels, pumps, valves, alarms, control rod movements, coolant fractions etc. The CBP were shown on a supplementary VDU whereas PBP were given to the operators in hardcopy format. ABP were functioning on ipad

¹ <http://www.microsimtech.com/pcttran/>

which the operators held at a specific position and orientation to receive augmented instructions to carry out the tasks.

Different **NPP** scenarios had to be shortlisted and the **NPP** simulator had to be configured accordingly. For this experiment three similar scenarios were selected such that all three of them had emergency situations, where operators were expected to employ **EOP**, as well as standard situations, where operators were expected to execute **SOP** or undertake monitoring activities.

The normal operation control, which included reactor start up, shutdown, power ramp, was tested in all three scenarios whereas the first scenario tested loss-of-coolant-accident and recirculation pump trip, the second scenario tested turbine trip without bypass and loss-of-load and the last scenario tested inadvertent rod withdrawal and steam generator tube rupture.

Due to the novice nature of the participants, the overall complexity and number of steps in each of the three scenarios was reduced and balanced. Participants were chosen in a group of two and were required to randomly play roles as a **RO** and an **ARO**. The operators were requested to follow a specific pattern to adopt the two roles (**ARO, RO**) and experience the three different scenarios using three different procedural methods (**ABP, PBP, CBP**) such that each of these conditions were all randomly balanced and equally tested across subjects using a Latin square design method.

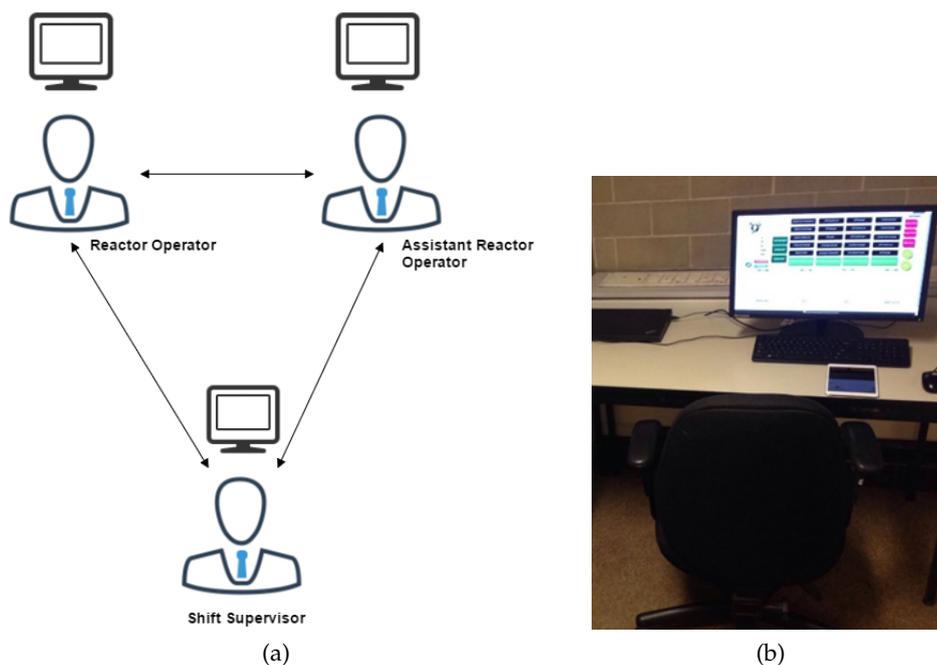


Figure 11.1.: Figure 11.1a shows the setting of **NPP** personnel during experimentation (Lin et al., 2016). Figure 11.1b represents the operational space of the **RO**, **ARO** and **SS** (they have similar seating arrangements).

11.1.3 Experimental Design and Measures

The experiment used a within-subject design. The independent variable were the type of procedural method used in this experiment that included three conditions: **ABP**, **PBP** and

CBP. The dependent variables included memory retention, mental workload, SA, task completion time, team communication and operator error. Each dependent variable was individually measured for the three procedural aid conditions.

In order to measure memory retention performance, the participants were provided with an unlabeled control panel diagram. Participant had to label the specific components that they interacted with during experimentation. This exercise was conducted a week after the experiment and only those control panel components were chosen that were distinct to every scenario and every procedural aid method. Participants were asked to label five distinct components that they interacted using a particular procedural aid method and hence the participants labeled 15 distinct components in total for the three scenarios. The number of correct responses depicted how feasible a particular method would be in supporting memory retention and skill learning.

The performance evaluation consisted of two variables that included task completion time and operator error. The amount of time the team took to accomplish a particular task was recorded by the simulator and designated as average task completion time. The errors made by the operator while executing tasks were also recorded by the simulator and classified as operator error.

The number of commands the team exchanged was recorded by the experimenter and defined as command communication. Command communication were expected to be mostly orders that team members would exchange while interacting with the NPP simulator. Inquiry communication was also recorded that was defined as team members requesting or enquiring information from each other.

Subjective evaluation questionnaires were also queried which included workload and SA. Mental Workload was computed using NASA-TLX questionnaire which is a subjective, multidimensional assessment tool that rates perceived workload on six different subscales that include mental demand, physical demand, temporal demand, performance, effort, and frustration. Situation Awareness Rating Technique was employed to calculate SA. This technique delivers an evaluation of SA from self-rated perspective on attentional demands (D), attentional supply (S), and understanding (U). The rating score is calculated using the formula (Selcon et al., 1992): Situation Awareness = $\frac{1}{4}U - (D - S)$.

11.1.4 Procedure

First, the participants read the information letter that described the details of the experiment, and then they filled the consent form and the pre-experiment questionnaire. Participants were also categorically informed with regards to the duties of the ARO and RO during the pre-experiment brief. Participants were provided with time to practice with the different procedural methods until they felt fully confident to initiate the formal experiment. In each of the three trials, each participant was instructed to collaborate with the team and utilize the procedural method to implement the task operating instructions. The SS followed the experiment protocol and supported the participants when required. As the participants undertook the experiment (certain screenshots of participants shown in figure 11.2), their communication was being recorded that included the inquiry communication as well as command communication. After the participants completed a scenario, they filled the situation awareness rating technique questionnaire as well as the NASA-TLX questionnaire in a 6 minute break period until the initiation of the next scenario. The errors and the task completion time was being recorded by the simulator. Participants were also asked to comment on their preferred device once they had finished the entire experiment. Participants were enquired with regards to memory retention through a questionnaire that they completed

a week later. The memory retention questionnaire tested whether participants remembered the exact position of the elements (buttons, dials, switches, alarms etc.) that they interacted with during the experimentation when they were performing task operations on the simulator. The elements of the simulator were designated with specific numbers rather than their actual names. In the questionnaire the participants inserted the number which represented the position of that element on the interface. The analysis of this recall task revealed the characteristics of which assistive aid would have better supported memory retention.²

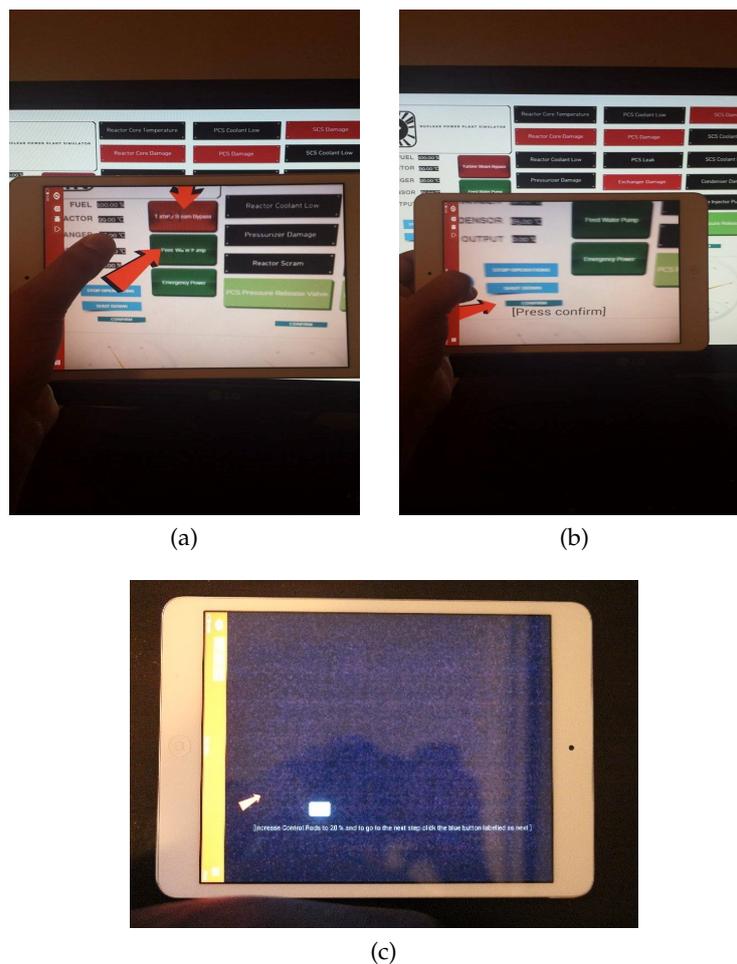


Figure 11.2.: The figures depict typical tasks being implemented using our prototype. Audio, text and visual arrows all work in synchrony to direct operator's attention. Figure 11.2a exhibits operators handling an emergency scenario that requires multiple tasks being implemented at once. Figure 11.2b represents a monitoring task. The operator is being reminded to press confirm on the simulator's interface in order to ensure that all the required elements have been observed. In 11.2c, the iPad is placed on the table. The AR instructions remain visible to the operators even when the iPad is not focusing towards the control panel. When the iPad gets pointed towards the control panel, the virtual information would automatically be directed towards those elements that require operator's attention.

² Refer to Appendix B to view the questionnaire.

11.2 RESULTS

One-way repeated measures analysis of variance using SPSS (Version 22) were conducted to examine the effects of procedural methods, and pairwise comparisons were conducted (with Bonferroni correction) to compare the three types of procedural methods (i.e., ABP, PBP and CBP). There were no outliers and the data was normally distributed, as assessed by boxplot and Shapiro-Wilk test ($p > .05$), respectively.

11.2.1 Communication

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 2.208$, $p = .332$. The effect of procedural method on inquiry communication elicited statistically significant results, $F(2, 22) = 15.963$, $p < .0005$, partial $\eta^2 = 0.592$ (Figure 11.3). ABP required least inquiry communication ($M = 21.67$, $SD = 6.11$), when compared against CBP ($M = 31.50$, $SD = 8.34$) and PBP ($M = 47.00$, $SD = 14.28$). Post hoc analysis with a Bonferroni adjustment revealed that statistically significant difference was present in the results of inquiry communication between ABP and CBP ($M = 9.83$, $p = .042$), as well as ABP and PBP ($M = 25.33$, $p < .05$). The result of inquiry communication between PBP and CBP were also significant ($M = 15.5$, $p = .029$).

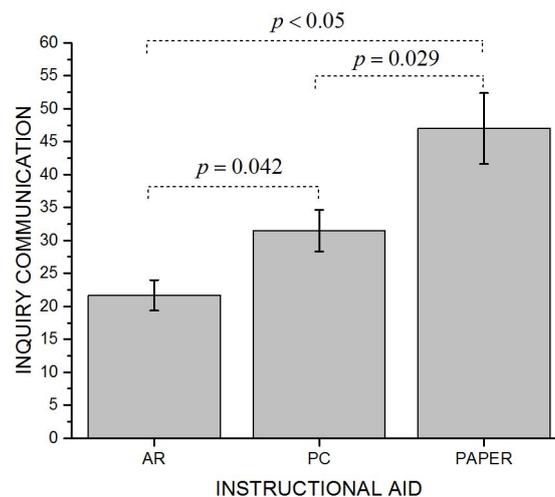


Figure 11.3.: The main effect of procedure type on inquiry communication.

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = .420$, $p = .811$. The effect of procedural method on command communication did not lead to any statistically significant results, $F(2, 22) = .041$, $p = .959$, partial $\eta^2 = .004$. ABP required least command communication ($M = 8.08$, $SD = 2.90$, when compared against CBP ($M = 8.50$, $SD = 4.70$) and PBP ($M = 8.42$, $SD = 4.40$) however the results were roughly the same.

11.2.2 Task Completion Time

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 5.86$, $p \geq .05$. The effect of procedural method on time of experiment, elicited statistically significant results, $F(2, 22) = 11.365$, $p < .0005$, partial $\eta^2 = 0.508$ (Figure 11.4). Participants required the least amount of time with ABP ($M = 17.58$, $SD = 5.93$), when compared against CBP ($M = 20.25$, $SD = 5.10$) and PBP ($M = 30.42$, $SD = 8.61$). Post hoc analysis with a Bonferroni adjustment revealed that the results for the time taken by the participants to complete the experiment between ABP and CBP ($M = 2.67$, $p = .986$) were insignificant however the result for ABP and PBP ($M = 12.83$, $p = .014$) were statistically significant. The result for the time taken by the participants to complete the experiment between PBP and CBP were also significant ($M = 10.17$, $p < .05$).

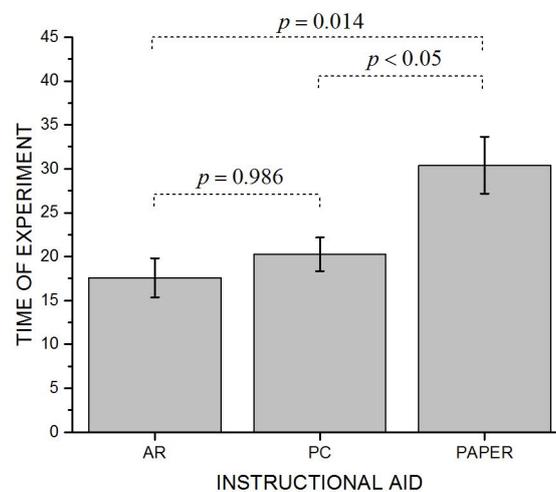


Figure 11.4.: The main effect of procedure type on task completion time.

11.2.3 Number of Errors

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 4.18$, $p \geq .05$. The effect of procedural method on the number of errors made by the participants, elicited statistically significant results, $F(2, 22) = 6.082$, $p < .05$, partial $\eta^2 = 0.356$ (Figure 11.5). ABP rendered the least number of errors ($M = 7.67$, $SD = 3.55$), when compared against CBP ($M = 10.92$, $SD = 4.44$) and PBP ($M = 16.42$, $SD = 8.21$). Post hoc analysis with a Bonferroni adjustment revealed that operator error between ABP and CBP ($M = 3.25$, $p = .223$) were insignificant however the result for ABP and PBP ($M = 8.75$, $p = .029$) were statistically significant. The result of number of errors between PBP and CBP were also insignificant ($M = 5.50$, $p = .271$).

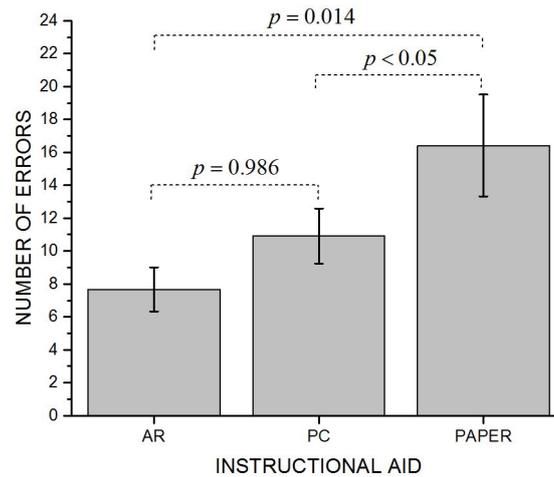


Figure 11.5.: The main effect of procedure type on number of errors made by operators during task implementation.

11.2.4 Situation Awareness

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = .06$, $p = .970$. The effect of procedural method on participants SA elicited statistically significant results, $F(2, 22) = 4.16$, $p < .05$, partial $\eta^2 = 0.274$ (Figure 11.6). Using ABP participants were most situationally aware ($M = 15.54$, $SD = 5.71$), when compared against CBP ($M = 12.71$, $SD = 4.51$) and PBP ($M = 10.58$, $SD = 5.87$). Post hoc analysis with a Bonferroni adjustment revealed that the results of SA between ABP and CBP ($M = 2.83$, $p = .354$) were insignificant however the result for ABP and PBP ($M = 4.96$, $p \leq .05$) were statistically significant. The result of SA between PBP and CBP were also statistically insignificant ($M = 2.13$, $p = .726$).

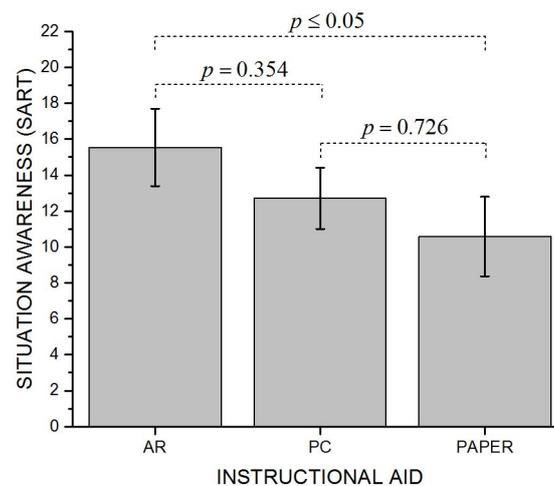


Figure 11.6.: The main effect of procedure type on SA.

11.2.5 Mental Workload

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 2.808$, $p = .246$. The effect of procedural method on NASA-TLX overall workload score elicited statistically significant results, $F(2, 22) = 26.06$, $p < .0005$, partial $\eta^2 = 0.703$ (Figure 11.7). Using the ABP participants reported least overall workload ($M = 33.35$, $SD = 3.35$), when compared against CBP ($M = 40.65$, $SD = 7.30$) and PBP ($M = 54.06$, $SD = 10.96$). Post hoc analysis with a Bonferroni adjustment revealed that statistically significant difference was present in the results of NASA-TLX between ABP and CBP ($M = 7.29$, $p = .029$), as well as ABP and PBP ($M = 20.71$, $p < .0005$). The result of NASA-TLX between PBP and CBP were also significant ($M = 13.42$, $p < .05$).

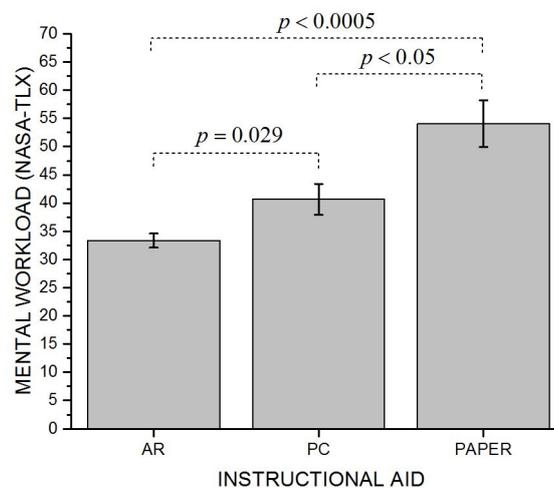


Figure 11.7.: The main effect of procedure type on mental workload .

11.2.6 Memory Retention

The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 1.238$, $p = .538$. The effect of procedural method on overall memory retention score elicited statistically significant results, $F(2, 22) = 19.03$, $p < .0005$, partial $\eta^2 = 0.634$ (Figure 11.8). Using the ABP, participants scored the poorest in the memory retention exercise ($M = 4.75$, $SD = .965$), when compared against CBP ($M = 6.50$, $SD = 1.17$) and PBP ($M = 7.75$, $SD = 1.06$) with the higher scoring meaning better memory retention. Post hoc analysis with a Bonferroni adjustment revealed that statistically significant difference were present in the results of the memory retention exercise between ABP and CBP ($M = 1.75$, $p < .05$), as well as ABP and PBP ($M = 3.000$, $p < .0005$). The result between PBP and CBP condition were however insignificant ($M = 1.250$, $p = .148$).

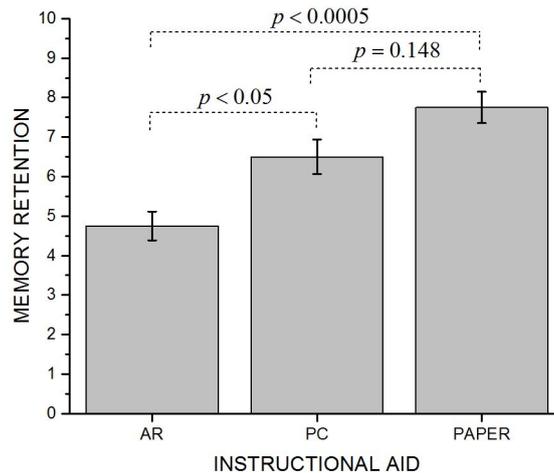


Figure 11.8.: The main effect of procedure type on operators memory retention.

11.3 HUMAN FACTORS STUDY DISCUSSION

ABP did provide considerable benefit to the participants recruited for this study, with improved task focus, enhanced SA, lesser mental workload and less frequent errors however it did decrease the amount of communication between operators and proved to be extremely vulnerable in supporting memory retention or skill learning as operators barely remembered the interface components they interacted with while using ABP. On the contrary the memory retention results while using the other procedural methods were much reasonable.

The memory retention results could be explained by the fact that the operators utilized minimal cognitive resources while using ABP and hence they formed weak cognitive maps whereas while using PBP or CBP, they formed comparatively stronger mental models. Operators had to properly understand the information on PBP or CBP so that they could hold this information for some time in their memory in order to utilize it later during task implementation. While using ABP, operators were essentially receiving mapped instructions directly superimposed on the control panel and hence the mental maps formed were temporary and indistinct.

Hayes-Roth & Hayes-Roth (1979) presents a cognitive model of planning which is important in understanding how operators approached these procedural task instructions. According to their research, the model includes the following stages:

1. How to approach the planning problem?
2. What knowledge bears on the problem?
3. What kinds of actions to try to plan?
4. What specific actions to plan?
5. How to allocate cognitive resources during planning?

Approaching the planning problem would largely be determined by the interface response of the control panel therefore it is important that the NPP interface is human centered. Modern NPP, like the one used in this experiment, would appropriately inform the user of

an emergency situation whereas operating procedures would provide operators with the best possible route of action in order to manage the incumbent situation. While using **ABP**, operators were not required to exert additional efforts in order to analyze and plan the necessary route of action. This reduced the amount of cognitive processing and facilitated decision making with fast motor responses. Tasks were automatically prioritized based on the situation and this essentially expedited operations.

PBP and **CBP** provided additional information that the operator in most emergency situations were not able to effectively assimilate. In **CBP**, operators were provided with models and visuals so that they could interact with the control panel elements at a faster rate however supplementary information increased workload and stress. A serious issue that still compels researchers to limit the amount of information delivered to the operators relates to a behavioral tendency that supplementary information encourages operators to use personal interpretations, assumptions and prior knowledge to implement procedures (Kieras & Bovair, 1984) that could lead to lapses in judgement and impaired performance. When using **PBP** or **CBP**, operators often used their own judgement in efforts to quickly implement a task rather than reading through the entire documentation and then proceeding towards implementation.

ABP reduced the time required to complete a task as procedural instructions were superimposed on the task location such that that the operator could view the task operating instruction and the control panel element in one field of view which minimized division of attention and improved task focus. Also, the operator did not get overwhelmed with **ABP** as instructions delivered on the control panel did not carry additional text, visuals or model. The simple and straightforward instructions facilitated procedural adherence and improved workspace awareness.

ABP automated the information collection process as operators were not required to specifically search for the desirable information from the procedures. They were provided with just the necessary information they needed to execute a particular task. Moreover miscommunication amongst team members got reduced as all operators viewed the same instructions on the secondary device, ipad, which ensured implementation of procedures was consistent and all team members were cognizant with operational processes. Therefore the reduction of inquiry communication was not a drawback in this case because **ABP** kept human in the loop through digital synchrony as operators were aware of the procedures that were being implemented.

Significant differences between **CBP** and **PBP** were discovered in term of mental workload, time of experiment and operator error. These results were similar to previous studies in the field (Lin et al., 2016; Yang et al., 2012). **CBP** presented additional features such as automatic display of process information, visual and diagrammatic models, step automation etc. that better supported operations and hence improved operator performance.

Participants were also asked to comment on their preferred device if they were to use it in actual **NPP** settings. In examining the **ABP** condition, participants were almost undivided in the approval of the system however they did point out certain weaknesses in the device type we used to render **AR** based information. A participant noted that *"It was as if the ipad was making all the decisions and all I had to do was follow without even thinking. I like the idea of computer making my decisions as I know I'll be more prone to errors. If the interface is given more time in design, it can change many things in the future however for now I would prefer an ipad handstand for this experiment."* Another participant reported that *"AR instructions felt the most efficient however it was awkward to hold the tablet and often I would get tired while using it. I would still prefer it because it really didn't feel like any work"*.

12 CONCLUSION AND FUTURE WORKS

In conclusion, we designed, developed and evaluated an [AR](#) based prototype solution to better assist [NPP](#) operators with task operating procedures. The performance evaluations and human factors study revealed that our prototype would reduce operator workload, increase operator [SA](#), make processes efficient and less prone to errors and reduce inquiry communication. The results also led us to derive that [ABP](#) poorly support memory retention and skill learning when compared against [PBP](#) and [CBP](#). Currently, no significant research has dealt with [ABP](#) in [NPP](#). While there has been research outside the [NPP](#) domain, similar research is still in early stages. Pioneering research for high risk industrial environments, such as [NPP](#), mostly succumb down in the idea or research phase. This usually occurs when there is a definite disparity between the requirements of the industry and the path followed by the researchers. Our efforts however were geared towards developing a workable prototype solution streamlined with the needs of the [NPP](#) operators.

From the comments of the participants, it was clear that despite the usefulness of [ipad](#) in this domain, handheld devices can be tiresome to manage. Since our experiment had a short duration therefore the impact of physically holding the [ipad](#) did not exasperate the participants considerably. We however recommend that further studies should either use an ergonomic handstand for holding the hand-held device or employ [HMD](#) that can support the use of computer vision applications for longer durations of time. Adaptive interfaces that can support learning and retention should be designed for this domain in order to ensure that operator skill does not degrade with the use of automation technologies such as [AR](#). Future studies should also focus on recruiting actual [NPP](#) operators or participants with extensive experience in operating [NPP](#). The results would be more reliable if real simulator settings were utilized therefore future experiments should be conducted in environments comparable to actual [NPP](#). Since this was a preliminary study conducted to obtain a proof of concept for the [AR](#) based solution therefore we mostly tested simple and easily executable procedures however complex procedures should also be tested in order to analyze how procedural complexity impacts operator performance.

Part IV

THESIS CONCLUSION

13 SUMMARY OF KEY FINDINGS AND LESSONS LEARNED

The earlier chapters detailed our efforts to quantify the benefits of using AR in these domains alongside providing us with an established architecture for creating these AR applications using the different tracking technologies, display devices and interaction techniques. This chapter however summarizes the overall key findings and lessons learned from the two studies.

13.1 KEY FINDINGS AND LESSONS LEARNED FROM PART II

1. The results revealed that the indoor navigation application developed was able operate ideally with maximum efficiency at normal walking speeds and the application could efficiently process and display the AR based directional information without making the user feel the system was sluggish or unresponsive.
2. The user study illustrated that AR technology enhanced the participant's indoor navigation capabilities when evaluated from human factors and performance perspectives regardless of the device type utilized to implement the AR application.
3. When AR is used for navigation, users tend to minimize the use of cognitive resources and hence develop weak mental models of their surroundings. This complacency contributes to poor memory retention. The device type (wearable or hand-held) has no influence on memory retention results as essentially the technology used and the mode of instructional processing remains unchanged.
4. Google glass was perceived as the most accurate device indicating that the users felt most confident while using it during navigation despite the fact that the traversal time and mental workload results were not significantly different between the google glass and the cell phone conditions. No significant difference was found on subjective comfort ratings (wearability comfort, usability control comfort, and display comfort) across all the three aids. These results prove two critical points:
 - AR based indoor navigation implemented on the wearable device was neither worse nor better than the cell phone implementation.
 - There is lack of correlation between perceived accuracy and traversal time as well as perceived accuracy and mental workload and perceived accuracy and subjective comfort readings. Mental workload and traversal time are however positively correlated.

13.2 KEY FINDINGS AND LESSONS LEARNED FROM PART III

1. AR based procedural instructions coupled with useful interaction techniques can significantly improve the performance of participants. The user study concluded that ABP: reduced user workload, increased user SA, expedited implementation of procedures, reduced the number errors during procedural implementation and lastly reduced team inquiry communication. ABP therefore were evaluated to be better alter-

natives to current industry solutions that include **CBP** and **PBP**. The performance of **PBP** was worse than **CBP** in all the above stated performance variables.

2. **AR** based decision and action support during implementation of operating tasks can impair user's ability to manually perform these tasks. The loss of skill proficiency with the use of **ABP** was identified as a potential risk factor during this study.
3. We did realize that participants were willing to temporarily tolerate the ergonomic limitation of hand-held assistive devices for shorter time periods however in **NPP** domain a hands-free experience would be crucial in facilitating users. It would therefore be necessary to explore the utility of advance **HMD** for running similar **AR** based application for longer time durations.

13.3 COMMON FINDINGS AND FUTURE DIRECTIONS

The two experiments have some common findings as well that prove that **AR** based assistive aids could support faster task completion time, lower mental workload and higher accuracy. The disadvantage of using **AR** however was the memory retention aspect as participants quickly forgot the task they accomplished with the help of augmented cues. From the two user study's we also concluded that **AR** based applications were preferred over traditional industry solutions despite the ergonomic and technical shortcomings of the devices that were used to run these applications.

It was encouraging to see the positive prospects of **AR** based assistive aids. In the future, our contributions could be further extended to other opportunity filled domains such as aviation, healthcare, education etc. It would be important that future **AR** applications are designed 'astutely' such that they could support task learning and retention alongside providing operators with automated task assistance. In this modern era of automation, it would be significant to figure out ways in which contemporary interfaces could also assist operators remain well versed with machine operations to prevent skill degradation.

Hardware of the devices that are being used to run these **AR** applications must be considerably improved in order to support faster processing speeds, better display technology and longer battery life. The necessary technology however is enhancing rapidly and we are confident to see more advanced consumer versions of **AR** devices in the near future.

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APPENDICES

A URL LINKS ¹

1. Figure 1.1 on page 3 <http://goo.gl/bwQ13f>.
2. Figure 1.2a on page 4 <http://goo.gl/sqZsCE>.
3. Figure 1.2b on page 4 <https://goo.gl/EmcxPs>.
4. Figure 1.2c on page 4 <http://goo.gl/rTqUGe>.
5. Figure 1.3a on page 5 <http://goo.gl/F1BtHu>.
6. Figure 1.3b on page 5 <http://goo.gl/xBNqPm>.
7. Figure 1.3c on page 5 <http://goo.gl/4aN4qu>.
8. Figure 1.3d on page 5 <http://goo.gl/MpSqa0>.
9. Figure 1.4a on page 6 <http://goo.gl/d2QMct>.
10. Figure 1.4b on page 6 <http://goo.gl/xdHDEH>.
11. Figure 1.4c on page 6 <https://goo.gl/p6mA20>.
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13. Figure 8.1a on page 38 <http://goo.gl/kXj3Eu>.
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16. Figure 8.2a on page 40 <http://goo.gl/IRhoiN>.
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20. Figure 8.4b on page 42 <http://goo.gl/6gWFmG>.
21. Figure 8.4c on page 42 <http://goo.gl/etBNQx>.
22. Figure 8.4d on page 42 <http://goo.gl/uwkRjG>.
23. Figure 8.5a on page 44 <https://goo.gl/iFFKwX>.
24. Figure 8.5b on page 44 <http://goo.gl/j4siVI>.
25. Figure 8.6a on page 45 <http://goo.gl/89ySxh>.
26. Figure 8.6b on page 45 <http://goo.gl/JKYajm>.

¹ THE LINKS HAVE BEEN PURPOSELY SHORTENED FOR EASY TRACKING.

B MEMORY RETENTION QUESTIONNAIRE

POST EXPERIMENT QUESTIONNAIRE	
<p>In this questionnaire, we are testing your memory in regards to whether you remember the exact position of the elements (buttons, dials, switches, alarms etc.) that you interacted with during the experimentation when you were performing task operations on the nuclear power plant simulator. The elements of the nuclear power plant simulator have been designated with specific numbers rather than their actual names. In the questionnaire below, insert the number which shall represent the position of that element on the interface? If you are not sure about the exact position, please give a closest position guess.</p>	<p>Insert the number which represents the position of Target Output Button?</p> <input type="text"/>
<p>Your age?</p> <input type="text"/>	<p>Insert the number which represents the position of Repair Button?</p> <input type="text"/>
<p>Name?</p> <input type="text"/>	<p>Insert the number which represents the position of Refuel Button?</p> <input type="text"/>
<p>Email?</p> <input type="text"/>	<p>Insert the number which represents the position of Off-Site Power Button?</p> <input type="text"/>
<p>Insert the number which represents the position of "Control Range Slider & Indicator"?</p> <input type="text"/>	<p>Insert the number which represents the position of Emergency Power?</p> <input type="text"/>
<p>Insert the number which represents the position of "Output Indicator"?</p> <input type="text"/>	<p>Submit Your Answers</p>
<p>Insert the number which represents the position of "Primary Coolant Pump Button"?</p> <input type="text"/>	<p>Insert the number which represents the position of SCS (Secondary Coolant System) Pressure Release Valve Button?</p> <input type="text"/>
<p>Insert the number which represents the position of Feed Pump Button?</p> <input type="text"/>	<p>Insert the number which represents the position of SCS (Secondary Coolant System) Reserve Pump Button?</p> <input type="text"/>
<p>Insert the number which represents the position of Turbine System Bypass Button?</p> <input type="text"/>	<p>Insert the number which represents the position of Reactor Dial?</p> <input type="text"/>
<p>Submit Your Answers</p>	<p>Insert the number which represents the position of Condensor Dial?</p> <input type="text"/>
	<p>Insert the number which represents the position of Reactor Scram Alarm?</p> <input type="text"/>
	<p>Submit Your Answers</p>