APPLIED AUGMENTED REALITY FOR MAINTENANCE ON BOARD SHIPS

LIM Bee Hua Lena, POH Chun Siong, ONG Beng Shen Aaron, GOH Chue Hsien

ABSTRACT

Maintaining complex equipment while at sea is part and parcel of work for the Republic of Singapore Navy's (RSN) Marine Engineers. To support these marine engineers, the team adopted rapid design and development processes to develop a Minimum Viable Product (MVP) that leverages smart phones and augmented reality (AR) glasses to encapsulate and augment their maintenance work processes, as well as provide timely safety reminders. The approach of the demonstrator project was to employ commercial off-the-shelf (COTS) hardware and software for the deployment of an MVP for the study of the value of AR in supporting maintenance works carried out by the RSN on board ships. Thereafter, the ship's crew performed maintenance work using the MVP while the team measured the performance and evaluated their user experience. Through its design and development, the team assessed the type of tasks where AR would bring more value, the performance and limitations of COTS AR development software, potential scale-up challenges, and proposed general recommendations for deployment of AR in the near future.

Keywords: augmented reality, rapid development, shipboard maintenance, cognitive science engineering

INTRODUCTION

To augment the efficiency and effectiveness of failure diagnosis, defect rectification and critical maintenance processes on board the Republic of Singapore Navy's (RSN) Formidable-class frigates, an inter-disciplinary DSTA team collaborated with the RSN to demonstrate the use of augmented reality (AR) technology through a three-month prototyping project.

The project scope included the development and evaluation of a prototype involving AR glasses and a handset app with the aim of reducing the time needed to perform 'O' / 'I'-level maintenance on the Frigate's Diesel Generators (DG), and achieving a higher assurance of job accuracy. The prototype would focus on demonstrating functional capabilities for five identified maintenance processes. These processes were selected mainly on factors such as the criticality of the fault and complexity of the rectification procedure. In order to achieve a better problem-solution fit, the team worked closely with the RSN to understand its current defect rectification processes and identify areas for improvement.

USER REQUIREMENTS REVIEW

With the objective of understanding how maintenance time may be reduced while improving human accuracy in the maintenance environment, the following requirements were gathered from engaging and observing operators that carried out shipboard maintenance:

Physical Comfort

The environment in which DG maintenance processes are carried out is warm and humid. The use of AR glasses should be kept to a minimum as far as possible and only utilised when hands-free guidance is deemed cardinal. Majority of the system functions that do not require hands-free access could be kept on smartphones, which are less physically intrusive and a device many users are already proficient in.

Cumulated Non-obvious Experience in Trouble-shooting Processes

While collating the maintenance procedures for digitalisation, it was discovered that the links between errors observed on the ship management system (SMS) and the DG fault isolation processes were not documented. Knowledge on error combinations, their corresponding DG component failures and the respective trouble-shooting steps to take resided among the senior engineers, and differed from ship to ship. Together with the crew of RSS Steadfast and Supreme, the team collated these undocumented knowledge and placed them into a workflow format, so as to set the stage for the digitalisation of the complex diagnosis and troubleshooting processes. These processes were then submitted to the appropriate endorsing authority for approval. In the long run, data analytic platforms would be able to isolate faults better based on the pattern of system errors encountered in both the SMS and the DG.

De-Centralised Maintenance Procedure Instructions

The maintenance procedures for the DG as recorded in the maintenance manual required traversing between various maintenance cards (chapters) and making sense of their logical flow. To reduce this cognitive load, the prototype should be designed to consolidate instructions from various information sources (SMS, undocumented expertise, maintenance cards) into a rational and easy-to-follow sequence.

UNDERSTANDING THE ADVANTAGES OF AUGMENTED REALITY

To better harness the advantages of AR, the team reviewed literature that presented the ways commercially available AR systems were being used to support outfield maintenance processes. The value of AR as understood by the team is captured in the following paragraphs.

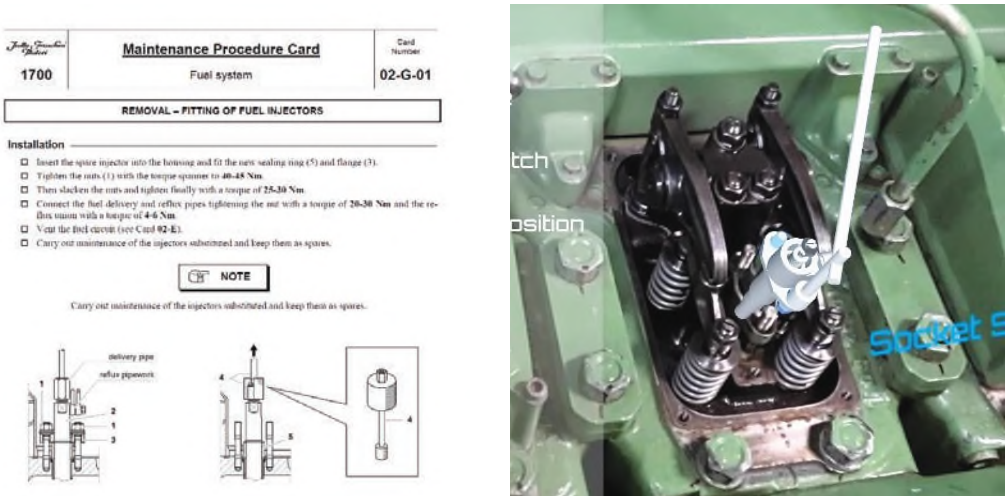
In human information processing, Donald Norman explains that our understanding of how an action should be carried out is "knowledge in the head" (Norman, 1988). The successful first execution of an action depends on whether the design of the product, i.e. "knowledge in the world", helps the human to make a correct interpretation of the action that has to be taken, thereby bridging the gulf between "knowledge in the head" and "knowledge in the world". This gulf is known as the Gulf of Execution.

Maintenance training has been largely done on actual shipboard equipment. For failures that do not happen regularly, RSN engineers would have less experience in carrying out the corrective actions. As such, their understanding of how the corrective actions should be performed, i.e. "knowledge in the head", would comprise observations of past maintenance as well as what they can glean from the maintenance cards. The "knowledge in the head", based on memory or 2D line drawings, would likely be limited, and could look quite different from the actual equipment.

Figure 1. An RSN Marine Engineer working on a DG

Moreover, mechanical shipboard systems were traditionally designed with performance and compactness taking precedence over ease and intuitiveness of maintenance (see Figure 1). The equipment design would likely provide few clues on the corrective maintenance process. Thus, the "knowledge in the world" provided by the equipment's design would be limited.

AR helps the engineer to bridge the Gulf of Execution more easily, by overlaying an animated playout of how each component should be removed, directly over the actual component he is working on (see Figure 2). This significantly reduces the amount of "information processing" that the engineer has to do in order to carry out an action, and consequently reduces the time taken and probability of error. This also addresses why step-by-step AR overlays have an advantage over a video playback on a portable device – a video playback would still require the engineer to make the link between what he has just seen and processed in short-term memory, relate it to the actual equipment he is working on, and recall the steps he should be taking.



1700

Maintenance Procedure Card

Fuel system

Card Number

02-G-01

REMOVAL – FITTING OF FUEL INJECTORS

Installation

- ☐ Insert the spare injector into the housing and fit the new sealing ring (5) and flange (3).
- ☐ Tighten the nuts (1) with the torque spanner to **40-45 Nm**.
- ☐ Then slacken the nuts and tighten finally with a torque of **25-30 Nm**.
- ☐ Connect the fuel delivery and reflux pipes tightening the nut with a torque of **20-30 Nm** and the reflux union with a torque of **4-6 Nm**.
- ☐ Vent the fuel circuit (see Card **02-E**).
- ☐ Carry out maintenance of the injectors substituted and keep them as spares.

NOTE

Carry out maintenance of the injectors substituted and keep them as spares.

Figure 2. Maintenance Card (Left) versus step-by-step AR Overlays (Right)

AR TECHNOLOGY SURVEY

Capabilities and Limitations of Commercial off-the-shelf (COTS) Technology

AR Software Development Kit Selection

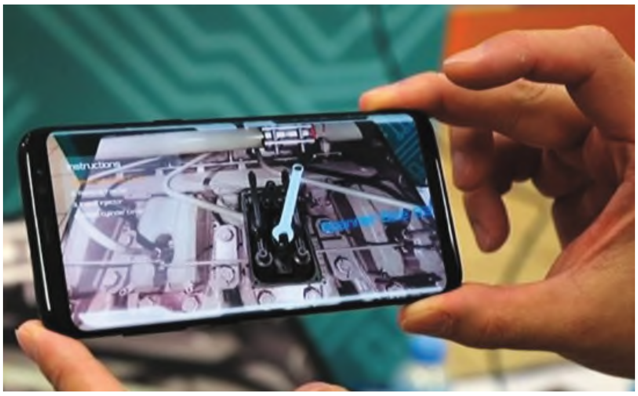


Figure 3. Augmenting Information onto a Diesel Engine

In AR, a computer must first recognise what it is looking at and be able to track components within its vision in order to overlay digital pictures or animations in a scale and perspective that matches reality. In recent years, recognition and tracking of 2D images and 3D objects through camera vision have achieved significant technological improvement through commercial innovations and increased computing power. Many software companies and start-ups have taken the opportunity to avail AR Software Development Kits (SDK) for application developers to easily customise and deploy AR applications on smart devices, as shown in Figure 3.

Most commercial AR SDK provide recognition and tracking of both 2D images and 3D objects. Marker-based AR recognises and tracks 2D images that are flat planar images such as barcodes, markers and natural 2D-like objects (i.e. photograph, road sign, labels) as shown in Figure 4. Another approach to AR is the recognition and tracking of 3D objects (i.e. cup, laptop and car) using an algorithm such as Simultaneous Localisation and Mapping to overlay 3D models or animations in a 3D space.

Figure 4. Marker-based Image (Left) and 2D Image (Right)

The team evaluated four commercial AR SDK listed in Table 1 that provided interface support for wearables. The SDK were largely similar in terms of detection speed and tracking robustness in the recognition and tracking of 2D images. This was not surprising, as 2D image detection and tracking have been well researched on and have matured for industrial use. The key difference between them was the ability to detect and track multiple targets simultaneously.

SDK	Supported Platforms	2D Mode	3D Mode
EasyAR	Android, iOS, Windows, MacOS, Unity	- Offline model building - On-device tracking - Multi-target simultaneous (up to 100) detection and tracking	- Uses 3D model to define target objects - On-device tracking - Multi-target simultaneous detection and tracking
MAXST	Android, iOS, Windows, MacOS, Unity	- Online model building - On-device tracking - Multi-target simultaneous (up to three) detection and tracking	- Offline model building using Original Equipment Manufacturer (OEM) app - On-device tracking - Multi-target simultaneous (up to three) detection and tracking
Wikitude	Android, iOS, Windows, Unity, Cordova, Xamarin, Titanium	- Online model building - On-device tracking - Multi-target simultaneous (up to eight) detection and tracking	- Online model building - On device tracking - Multi-target simultaneous detection and tracking
Vuforia	Android, iOS, Windows, Unity	- Online model building - On-device tracking - Multi-target simultaneous (up to 20) detection and tracking	- Online model building using OEM app - On-device tracking - Multi-target simultaneous (up to two) detection and tracking

Table 1. AR SDK and their capabilities[1]

To train an AR algorithm to recognise and track 3D objects, three of the assessed SDK (i.e. MAXST, Wikitube, Vuforia) require a video of the object to be taken. EasyAR is the only SDK that requires the use of a true-scale 3D model for algorithm training. For the majority of developers, a video of the target object was more easily available than a true-scale 3D model, as was in this case. This would explain why more SDK providers adopt the approach of algorithm training through videos.

However, the team found that using a video of the object as the mode of training required re-training of the algorithm for the same object in different surroundings. This meant that an algorithm trained for the diesel generator on one frigate would not be able to recognise a diesel generator of the same make and model on another frigate. Slight changes in the environmental conditions affected the algorithm's ability to recognise the object. This would mean significant effort in algorithm training for multiple similar equipment across the fleet.

As part of this study, the team visited Fraunhofer, an applied research centre at Nanyang Technological University, which shared its experience in AR technology research and demonstrated the use of a 3D tracking method that uses a scaled digital 3D model for recognition and tracking of a BMW i8. The algorithm was able to recognise and track the actual physical car robustly in different lighting conditions and overlay information with pinpoint accuracy. Figure 5 shows the detection and tracking of a scaled BMW i8 model with the persistent overlay of a glowing surface on the captured image of the car through an iOS AR application.

Figure 5. 3D Detection and Tracking using scaled 3D Model

Two AR SDK were used in this prototype. Their considered advantages and disadvantages are presented in Table 2.

AR Hardware Selection

Today, AR applications in industries are still considered an emerging trend. Although software companies such as Vuforia and Wikitude have made significant progress in providing robust software development kits for the quick deployment of AR, the hardware of eyewear platforms that deliver these solutions seem to be maturing at a slower pace. The eyewear models currently available are limited, and have been observed to be susceptible to over-heating after approximately 30 minutes of camera use. For the selection of a suitable model of AR glasses for this project, the team tried on several models and made assessments based in part on the parameters presented in Table 3.

EasyAR for 2D Recognition and Tracking	
Advantages	• Ability to recognise and track up to 100 images simultaneously • Only SDK with offline model building • Ability to track under different lighting conditions • Ability to maintain tracking when target object is partially obscured
Disadvantages	API not as well documented
MAXST for 3D Recognition and Tracking	
Advantages	• Ability to detect and track up to three simultaneous targets • Ability to do offline model training with OEM mobile applications • Ability to track under different lighting conditions • Ability to maintain tracking when target object is partially obscured
Disadvantages	Requires extensive effort to train the 3D model and overlay information onto it using the Unity3D environment

Table 2. Advantages and disadvantages of the two AR SDK[2]

The shortlisted model of AR glasses was selected due to the following features:

- It was binocular and had a field of view sufficient to fill the work space of a large mechanical equipment.
- It was the lightest in its class.
- The battery and processor were located away from the headpiece, allowing the headpiece to remain cool to wear even after extended periods of use.
- The control module consisting of the battery and processor had a user interface that was functional when used with gloves.
- The lenses were narrow and functioned like a bifocal. The user sees the AR overlays when he looks straight ahead, but has a clear field of view when he lowers his view perspective. This was assessed to be an advantage for safety as a clear field of view may be achieved without physically moving or removing the AR glasses.

The disadvantages of the model selected as observed during the experiment were as follows:

- The AR glasses overheated and the software had to be reset after 30 minutes of continual camera use.
- As the control module was separate from the headpiece, there was a cable tether connecting the two that may be a hazard if caught on equipment around the operator.

Model	Field of View	Headset Weight (grams)	Battery Operation Duration (hours)	Remarks
EPSON Moverio BT350	23	119	6	Binocular. Screen was easy to see in various lighting conditions.
ODG R-9	50	187	5-6	Binocular. Battery and processor are located at the front of the headset, above the nose bridge. Unbearably hot to the skin after 10 minutes of use. Front-heavy and prone to slipping off the face.
Vuzix M300	20	140	2-12	Monocular. Reliability issues observed. Projector arm intruded into field of view.
Microsoft Hololens	35	579	2-3	Binocular. Built-in gesture recognition for user interface. Removal is a two-handed action.
Meta 2	90	500	-	Binocular. Built-in gesture recognition for user interface. Requires separate PC and power source to be tethered to the headset.

Table 3. AR glasses models that were evaluated for the prototype

PROJECT DEVELOPMENT

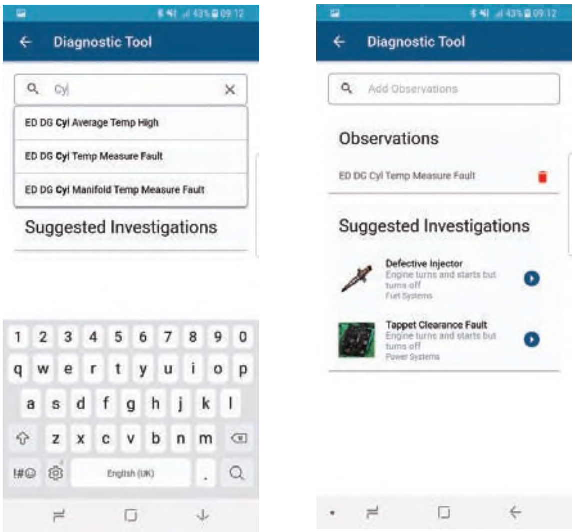
Rapid App Development with Ionic Framework[3]

A mobile app was developed to support fault diagnosis prior to putting on the AR glasses for AR-assisted defect rectification. The application was developed with Ionic Framework, a mobile app development platform which allows developers to build, test and deploy cross-platform mobile apps quickly. Employing agile development also enabled iterative versions of the app to be previewed to users frequently, constantly involving them in the design process, and ensuring a good problem-solution fit that could ultimately benefit the ship crew.

Through a series of iterations, the mobile app was developed to support the user throughout the end-to-end process; from receiving an alarm to fault diagnosis and rectification.

Receiving an Alarm

When an alarm is triggered on the ship monitoring dashboard, the engineer enters the reported alarm in the mobile app, and a list of common alarms will be suggested. After selecting the alarm, a list of troubleshooting flows is suggested (see Figure 6).



ED DG Cyl Average Temp High

ED DG Cyl Temp Measure Fault

ED DG Cyl Manifold Temp Measure Fault

ED DG Cyl Temp Measure Fault

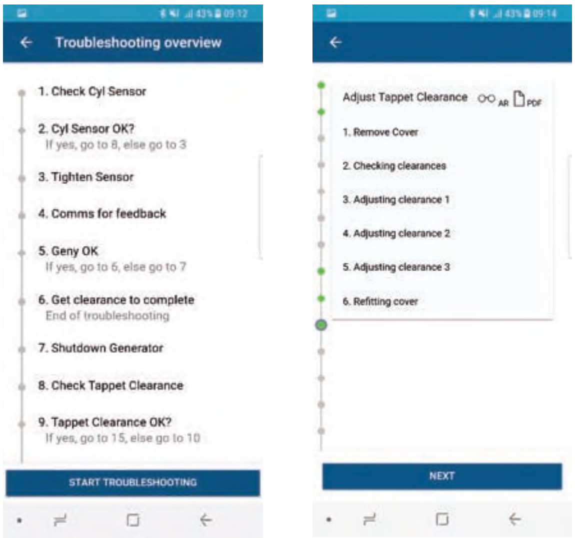
Defective Injector
Engine turns and starts but turns off
Fuel Systems

Tappet Clearance Fault
Engine turns and starts but turns off
Power Systems

Figure 6. Entering the reported alarm and receiving suggested investigations

Fault Diagnosis

Using the troubleshooting flow shown on the mobile app, the engineer can follow the steps shown to troubleshoot the fault and eventually arrive at a likely diagnosis of what went wrong (see Figure 7).



1. Check Cyl Sensor
2. Cyl Sensor OK?
   If yes, go to 8, else go to 3
3. Tighten Sensor
4. Comms for feedback
5. Geny OK
   If yes, go to 6, else go to 7
6. Get clearance to complete
   End of troubleshooting
7. Shutdown Generator
8. Check Tappet Clearance
9. Tappet Clearance OK?
   If yes, go to 15, else go to 10

Adjust Tappet Clearance

1. Remove Cover
2. Checking clearances
3. Adjusting clearance 1
4. Adjusting clearance 2
5. Adjusting clearance 3
6. Refitting cover

Figure 7. List of troubleshooting steps

Fault Rectification

Now that the fault is known, the engineer can choose to refer to a digitised copy of the manuals, or trigger the AR procedure on the AR glasses. If he chooses to use AR to assist fault rectification, the engineer can simply put on the glasses and follow the procedure.

3D Modelling with Google SketchUp

In developing 3D models to overlay the actual equipment, the team took advantage of Google SketchUp's extensive libraries to import common components such as nuts, bolts and mechanical tools. The configuration of unique parts was traced and drawn from 2D outlines presented in the maintenance cards, and then extruded to 3D. The model achieved was an approximation of the parts, as intricate details were deemed to be unnecessary for this purpose (see Figure 8). With such broad representation, the models required less processing power for display, thereby reducing lag when they were projected through the AR glasses and improving the overall user experience.

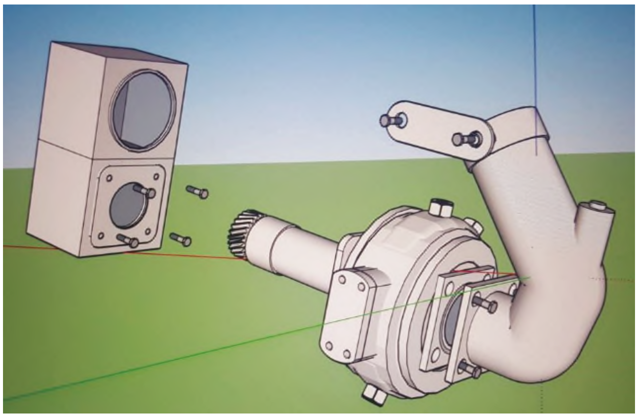


Figure 8. Google SketchUp model of the coolant pump

3D Animation and Positioning with Unity3D

In the development of this prototype, MAXST's 3D Object Tracking was used to recognise and track the DG and its various components. MAXST Map Creation[4] mobile app was used to create a 3D point cloud of our target of interest to be imported into Unity3D[5].

To ensure that the information is easily understandable, the team used Unity3D to develop detailed instructions and safety warnings with intuitive animation to be overlaid onto the physical target via AR glasses (see Figure 9). A key challenge faced here was the difficulty to overlay information such as spanners, bolts, nuts and warning messages accurately onto the video seen via AR glasses. While MAXST SDK allowed the visualisation of the point cloud in Unity3D to aid the overlaying process, it was not sufficiently accurate for the team's intent and purposes. In the initial attempt, the team took a whole day to align a single diesel generator cylinder cover accurately with the video seen on AR glasses. To overcome this, the team introduced the use of reference anchors and developed a calibration app to enable the live adjustment of anchors. This enabled the team to reduce the time required to calibrate the diesel generator by as much as 70% while achieving better accuracy.

Instructions

1. Switch on the light next to the generator
2. Switch to Manual via the switch board
3. Crank piston to the highest position
4. Remove cylinder cover
5. Remove injector
6. Check rocker arm tappet clearance
7. Install injector
8. Install cylinder cover

Figure 9. Screenshot of animated instructions of cylinder head cover removal

USER EXPERIENCE EVALUATION AND REVIEW

User Experience Assessments

User Experience (UX) assessments were conducted to assess the impact that the handset app and AR glasses have on the maintenance work of the Frigate DG, primarily from the perspective of the maintenance engineers. These UX assessments were done by getting two groups of maintenance engineers with similar levels of experience and competency to perform a selected set of maintenance tasks. One group performed the tasks with the aid of the handset app and the AR glasses while the other group did not, effectively serving as the control group. The assessments commenced with a simulated error message being shown to the maintenance engineers, who were then required to perform the necessary diagnostic and rectification actions.

Measurements and Findings

For these UX assessments, measurements were taken according to the categories described in the following paragraphs.

Time

The time taken for each maintenance engineer to perform the necessary diagnostic and rectification tasks. This was recorded by the project team observing the assessment.

The timings recorded indicated that the handset app and AR glasses enabled the maintenance engineers to complete their tasks and achieved time savings of between 65% and 80%.

Accuracy

The correctness of all actions taken by the maintenance engineer. This correctness was determined by experienced maintenance engineers observing the assessment.

All maintenance engineers carried out all their required tasks accurately when guided by the handset app and AR glasses. There was only one exception when one engineer did a redundant task, but was then guided to the correct actions by referring to the AR glasses.

Usability

The perceived usability of the mobile app and AR glasses. This was measured by having each maintenance engineer fill out a System Usability Scale (SUS) survey after completing his tasks. The SUS is a widely used industry tool to evaluate the usability of a system.

In this UX assessment, the team obtained an average SUS score of 70.5 for the mobile app and 68.5 for the AR glasses, which compared favourably to the industry average of 68. This suggests that the maintenance engineers found the handset app and AR glasses largely user friendly, though there is still some room for improvement.

Desirability

The perceived desirability of the mobile app and AR glasses. This was measured by having each maintenance engineer fill out a Bipolar Emotional Response Test (BERT) survey after completing his tasks. The BERT is a widely used industry tool to evaluate the desirability of a system experience.

In this UX assessment, the maintenance engineers largely reported positive BERT scores for both the handset app and the AR glasses. In particular, the maintenance engineers found the handset app to be friendly to use, high quality, and professionally designed. As for the AR glasses, the maintenance engineers found them to be cutting edge, high quality, and professionally designed.

General User Feedback

General user feedback was measured by having each maintenance engineer fill out a general survey after completing his tasks. The general feedback given by the maintenance engineers was largely positive. In particular, the engineers liked how the handset app and AR glasses guided them in performing their tasks, and they commented that it would be particularly useful for those who are new to the job and unfamiliar with those tasks. The engineers suggested that the stability of the AR image on the glasses could be improved, which would enhance the user experience of the AR glasses. Other feedback and suggestions were recorded, which can go into future iterations of the handset app and AR glasses.

CONCLUSION

Through the development of a Minimum Viable Product for diagnostics, and AR walk-through support for the RSN's shipboard DG maintenance processes, it may be concluded that COTS hardware and software are ready technically to support the identified use cases. However, given the performance limitations observed in AR glasses, the AR solution should also be deployable on a bigger scale through smart phones. The AR software developed should also be platform-agnostic, so that it would remain compatible with newer and more capable AR glasses models. AR was assessed to be more useful for a reduced subset of tasks that are less frequently performed, and therefore less familiar to the engineers. They are also more applicable to engineers undergoing on-the-job training as the design of the DG may not be optimised for maintenance, and the steps to be taken are not obvious to the layman. In these use cases, AR may also be applied in a collaborative environment, such that the instructor is able to conduct his course interactively with multiple trainees. The advancement of AR-related hardware and software development kits should be monitored closely and assessed against the usability and efficiency of the solution in specific operating environments, so that such technology may be more rapidly and effectively operationalised.

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ENDNOTES

[1] Evaluated in June 2018.

[2] Evaluated in June 2018.

[3] Ionic Framework is a developer-friendly app platform for building cross-platform apps for any device with the web using one codebase. Ionic Framework is licensed under MIT. Docs under Apache 2.

[4] MAXST Map Manager App is an OEM mobile application designed to create 3D feature map of a physical 3D object for object tracking.

[5] Unity3D is a real-time 3D game engine and is popularly used within the AR developer community for AR application development.

BIOGRAPHY

LIM Bee Hua Lena is a Senior Programme Manager (Digital Hub) from the experimentation and prototyping group at Digital Hub. She was previously a combat systems integrator at Naval Systems Programme Centre, and was part of the Littoral Mission Vessel team that won the Defence Technology Prize Team (Engineering) Award in 2016. To pursue an interest in product design, she obtained a Master of Science (Smart Product Design) from Nanyang Technological University (NTU) in 2017. She was conferred a Postgraduate Diploma in Education at the National Institute of Education in 2005, and graduated with a Bachelor of Engineering (Mechanical and Production Engineering) degree with Honours from NTU in 2004.

POH Chun Siong is a Senior Development Programme Manager (C3 Development) who leads the development of maritime security command and control systems for the RSN. He was part of the team that won the IES Prestigious Engineering Achievement Awards for National Maritime Security System. Chun Siong graduated with a Bachelor of Engineering (Computer Engineering) with Honours from NTU in 2008. He further obtained a Master of Science (Web Science and Big Data Analytics) with Distinction from University College London (UCL), UK, in 2017.

ONG Beng Shen Aaron is a Senior Engineer (Digital Hub) who specialises in User Experience Design. In his work, Aaron plans and leads user experience activities for projects across DSTA with the aim of delivering useful, usable and desirable systems. He was part of the Littoral Mission Vessel Integrated Project Management Team that won the Defence Technology Prize Team (Engineering) Award in 2016. Aaron graduated with a Bachelor of Science (Electrical and Computer Engineering) degree with Honours as well as a Master of Science (Electrical and Computer Engineering) degree from Carnegie Mellon University, USA, in 2008 and 2009, respectively.

GOH Chue Hsien is a Senior Engineer (Enterprise IT). As a software developer, he works on the Fleet Management System which aims to enhance and streamline logistics operations of the SAF. Chue Hsien graduated with a Bachelor of Engineering (Computer Engineering) from Carnegie Mellon University in 2015. He further obtained a Master of Science (Management Science and Engineering) from Stanford University in 2016.