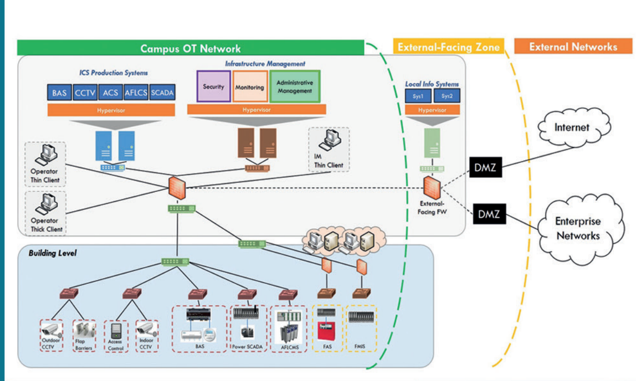

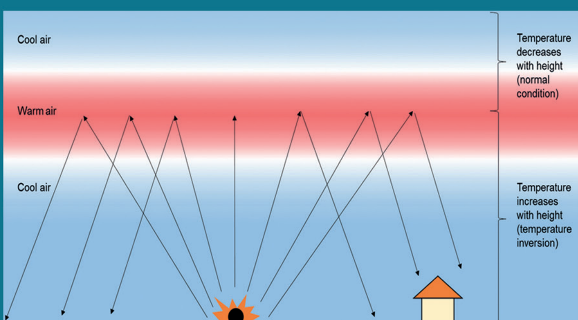

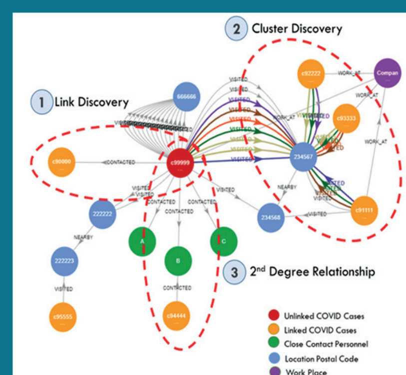

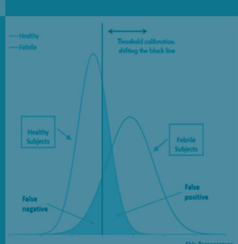

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2021/2022

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CONTENTS

EDITORIAL

Koh Tuan Yew
President
DSTA Academy

The COVID-19 pandemic has brought unprecedented disruptions and accelerated the trend of digitalisation. At the same time, technology continues to advance rapidly. As we adapt to a new normal, it is imperative that DSTA continues to innovate and harness technology to deliver advanced capabilities for the nation's defence and security needs.

The sixteenth issue of DSTA Horizons features seven articles that share DSTA's efforts in leveraging new ideas and tools to improve existing processes and create new defence capabilities, as well as some of our contributions towards the nation's fight against the COVID-19 pandemic.

Cutting across DSTA's multidisciplinary domains, **'Nurturing a Design Innovation and User Experience Culture in DSTA'** highlights our move to transform the organisational culture through an increased focus on Design Innovation (DI) and User Experience (UX). The article looks at the importance of DI and UX and its applications in the organisation and the design of an integrated Command, Control and Communication System. In **'Operational Technology Capability Roadmap: Architecture and Competency as Key Enablers'**, the authors share the approach and capability development journey in developing safe and secured operational technology systems for MINDEF and the SAF. The article also outlines future work to be undertaken for further development in this area.

'Safety Design Considerations on Lithium Batteries Use in Underwater Systems' highlights the challenges in managing the safety of lithium battery use in underwater systems. It discusses the characteristics of lithium batteries, safety management approaches and how safety is addressed in the design of lithium battery-powered underwater systems using a system safety approach of hazard identification and mitigations.

'Evolution of DSTA's Fragmentation Lethality Assessment' offers insights into DSTA's fragment lethality assessment capability, and studies how advances in computer technology as well as digitalisation can further enhance this capability; while **'Management of Noise from Live Firing Activities'** studies the key factors that affect propagation of detonation sounds from live firing activities. It also touches on literature research, trials conducted, as well as the analysis and recommendations for noise mitigation measures.

When the COVID-19 pandemic hit Singapore, a Contact Tracing Centre was established and contact tracing was adopted as one of the national strategies to curb the spread of the virus. **'Digitising Backward Contact Tracing'** captures the DSTA team's experiences and considerations in delivering the Network Analysis Tool to help identify clusters and sources of infection. As fever is one of the symptoms for those potentially infected with COVID-19, **'A Journey of Innovation - Developing a Robust and Accurate Temperature Self-Check Kiosk'** outlines how DSTA worked with various industry partners to develop the Temperature Self-Check Kiosk to allow individuals to conduct temperature checks easily.

Beyond the sharing of knowledge and insights to foster a culture of learning within the defence technology community, we hope DSTA Horizons will serve to inspire future generations of engineers and scientists to delve deep into various fields of technology for defence and beyond. We welcome and look forward to glean more deep insights from this community, and would like to express our appreciation to all authors for their contributions to this issue of DSTA Horizons.

NURTURING A DESIGN INNOVATION AND USER EXPERIENCE CULTURE IN DSTA

CHANG Yong Chia Jennifer

ABSTRACT

Design Innovation (DI) is a human-centred and interdisciplinary methodology to innovate and address complex challenges in engineering. It can be seen as an integrated approach that comprises four elements - People, Process, Methods and Principles. User Experience (UX) encompasses all aspects of the end-user's interactions with an organisation, its services and products. In DSTA, DI and UX are combined for strategic impact and organisational transformation while enhancing user experience and satisfaction in the solutions it creates for defence and national security. This article describes the importance of DI and UX (collectively referred to as DI-UX) and discusses its application in the organisation and the design of an integrated Command, Control and Communication System.

Keywords: design innovation, transformation strategy, design methodology, user experience, user-centric design

INTRODUCTION

We live in a world that is perpetually changing, one that is fraught with complex challenges and uncertainties. The ever-evolving threat landscape and technological climate today means that the Singapore Armed Forces (SAF) will need to rapidly innovate and transform the way in which wars are fought in the digital age to maintain a technology edge over its adversaries.

Singapore's declining citizen population is another immutable challenge that the SAF will need to tackle. With up to 30% fewer National Servicemen by 2030 (Ng, 2016), any technology developed for the SAF must not only be manpower-efficient, but also intuitive to use.

The need for enhanced user experience (UX) in our solutions is even more important as the younger generation of SAF soldiers are accustomed to the latest technology and interactive devices. As leading consumers of technology in the future (Ostermeier, 2021), UX can no longer be an afterthought, but will be an increasing necessity in military solutions.

THE DSTA DESIGN JOURNEY

As a statutory board under the Ministry of Defence, DSTA is responsible for delivering technological solutions to the SAF. The nature of work in DSTA spans a wide spectrum to ensure that the SAF continues to be a formidable fighting force. In light of the changing threat landscape and increasing expectations for superior UX in our solutions, DSTA has invested heavily in developing Design Innovation (DI) and UX capabilities since 2015.

The goal of DI is to tackle complex problems using the mindset and approach of a designer. It is a user-centric methodology for systematic innovation, and aims to find the right solutions that will create the desired results for the right problem. DI acts as a catalyst to effect innovative, user-centric and future-oriented thinking to drive enterprise-level transformation. It emphasises empathy, which is a key skill to enable deep understanding of users, opens up opportunities in their business objectives and missions, and consequently informs how technologies can be better designed to deliver real value and impact.

UX aims to create frictionless and desirable experience in all aspects of the end-user's interaction with products, services and systems. The increase in expectations for good UX and the gradual reduction of manpower has driven the need for DSTA to raise the bar of design quality. Together, DI and UX design aims to deliver impactful solutions with delightful experience.

Seeding the DI Culture

DSTA began seeding a culture of DI within the organisation with a series of initiatives to equip staff with DI knowledge and skills through a strategic partnership with the Singapore University of Technology and Design (SUTD), more specifically, the SUTD-MIT International Design Centre (IDC). The partnership (DesignSingapore Council, 2020) resulted in a bespoke DI Course co-designed by both partners to train DSTA engineers with DI skills simultaneously while working on high priority projects. Depending on the area of application, DI course outcomes typically ranged from solution proposals in the form of digital products, to policy changes and services provided.

With its commencement in 2015, the DI course focused on two key objectives: (1) to develop engineers with foundational DI mindsets, principles and methods; and (2) to enhance understanding through application of DI on real topics and projects. This collaboration combined DSTA's strength in systems engineering and SUTD-IDC's expertise in taking a human-centred multidisciplinary approach to engineering design.

Designing the DI Course

Duration, Format and Structure

Every run of the course conducted was improved from the preceding run based on participant feedback. Beginning with a two-day workshop that grew into a three-day bootcamp, the course duration was eventually expanded from 12 to 15 weeks and incorporated multiple opportunities for project consultation with SUTD and DSTA DI experts (e.g. framing workshop to help teams frame and strategise their approach, sprint consultations, experiential wall reviews, etc.). At the end of the course, a final presentation would be made to DSTA's senior management where participating teams showcased their innovations and solutions for their project topics. With support from management, the proposals for the project would subsequently be pursued by the respective programme centres (PCs), and the presentation archived as case studies for future sharing.

Topic Curation and Team Formation

The approach to curating topics was also adjusted over the years as DI maturity in the organisation grew. During the formative years of the DI course, participants would scope out slices of their existing projects to apply DI. However, leading impactful change in capability development required experience and expertise from multiple disciplines, thereby driving the need to change how teams were formed, both in composition and in size. This resulted in a progressive elevation from applying DI at a project-level to the enterprise-level, where senior leadership would take on the role as "domain champions" to identify crucial and high impact challenges to SAF and DSTA. These topics would then be undertaken by participating teams from different PCs and corporate entities, and in some cases, with users from the SAF.

Benchmarking Progress in DI Culture

Over the years, DSTA's DI strategy continuously evolved alongside advancements in the field, organisational needs and staff feedback.

A user research study was conducted in 2019 with the course participants holding appointments ranging from Engineers to Head Capability Development to gain insights into their experience with their DI journeys. The research informed that the programme provided participants with learning opportunities that were rare in their day-to-day work routines. The exposure opened their eyes to new possibilities that would otherwise have gone unnoticed, and allowed them to build on one another's strengths in developing and creating innovative solutions. DI provided them with a common language and platform for innovation and collaboration, even if they possessed different skills with varying experience.

In 2019, DSTA also began conducting annual organisation-wide surveys (Moultrie, Clarkson, & Probert, 2007) and stocktaking to track the impact of DI on the organisation and on staff through their project outcomes. In the most recent survey conducted, the results showed an increase in the organisation design maturity from an overall score of 1.97 (Level 2) before 2015 to 3.05 (Level 3) in 2020 – see Figure 1.

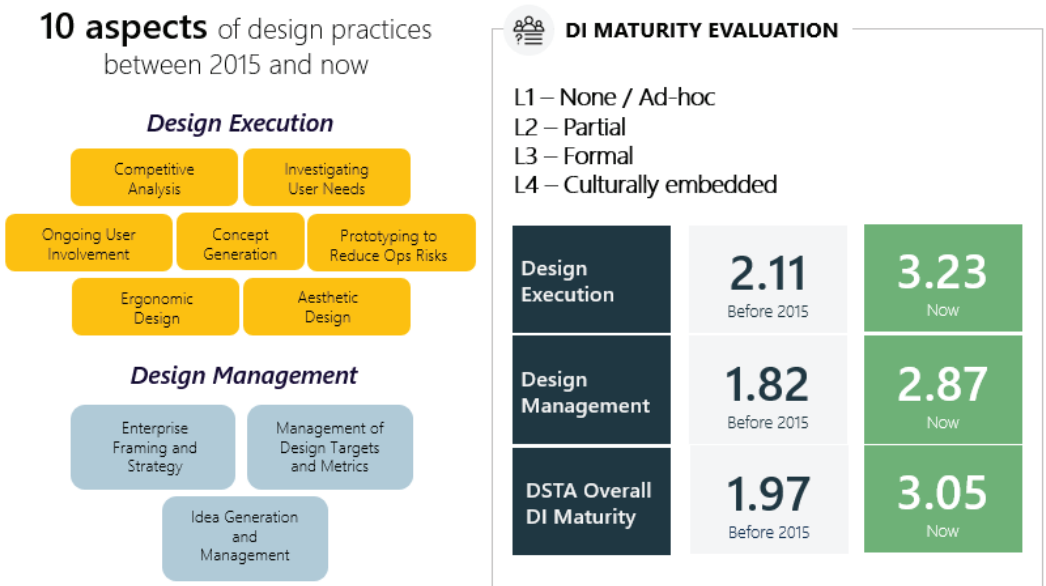

Figure 1. DSTA design maturity evaluation (2015-2020)

In the same year, DSTA also received the Singapore Good Design Mark[1] 2019.

Advancing DI and Strengthening Culture

To date, more than 700 staff have been trained across the organisation — achieving a ratio of one DI Practitioner to five staff. Advancing the skills and mindsets of our existing DI practitioners has become equally key to ensure continued relevancy and impact in their work.

Engagement initiatives such as Fireside Chats, Workshops and Seminars were started to understand ground challenges, advance practitioners' knowledge in design practices and techniques, and promulgate lessons learnt as part of knowledge sharing within the organisation.

DSTA has also taken a further step to establish a centralised DI-UX team comprising a growing pool of specialist UX Architects and UX Designers. The UX practitioners complement DI-trained engineers and bring specialist UX design skillsets into key projects. Key projects will now be supported by at least one pair of UX Architect and UX Designer to lead in UX activities, while they work closely with DI-trained project engineers.

With this new project teaming, DSTA conceived a DI-UX process by combining lessons learnt from various design work and collaboration with leading technology companies. One key aspect that differentiates the DSTA DI-UX process from general design thinking methodology is the integration of best practices and techniques from DI, lean UX and agile methodologies (see Figure 2).

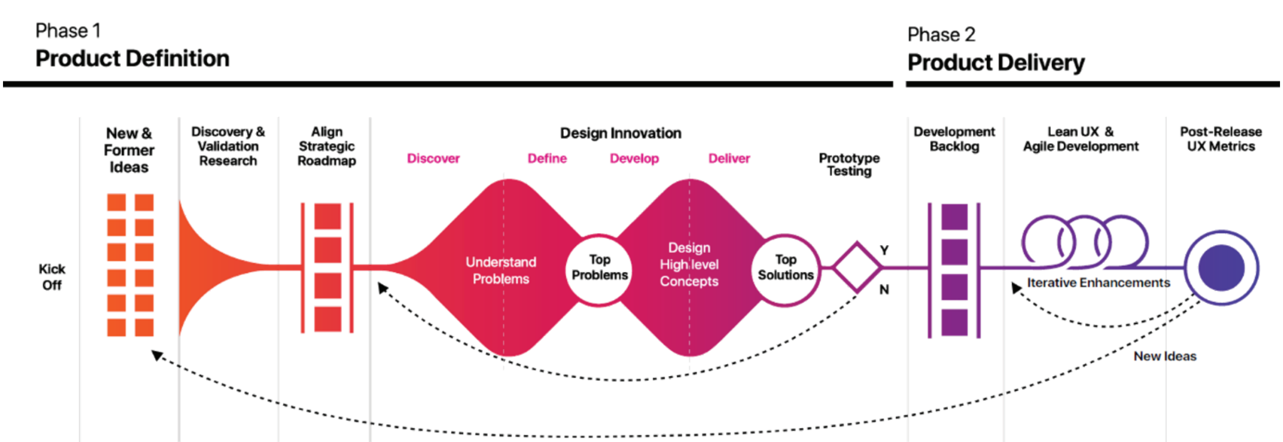

Figure 2. DSTA end-to-end design process for digital systems

CHALLENGES IN APPLICATION

As one may expect, challenges arose as DI-UX was applied across the board in projects under different circumstances. Practitioner feedback during the DI Fireside series revealed three key challenges faced across the organisation, as summarised below.

Resource and Skillset Limitation

DI can be applied in any phase of a project, and practitioners often find it difficult to apply DI late into the project phase, especially when many other constraints had already set in. When DI efforts were not catered for early on in the project, managing project schedule, resources and scope became challenging when changes needed to be made downstream. Some of these changes required additional effort to effect change, which was difficult due to a lack of bandwidth. Others required competency in specialist design areas, namely UX architecting and UX design, which were lacking among the practitioners.

Gaps in Mindset

Fear of risk-taking and resistance to change were two of the most prominent gaps in mindset raised by practitioners. For example, some stakeholders sought risk-free solutions, while others were unwilling to change workflows and processes. This unwillingness to deviate from established norms was also observed in some teams as some of them felt that they were not senior enough to effect change.

Design Processes, Systems and Infrastructure

It was observed that the full design process was usually too tedious to execute because of two main reasons. First, DI and UX activities were mostly executed manually, generating physical design artefacts in the process. Practitioners faced high barriers in digitising these artefacts due to additional efforts required to do so. Second, design templates or UX patterns were not standardised across the organisation, and individuals had to create their own.

Initiatives

These challenges compelled DSTA to reorganise DI-UX at the organisation level. The DI-UX Team is presently exploring various ways to address challenges associated with resource and skillset limitation.

First, UX support will be progressively scaled up across PCs. Second, DI fireside activities will continue to be conducted to imbue the right mindsets and knowledge sharing to strengthen the overall culture of DI among staff. This is to address the general lack of confidence in applying DI. Third, the DI-UX Team has also developed a DI Operations Playbook with templates to streamline design processes across the organisation. This will eliminate the need for additional efforts from individual PCs to create separate templates. To enable consistent design quality and practices across the organisation, the team has also built a design system containing reusable patterns for digital systems.

DI-UX APPLICATION IN THE INTEGRATED C3 SYSTEM

Background

The integrated Command, Control and Communication (C3) System was envisaged to be a platform for multiple government agencies to command, control and communicate when managing and responding to incidents in large-scale events, such as the Singapore's National Day Parade.

DI Methodology

The team began with the discovery of the problem space within a few agencies in the public sector. User research was conducted over seven months, with over 100 users from 40 operational units across four government ministries, to understand their respective operations, work processes and challenges. Research methods included user interviews, focus groups, in-situ observations, ideation methods and design critiques. The research informed three key persons involved in the management of large-scale events: Decision Maker, Coordinating Officer and Ground Officer. To facilitate deeper conversations with the users and stakeholders, several versions of C3 prototypes were created in varying fidelity and shared with them for their feedback.

Discovering and Defining the Problem Space

Some of the key opportunities and insights gained from the user research were as follows:

(1) **No Access to C3 When Needed As Users Were Always on the Move** – Many of the C3 systems were housed only

in operation centres at different locations. Users had to visit these operation centres and log in to terminals before they could access the C3 systems. This hindered users who were frequently on the move.

(2) **Users Rely on WhatsApp and Emails** – A number of users did not have access to the C3 systems. Yet, they were still called on to contribute to the operations, and they had to rely on personal applications like WhatsApp and emails. However, WhatsApp was not designed for C3 operations, and users often became lost in the large volume of messages. Sensemaking and locating relevant information became a major challenge in large-scale missions where multiple groups and agencies had to work together. The challenge was exacerbated by having to port information over to multiple applications.

(3) **Multiple Action Parties Lacking a Common Platform to Facilitate Coordination** – The team observed that multiple action parties were involved when working on incidents. Even if the incident was under the jurisdiction of one specific agency, people from various departments would have to work together. There was no single integrated system that could be used.

(4) **Disparate Systems in Peace Time and Crisis Means More Training is Required to Prevent Deskilling** – Although users do not necessarily need to manage large-scale events frequently, they still needed to manage daily operations that required coordination and collaboration with different parties. Should an incident escalate into a major event, these users would be required to be familiar with their systems in order to respond quickly to the event. However, users have various systems with different operating procedures for different types of scenarios. This led to frequent training to familiarise themselves with systems to prevent deskilling.

Developing and Delivering the Proposed Solution

Several versions of the prototypes were created through the design journey. Figures 3, 4 and 5 illustrate earlier versions of the key screens designed for the core functions.

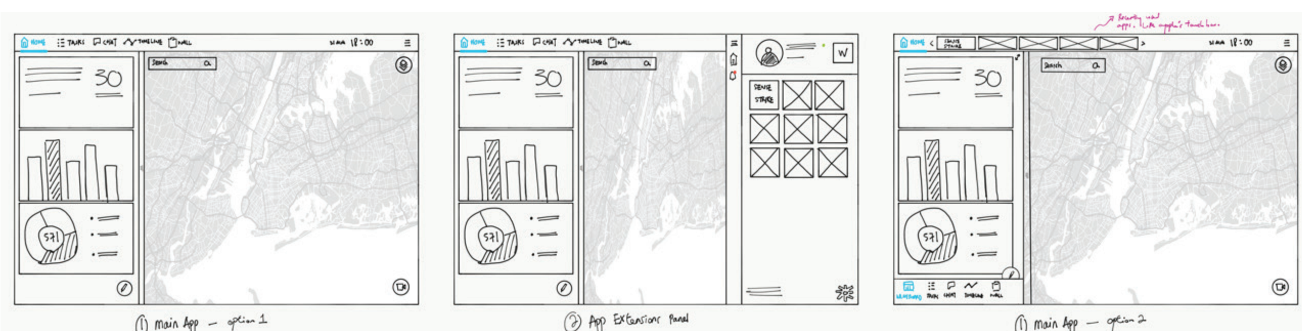

Figure 3. Initial sketches of screens

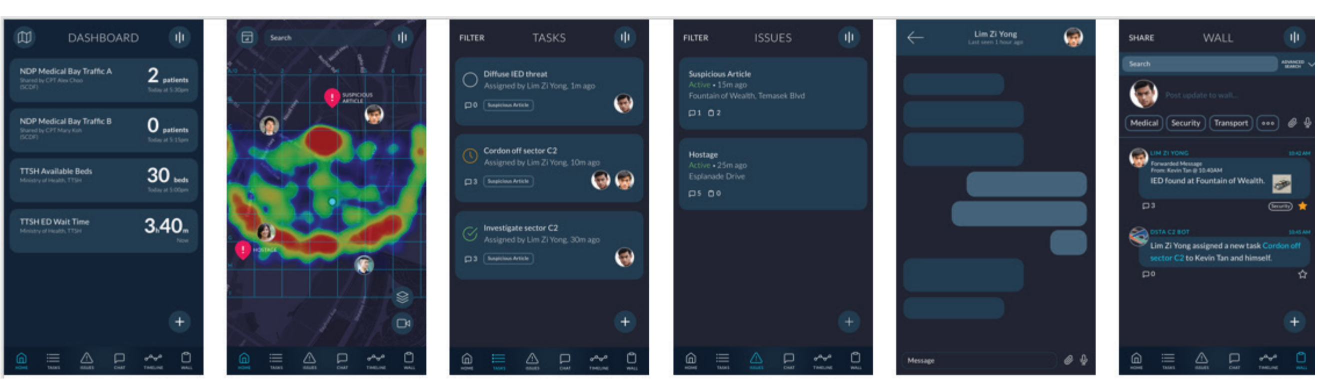

Figure 4. Mobile screens showing core functions of the Integrated C3 System

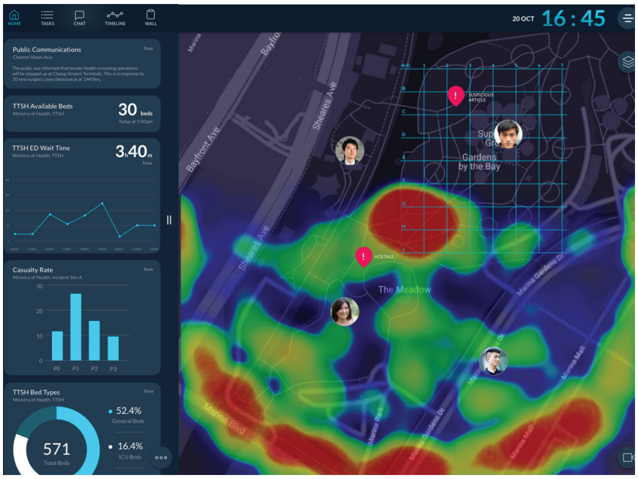

Figure 5. Initial desktop screen of Integrated C3 System

The prototype went through many iterations with the various agencies on multiple tracks of design and development. Every new insight from each iteration contributed to the product improvement. Based on insights gained, the team designed a generic C3 system that achieved the following goals:

(1) Integrated C3 System – As mentioned earlier, users across agencies did not have access to C3 systems when they needed to respond to incidents, and when they did, they had to work with disparate systems. Having a single integrated C3 system fundamentally transformed the way agencies collaborated with one another by breaking down operational silos.

(2) Significantly Quicken End-to-end Response Time – Using multiple systems slowed down response time because information had to be duplicated and transferred across systems. All parties now accessed and worked on the same system and used a common source of information without having to rely on personal applications like WhatsApp or emails.

(3) Scalable and Minimise Waste – With a generic C3 platform, the development teams would not need to recreate the same features repeatedly in C3 systems for each agency. Instead, they could build on the generic platform to develop bespoke functions by creating the dedicated applications required by different agencies. This helped to streamline and minimise the overall effort.

To demonstrate how the solution worked, the team created a video storyboard depicting a counter-terrorism scenario and how users should use the system to respond to the incident. Before the video production started, the team created scripts of the story and paper storyboards (Figure 6) that described the scenes to be included. Figure 7 shows some screenshots from the concept video.

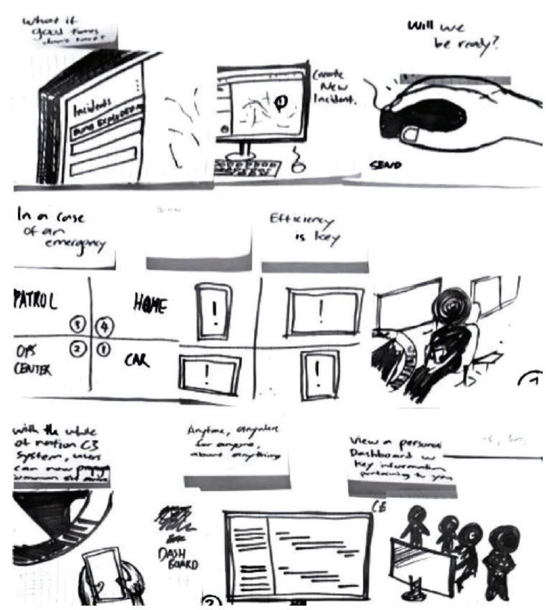

Figure 6. Initial draft of paper storyboard

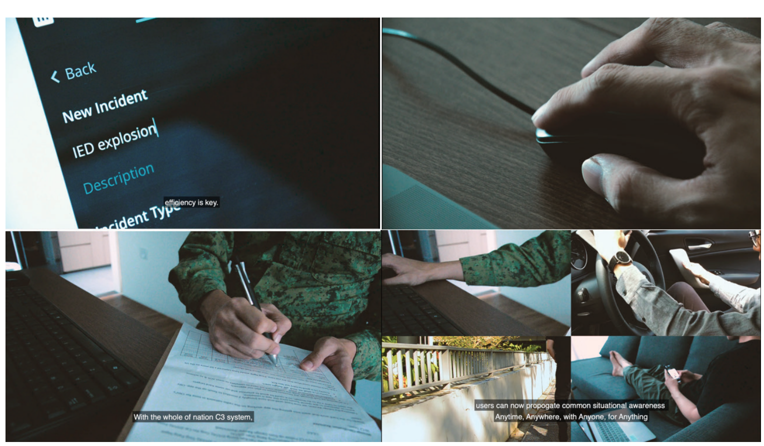

Figure 7. Screenshots of the concept video

User Feedback

The video was presented to various user groups to obtain feedback on improvements, and specific applications that they would need. The users were better able to articulate their needs because they understood how they would coordinate with other agencies, and the specific apps they would need to fill any operational gaps.

The users were encouraged by the design and could see the value of the system. Others were excited by the new capabilities and potential use cases that they could apply to their own agencies.

The system went on trial during Singapore's National Day Parade in 2019, and has since been adapted as a baseline for other C3 systems.

Figures 8 to 11 show the final design of the Integrated C3 System at a glance.

Figure 8. Mobile and web based Integrated C3 System

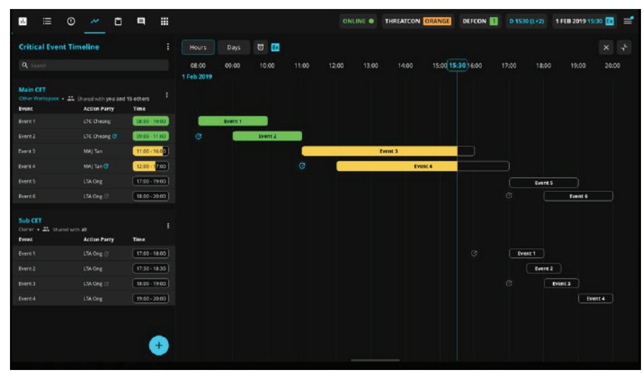

Figure 10. Smart timeline

Figure 9. Dynamic dashboard

Figure 11. Real-time reports and interoperable apps

CONCLUSION

DSTA has come a long way in her design journey. The DI course has trained over 700 staff and built a critical mass of DI practitioners across various PCs and corporate entities. Although training will continue as part of the strategy to raise, train and sustain the DI practice in the organisation, DSTA will now focus on strengthening the community and design culture within the organisation. Apart from the regular ongoing fireside activities to refresh and improve understanding in design practices, formal UX teams will be established to extend specialist design support in key projects across the organisation. The UX teams will also drive enterprise-level design strategies. DSTA will continue to scale design practices and strive to become an organisation that brings innovation through the way design is managed and executed in her projects.

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ENDNOTES

[1] The Singapore Good Design (SG Mark) was launched in 2013 by Design Business Chamber Singapore in partnership with the Japan Institute of Design Promotion that founded the prestigious Good Design Award (G Mark). SG Mark's overarching goal is to impact businesses, improve quality of life of different communities (individuals, corporations and countries) and influence culture.

BIOGRAPHY

CHANG Yong Chia Jennifer is a Principal UX Architect (C3 Development). She leads the technical build-up in Design Innovation (DI) literacy and advances the DI methodology and application through partnership with Institutes of Higher Learning. She plays a key role in the elevation of DI to the enterprise level and drives the advancement of DI practice in DSTA through Fireside sessions. Jennifer graduated with a Master of Science (Information Studies) from Nanyang Technological University in 2007 and a Bachelor of Science (Computer & Information Sciences) from the National University of Singapore in 2000.

OPERATIONAL TECHNOLOGY CAPABILITY ROADMAP: ARCHITECTURE AND COMPETENCY AS KEY ENABLERS

YEO Kai Leng Teresa, TONG Ming Shu, YING Jie Hao Jeff, SHEN Zihong

ABSTRACT

Operational Technology (OT) systems are present in our everyday lives, and will bring about significant impact when disrupted. The push for digitalisation and connectivity has magnified the inadequacies in security considerations in OT systems, and highlighted their susceptibility to cybersecurity threats. This article will share the approach and capability development journey taken to cyber secure and cater for future digital needs of Ministry of Defence and Singapore Armed Forces' OT systems. The focus is on developing a practical and secure architecture to meet future needs and demands of Industrial Control Systems, and also on training human capital to undertake these works. Finally, the article provides some outlines for the future work in this capability area.

Keywords: operational technology, cybersecurity, capability development

INTRODUCTION

Operational Technology (OT) refers to technologies involving interconnected devices and computers for the monitoring and controlling of physical processes. These OT systems are commonly found in the transport, energy, water and defence and security sectors, as shown in Figure 1.

Many may not be aware that OT systems are present in our everyday lives and drive the way we function and work. However, these systems are not designed with cybersecurity in mind, as the focus is on functionality and availability. This makes them attractive targets of cyberattacks, which can cause high mission impact, bring disruption to lives and result in financial losses. One of the most significant attacks was the Stuxnet event, a cyberattack which caused physical and irreversible damage to the centrifuges in Iran's nuclear plants.

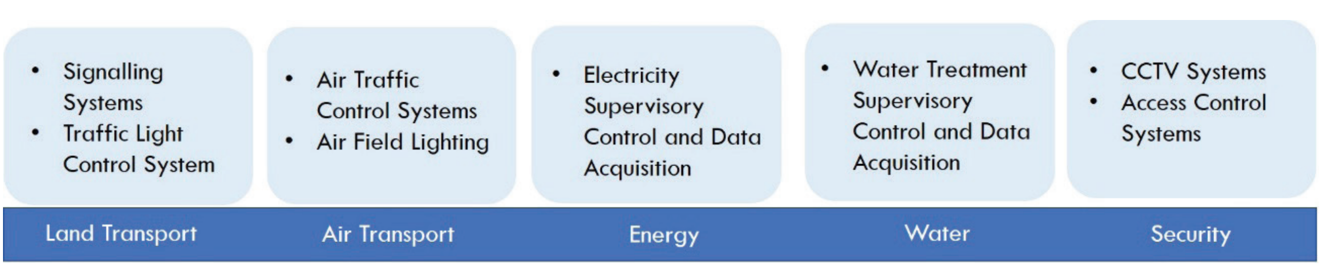

Figure 1. OT Systems found in various sectors

Recognising the increasing use of cyber means to disrupt OT systems, DSTA embarked on a journey to develop an approach to address the new needs brought about by the convergence of the Information Technology (IT) and OT spaces to achieve new capabilities and productivity. The two key enablers to secure OT were identified to be architecture standardisation and competency development. In the defence context, OT comprises control systems on ships or aircraft, data links and building control systems. The focus of this article is on building control systems, which are becoming increasingly digitalised with remote monitoring and control capabilities. The article aims to describe DSTA's journey in developing the two key enablers, as well as identifying future efforts and priorities.

WHAT ARE INDUSTRIAL CONTROL SYSTEMS?

An Industrial Control System (ICS) is a subset of OT systems. It is a combination of control components (e.g. electrical, mechanical, hydraulic, pneumatic) that act together to facilitate detection and maintain control of physical operations through data acquisition, visualisation and controls. They play a critical role in maintaining continuous operations, as well as ensuring functional and technical safety in the prevention of accidents and disasters.

ICS includes Supervisory Control and Data Acquisition (SCADA)[1] systems, Distributed Control Systems[2], and other control system configurations such as Programmable Logic Controllers (PLC)[3]. Figure 2 shows the typical components and connectivity of an ICS. They are typically deployed for monitoring and/or the control of building related services and geographically dispersed operations including utility distribution such as power, water and fuel, cooling, mechanised equipment and physical security.

The instrumentation layer in Figure 2 comprises sensors, which are analogue devices used to monitor and measure the telemetry of equipment such as the rotational speed of a generator. The sensors will interpret the readings and report back a change of state. Actuators are used to execute the controls via a change of contact point (ON or OFF state). PLCs are embedded devices that are pre-programmed with algorithms known as ladder logic. The role of the PLC is to compare the inputs received from the sensors against a pre-

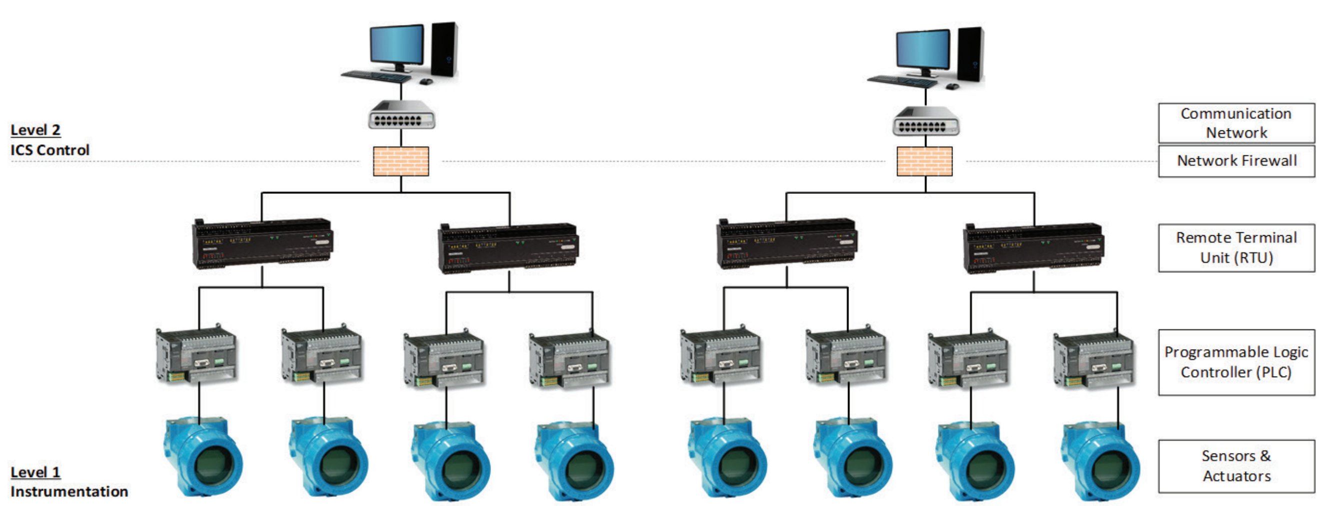

Figure 2. Components and connectivity of an ICS

set threshold. When there are deviations, the PLC will issue the necessary control signals to the actuators to bring the system back to the ideal state. The PLC is also the interface with the IT server, and will be able to receive overriding commands from the server to change the pre-set threshold. Remote Terminal Units are used to interface multiple PLCs to the server, and handle the interface and translation of ICS protocols, for example Serial to Ethernet.

The ICS control in Figure 2 comprises the Human-Machine Interface (HMI), servers and networking equipment to monitor and control the entire ICS system. The HMI is generally the Graphical User Interface of the software application that presents information to the operator. The HMI may also accept control instructions from the operator and sends it to the server for processing. The ICS servers will poll the status of the systems periodically and present the information on the HMI workstation. It will also receive the control instructions from the HMI and send the commands to the field device to activate the control process. The Historian is the database that keeps tracks of all systems status and commands for fault troubleshooting purposes.

EVOLUTION OF INDUSTRIAL CONTROL SYSTEMS

Early versions of ICS started with little automation and digitalisation. Many of the control and monitoring functions used to be done locally with hard-wired relays and timers coupled with man-in-the-loop processes. As time progressed, the push for automation and enhacement to productivity led to the development of remote monitoring and control capabilities.

When these systems and capabilities were developed in the 1970s, they were based on an air-gapped and standalone concepts, with vendor or Original Equipment Manufacturer specific components and protocols. The focus of the ICS developer and users then was on availability and safety, with scant consideration for security. In fact, the main security feature was physical security, by keeping these devices behind locked gates and security guards. This has been the industry practice for the last 30 years.

In the early 2000s, ICS started to shift from the use of proprietary computing and communications to adopting common industrial standards and open protocols which made them more "IT-like". Yet, the mindset on how these systems were used and designed did not change. Engineering teams managing these systems had little or no security awareness and continued to rely on standalone designs and physical access control measures to protect these systems. The industry was also not well prepared to support new digital models of ICS and was slow to apply IT security best practices. This resulted in fundamental security gaps and resulted in several critical ICS becoming targets of cyberattacks.

THREAT LANDSCAPE

The Stuxnet malware attack which damaged the centrifuges in Iran's nuclear plants in 2010 was a significant event and demonstrated how a cyberattack could wreak havoc on ICS, resulting in the severe degradation of a strategic national capability. Since then, there have been multiple attacks over the last decade targetting ICS, with the aim of disrupting essential civilian services and lives.

The December 2015 Ukraine power grid cyberattack, where attackers gained control of the SCADA and remotely switched off the substations, resulted in power outages for roughly 230,000 consumers in Ukraine. It was a wake-up call for critical infrastructure operators, as networked SCADA systems were already widely in use to control and monitor geographically dispersed substation facilities. The attack showed the sophistication and determination of advanced persistent threat actors, who had carefully planned their attack in a stealthy and targeted manner. Using stolen credentials to gain remote access, changing the passwords to maintain access and overwriting firmware of critical devices to deny remote access, the attackers disrupted the power supply to residents for up to six hours in various parts of Ukraine. More importantly, remote access to the substations and breakers was denied for months, forcing electric grid operators to open and close the breakers manually, while engineers struggled to restore remote management capabilities on the compromised PLCs. The attack emphasised the importance of securing critical infrastructure, and demonstrated that threats were real and credible, and would significantly affect businesses and day-to-day livelihoods.

More recently, in 2021, the ransomware attack on the Colonial Pipeline in the United States again demonstrated how valuable (as a target) and vulnerable (as a system) critical infrastructure systems are. This was not a sophisticated attack yet it still forced the gas pipelines running from Texas to New York to be shut down, resulting in fuel shortages at airports and gas stations. Attackers were able to gain access to the corporate network through a legacy virtual private network used by employees to connect remotely into the company's computer network, and this demonstrated how the convergence of IT and OT had enlarged the possible attack vectors into OT networks. Hence, there is a need to ensure that cybersecurity measures for ICS evolve with the introduction of new IT capabilites and their corresponding threats.

IMPETUS TO DEVELOP ICS CYBERSECURITY

What used to be standalone and physically isolated ICS implementation, with a flat network architecture, minimal IT security controls, and heavy reliance on physical controls, will no longer be viable in an increasingly digitalised world. Yet, the distributed and proprietary ICS industry was not evolving fast enough and effectively to cater to the new operational paradigm. This resulted in the introduction of terms such as "the convergence of Information Technology and Operational Technology" and "Physical-Digital Convergence". A robust solution requires more than implementing standard IT controls with the vain hope that ICS systems would automatically be well protected and remain functional.

The Cyber Security Agency of Singapore (CSA) recognised the diverse ICS landscape and published the OT Cyber Masterplan in 2019, with the key objective of providing guidelines and alignment among the OT cybersecurity industry. CSA wanted to create deeper awareness and understanding of the cybersecurity landscape, including the challenges faced by OT stakeholders, and to catalyse the development of local capabilities, technologies and competencies, which can aid Critical Information Infrastructure owners to strengthen the cybersecurity of their OT systems. In 2021, they also developed the OT Cybersecurity Competency Framework (OTCCF) to guide talent and competency development in the space of OT cybersecurity.

The defence sector was no different, and organisations like DSTA had to develop a model which would meet its needs. With the changing threat landscape, reduction in manpower and advancement in technology, DSTA also needed to re-organise, re-design and re-train to ensure defence systems were always available and operational.

DSTA CAPABILITY DEVELOPMENT JOURNEY

In 2018, a small team of engineers was assembled to explore and chart out a new domain for ICS cybersecurity. There was a need for a new way to architect and design ICS networks and systems, to be ready with the increased digitalisation of ICS, and the corresponding increase in cyberattack surfaces. If the industry was unable to develop solutions faster than the arising needs, the team would need to influence the ICS community in the long run. This also meant that the team needed new perspectives and new competencies to drive these changes.

NEW ARCHITECTURE

DSTA embarked on a journey to develop an architecture to manage and host the ICS centrally. The team started looking at what the IT domain could offer, and how they could bring together and leverage the best of the IT and OT domains. The journey started with industry exploration, where the team spoke to established ICS vendors to understand where they were in terms of their IT and cybersecurity maturity. Not surprisingly, each of the ICS product types had varying maturity levels. Figure 3 is a summary of the various levels of industry maturity for ICS in the environment. In the case of Building Automation Systems (BAS), in order to meet their commercial customer needs, many were already moving onto the cloud and offering services such as data analytics to aid owners to better manage utilities consumption. On the other end of the scale, fuel management systems were still very traditional and proprietary, as their key customers' focus was on system availability.

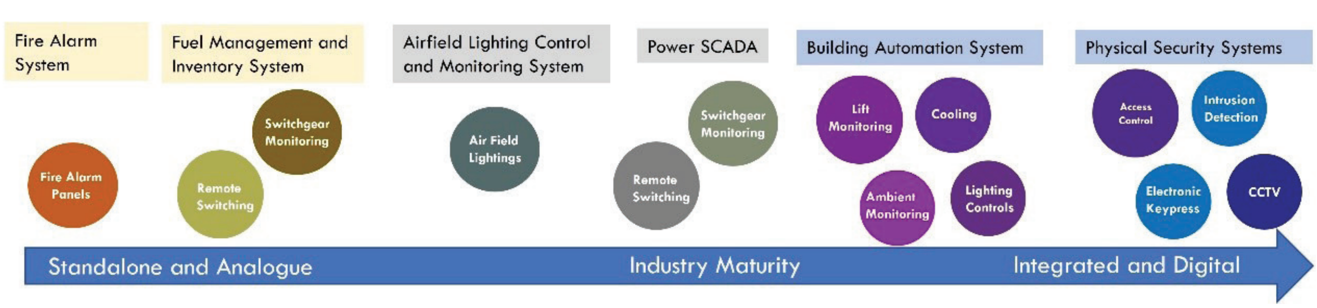

Figure 3. Digital maturity of various ICS

With this wide spectrum of products, vendors and use cases, the team deliberated on an architecture to manage and control these diverse systems centrally. Taking a systematic approach, the team evaluated each of these systems to assess the need to centralise and/or virtualise them at the local camp/base level. The architecture also had to support other business use cases which required connectivity to other enterprise networks, in a secure and effective manner.

Figure 4 shows the new architecture developed to host and manage ICS systems. The architecture was developed starting from the local campus OT. This was the centre piece of the architecture as it required a new way to architect and design traditional networking of ICS systems. As new business needs arose, to facilitate connectivity of the local OT network to other IT applications, the architecture was expanded to consider secured linkages to Enterprise networks. The subsequent sections will explain the considerations taken in developing each of these parts of the architecture.

The team started by examining which systems should be consolidated, taking into consideration the safety and availability aspects of each of the ICS, and also the digital maturity and readiness of virtualisation (refer to Figure 2) for each of the systems. A safety critical system that was first considered was the fire alarm systems. Fire alarm systems consist of sensors and simple PLCs, as their primary role is to sound an alarm during a fire outbreak to alert building occupants or a central operations centre. While they are increasingly integrated into BAS to alert operators, fire alarm systems are meant to operate automonously with little interaction and reliance on IT systems. Hence, in the proposed architecture, the team decided to set them up as standalone systems.

For the more digitalised systems, such as physical security and BAS, the challenge was to virtualise them and yet be able to ensure logical segmentation to limit the propagation of cyberattacks across different sub-systems. The team explored the implementation of Virtual LANs (VLANs) to segment the

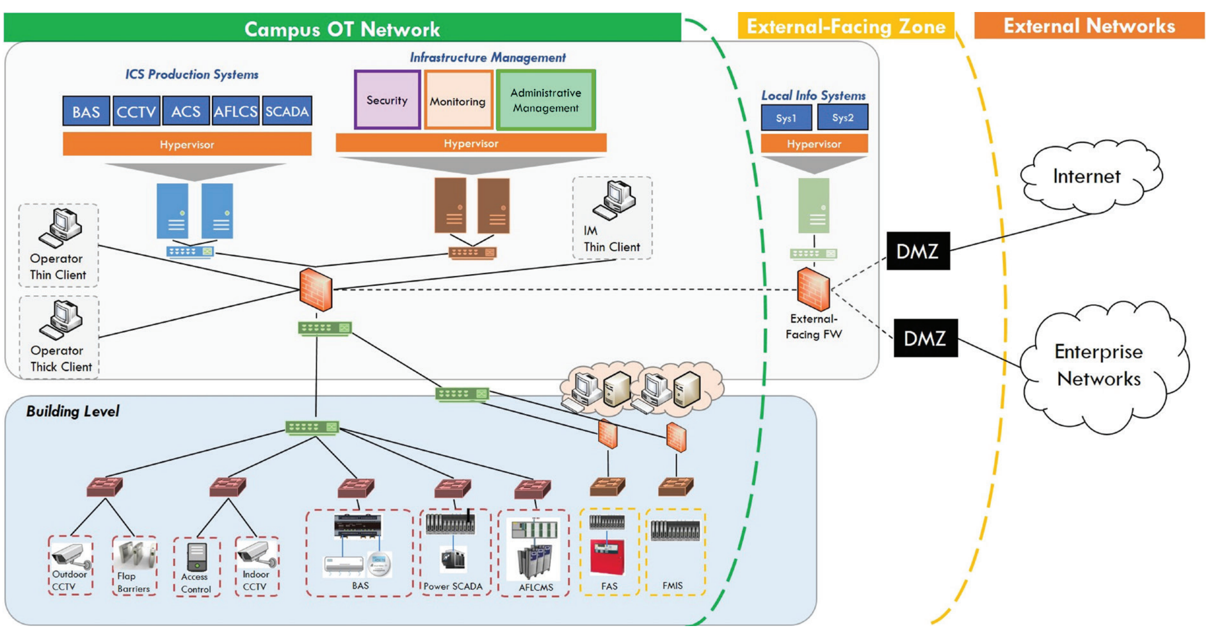

Figure 4. New architecture to manage ICS systems

Local Campus Network Infrastructure

The vision of the team was to set up a common OT network in each of the local camps and bases, moving away from the traditional standalone and bespoke networks for each of these ICS. This was to realise the objectives of (1) reducing maintenance efforts of many standalone networks; (2) providing greater asset and cybersecurity visibility of the ICS; and (3) enabling the consolidation of data to fulfill business needs.

different ICS sub-systems on the OT network. This required the team to work closely with the vendors to ensure correct devices were assigned the correct VLANs and tight control of the firewall rules. When testing out this configuration in one of the building projects, the team had to overcome some of the technical limitations of the PLCs, which had hardcoded IP addresses. The team worked closely with the ICS vendors to implement this concept for over 20 systems, in many other camps and systems. The systems were tested to be operational, and vulnerability assessments were conducted to validate the security implementation.

Having a large number of standalone systems also resulted in huge maintenance efforts to maintain their cybersecurity posture. The man-effort required to patch 50 standalone networks consisting of different equipment types, operating systems and applications would take around 90 days. The team validated that this effort could be reduced by three-fold to one month by implementing a common infrastructure management system. Setting up a common infrastructure management system was also necessary to enable operators to manage the more complex consolidated IT and OT infrastructure with technology and automation. The automated tools were able to facilitate IT asset visibilty and collection of security logs.

There were internal debates about the pitfalls of a standalone versus centralised solution. The inhererent risks of cascading failures and reduction in systems resiliency in a centralised infrastructure were fully recognised. However, weighing the impact of future manpower constraints, and the ability to leverage technology to secure and monitor multiple standalone systems, the centralised solution was deemed an appropriate trade-off.

Connectivity to External Networks

Some of the key operational capabilities of the Singapore Armed Forces (SAF) depend on the ability to piece together information from different domains – physical, digital, cyber – to derive insights and come up with a plan to out manoeuvre adversaries quickly and decisively.

In the ICS domain, there are also new business capabilities and user experience enhancements that can be achieved by interfacing ICS systems with enterprise networks. For example, a pilot was started to enhance the clearance process for visitors to enter camps/bases by leveraging Internet facing applications (which have wide user reach) for visitor pre-registration. These applications have secure interfaces with the physical security systems within the camps/bases to allow the entry of approved visitors.

Such new business requirements require security controls to mitigate the propagation of threats across the IT and OT domain. One of the key enablers is a Demilitarised Zone (DMZ) to secure information exchanges. While this DMZ usually comprises firewalls and proxy servers, the nature and criticality of our systems required custom developed security gateways to secure data exchanges to a high level of assurance, and yet meet the business latency needs.

Another use case is to enhance work productivity with a centralised management and control centre to manage many ICS across multiple SAF facilities more effectively. While this concept is not new commercially, it is more challenging in the defence context to connect all the camp/base level BAS while maintaining the overall system resilience. The central monitoring architecture is still a work in progress.

Operationalising the Architecture

Today, the architecture has been refined, tested in slices and expanded to support more use cases. The deployment across SAF facilities will be done in phases as there are extensive ICS and IT infrastructure requirements, which will need to be timed with the refresh of each facility's ICS.

With the introduction of the new architecture, important and fundamental conversations have started on how to manage these ICS as systems become "smarter" and increasingly vital in daily operations of camps and bases. This will continue to evolve, as the new concept and architecture is trialled, implemented and put in operation.

NEW COMPETENCY DEVELOPMENT

Operational Technology, Information Technology and Cybersecurity

The area of critical infrastructure requires cross domain expertise, as OT experts may not understand IT well, and vice versa. This is a recognised problem at the national level. To this end, CSA had also embarked on the development of OTCCF to guide the career pathways for OT cybersecurity engineers.

Starting from OT

In DSTA, building and infrastructure engineers with deep ICS domain knowledge have been identified and trained in the areas of IT and cybersecurity competencies. This approach has enabled the infrastructure engineers to apply IT best practices quickly to secure systems that they are familiar with, and work in hybrid teams with IT and cyber engineers to realise a security-by-design architecture for ICS.

While this approach seemed simple, it was a daunting undertaking for the small team of engineers, as there was a large market of ICS vendors with varying IT knowledge and competencies. Hence, new concepts had to be communicated to each and every ICS vendor. While some vendors had started to partner with IT companies to level up their competency and capabilities, the assessment is that there still is a long way to go for the ICS market to mature in the cybersecurity aspects.

Forming Hybrid Teams to Deploy Cybersecurity Tools and Solutions

Monitoring and detection have been very much discussed and implemented in IT environments over the last 10 years. In the last three years, there have been requirements for OT environments to be monitored for cyber threats too. This has led to the emergence of new products and tools, such as ICS-aware firewalls and anomaly detection solutions.

The challenge for infrastructure engineers is to evaluate such products and determine their effectiveness. While the functionality of ICS is well understood, abnormal behaviours and potential cyberattacks are not. Hybrid teams were established to include cyber engineers, and they provided knowledge on cyber anomaly detection to aid in system design and development of detection rulesets. A collaborative approach was required for cyber engineers to understand baseline ICS behaviour from the infrastructure engineers, and for the infrastructure engineers to assess the performance implications of proposed security modifications.

During the implementation of cybersecurity tools for ICS, cyber and infrastructure engineers worked together to examine traffic patterns to ensure that the cyber tools and analytical engine are able to detect attacks, with minimal false alarms. This is an interative process and requires commitment from all involved to find the right balance between effective cybersecurity and efficient operations. Adopting this model, DSTA has implemented anomaly detection solutions to the most critical ICS systems and is in the process of promulgating these solutions.

Developing Engineers with Dual IT and OT Competencies

To truly do well in the space of ICS cybersecurity, the goal is to train and develop hybrid OT/IT engineers who are well versed in both the ICS and IT cybersecurity domains. The training roadmap should take no more than three years to develop a competent OT/IT engineer. A career map will need to be clearly defined for OT/IT engineers to ensure their skills and competencies can be continuously developed through meaningful project work. In addition, engineers with the passion to learn can apply their skills and competencies in an industry that is developing, and this can lead to sustainable capability and competency development.

CONCLUSION

A capability development journey is one which continues to adjust and evolve to meet new needs and evolving threats in technology. In the nascent space of ICS cybersecurity, the journey has only just commenced. The immediate focus is to implement and test out plans and proposed architectures, and where necessary, make adjustments to improve them. With the progressive build up of many local campus OT networks, the next capability to realise would be an enterprise-level ICS network connecting all the local campus OT networks, which can be centrally managed, monitored and provide valuable operational data.

Aside from the technology, the focus is also on people and processes. There is a need to continue to develop and grow the team of hybrid IT/OT engineers, through continuous training and industry engagement. Significant effort will also need to be invested to develop and operationalise processes to sustain the cybersecurity posture of the ICS, through regular patching, logs reviews and password management. Addressing the key aspects of people, process and technology will help build resiliency against evolving threats to defence ICS.

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ENDNOTES

[1] Supervisory Control and Data Acquisition (SCADA) is a subset of ICS, and generally refers to control of systems that span a large geographical area such as gas pipeline, power, fire, building control or water distribution system.

[2] Distributed Control System is a computerised control system for a specific process, usually in a plan with many control loops. These are running on autonomous controllers, distributed throughout the system, with no central operator supervisory control.

[3] Programmable Logic Controller (PLC) is an industrial computer that has been ruggedised and adapted for the control of automation processes and process fault diagnosis.

BIOGRAPHY

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SAFETY DESIGN CONSIDERATIONS ON LITHIUM BATTERIES USE IN UNDERWATER SYSTEMS

BUI Mao Jin Alvin, LIM Hong Han, TAN Huang Hong

ABSTRACT

Lithium batteries are the leading rechargeable energy source. They exhibit high energy density, are lightweight, charge quickly, have a low self-discharge rate, and a low memory effect. The drive to use lithium batteries in underwater systems has increased the importance of having a deep understanding of lithium battery technologies and safety design considerations. This article describes the challenges in managing the safety of lithium batteries used in underwater systems, and the measures taken to address these safety issues.

Keywords: Li-ion, battery, thermal runaway, system safety, underwater system

INTRODUCTION

The importance of lithium battery safety cannot be understated, as exemplified by battery-related incidents encountered in the Boeing 787 Dreamliner (BBC News, 2013), Samsung Note 7 mobile phone (BBC News, 2017), and the fires involving lithium batteries in personal mobility devices (Asokan, 2019).

As naval missions become more complex and demanding, modern underwater (UW) systems are expected to operate at high speeds, with long endurance, and be re-deployable. Advancements in rechargeable lithium battery technology and their associated high energy density that can meet the required performance and quick turn-around, are the key benefits of these capabilities. With the proliferation of UW systems using rechargeable lithium batteries, there is a need for greater awareness of lithium battery system design, safety qualifications, and potential hazards associated with their usage in UW systems. This paper presents the considerations and hazard mitigations for the design and usage of rechargeable lithium ion (Li-ion) batteries in UW systems.

INFORMATION ON RECHARGEABLE LITHIUM BATTERIES TECHNOLOGY

Terminology: Li-ion, Li-ion Polymer, and Lithium Polymer Batteries

The term Li-ion used in this paper generally refers to batteries of lithium-based technologies. Although the names may sound similar, there are important technical differences between Li-ion, Li-ion polymer, and lithium polymer batteries, as summarised in Table 1. This article will focus on Li-ion and Li-ion polymer batteries, as lithium polymer batteries are not commonly used.

General Working Principle

Li-ion cells are rechargeable, and the energy conversion process from chemical to electrical forms is reversible; they are therefore considered secondary batteries. Li-ion cells offer improved energy density (J/m^3) and specific energy (J/kg) as opposed to other forms of secondary batteries (lead-

	Types of lithium batteries		
	Li-Ion	***Li-Ion Polymer***	***Lithium Polymer***
Electrolyte type	Liquid	Semi-solid, gel	Solid, dry electrolyte
Form factor	Rigid shell	Pouch or laminate form	Mechanical construct
Other remarks	- Damaged casing can lead to electrolyte leakage	- Commonly referred to as a lithium polymer battery, or “Li-Po” - Common in applications where weight-savings is a primary goal	- Batteries are heated (via external heat source) to allow ions to flow across the dry electrolyte - Not commercially viable and not in mainstream production

Table 1. Types of lithium batteries

acid, nickel cadmium, nickel metal hydride, etc.), and they are rapidly proving to be the most viable battery technology in many applications, especially in compact electronics devices, where energy density is key.

Li-ion cells rely on a phenomenon known as intercalation[1], and provide electrical power through the flow of lithium ions (Li^+) from the anode to the cathode through a separator, all of which is immersed in an electrolyte. The separator is impermeable to electrons, which must flow through an electrical circuit (i.e. current carrying conductor) external to the electrolyte, providing electrical power in the process as illustrated in Figure 1.

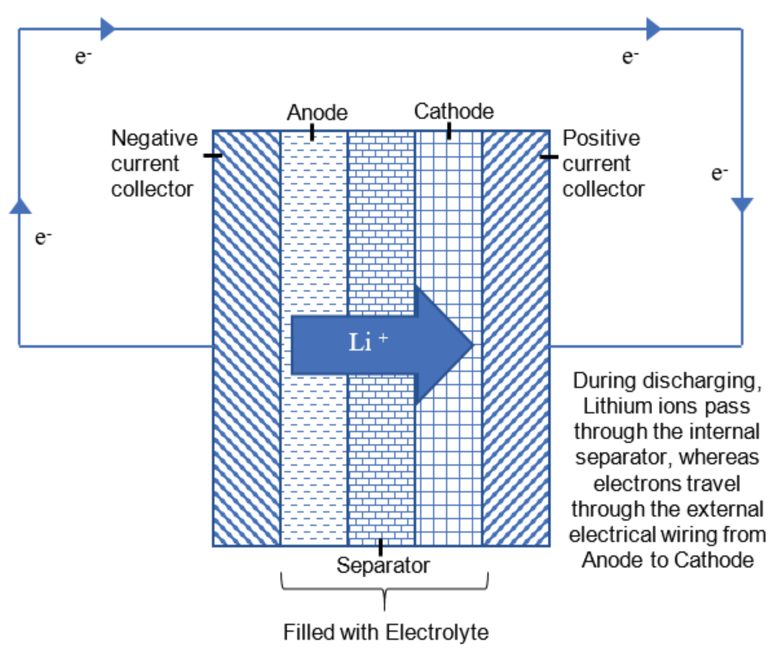

Figure 1. Illustration of internal Li-ion Cell components

ENSURING BATTERY SAFETY

Li-ion battery technologies are rapidly developing, and a plethora of technical papers and commercial information is available on the internet. Much of the information is focused on the design of the battery and accompanying systems that support the charge and discharge operations of the battery, such as monitoring and charging mechanisms.

As one of the biggest and most worrying hazards associated with Li-ion and Li-ion polymer batteries is that of thermal runaway, this paper will focus on addressing the residual risk of thermal runaway. The following section introduces causal factors of thermal runaway, and mitigation measures applicable to all systems operating Li-Ion batteries. These mitigations are to be considered the de rigueur of battery safety.

Lithium Ion Battery Short Circuit and Thermal Runaway

A thermal runaway is described as a hazardous occurrence whereby the rate at which heat is generated within a battery exceeds the rate at which the heat can be dissipated to its surroundings. As high temperatures can cause Li-ion cell protection mechanisms to break down, this can lead to a domino effect, where the high heat induces similar reactions in neighbouring cells in a self-sustaining pattern; hence the term “runaway”. The result is uncontrolled burning, high temperatures, and venting of gases from the battery, which can happen on a very short time scale. Thermal runaway by various root causes are elaborated below.

Formation of Dendrites

Dendrites are solid lithium metal “spikes” that grow from the anode over many charging and discharging cycles. This is part of the naturally occurring aging process and thus far cannot be completely eliminated. Dendrites naturally form a sharp tip, and as they grow, can eventually pierce the separator, leading to a short circuit between the Cathode and Anode of the Li-ion battery. The growth of dendrites is accelerated by various factors such as over-charging, exceeding the operational voltage limits, or using cells beyond the manufacturer-stipulated number of charge cycles. This can be mitigated to some extent (but not completely eradicated) by a comprehensive system of battery monitoring designed into the battery charger or the monitoring component of the battery module, and observing the manufacturer’s recommended charge-discharge and maintenance cycle.

Nanyang Technological University has invented a new battery component that can be used as an “anti-short layer” to overcome short circuits induced by dendrites, and this can potentially reduce the occurrence of this hazard when incorporated into the battery (Ang, 2021). This technology is currently being patented and commercialised.

Charging of Over-Discharged Battery

All cells (including lead-acid and nickel-based batteries) will self-discharge[2] when left in storage. When a Li-ion cell is stored for prolonged periods below the minimum operating voltage, copper shunts may form between the electrodes, leading to a direct short-circuit when charging is attempted. This root cause can be mitigated by observing the manufacturer’s recommended charge-discharge and maintenance cycle.

Internal Over-Temperature

All cells will generate some amount of internal Joule heating during charge and discharge because of internal resistance. Resultant temperatures above the melting point of the separator will lead to its failure, and hence create a short circuit between the Cathode and Anode. Cooling features that can be implemented include air gaps between cells to minimise self-heating and provide adequate dissipation, or heat resistant layers to provide insulation.

External Heating

All batteries are designed to operate within a manufacturer-stipulated range of operating temperatures. When a cell is utilised outside its intended operating range, a self-reinforcing heating cycle (i.e. thermal runaway) may be induced. Heating the cell above the melting point of the separator will induce fires due to an internal short-circuit. Users should be mindful to incorporate a battery that is designed to operate in the intended environment and installation location (away from any heat source).

Mechanical Abuse

This refers to physical damage to the cell due to shock, vibration or puncturing. If operated beyond the manufacturer-stipulated shock/vibration limits, the separator within the cell may be punctured, resulting in an internal short-circuit. Additionally, the separator can be directly punctured through mechanical means.

Manufacturing Defects

Battery internal defects due to poor manufacturing processes such as deformation of cell layers or the presence of microscopic foreign particles within the cell layers can result in thermally hazardous conditions. The selection of reputable manufacturers of battery systems is currently the only means to circumvent this, as there will be stringent quality controls and sampling checks done by these manufacturers.

It is hence crucial that all Li-ion batteries are designed, manufactured and tested adequately to ensure safety. A well-designed Battery Management System (BMS) is equally critical to monitor cell characteristics (e.g. temperature) and activities (e.g. charging), and intervene when required (e.g. isolation of cells/battery from the charging system to prevent further charging) to ensure safe operation of battery modules and systems.

Corrosion on Connectors and Printed Circuit Boards

The likelihood of an underwater system being exposed to damp conditions during maintenance and storage on board is relatively high, due to the nature of its operating environment. Over time, corrosion on connectors and printed circuit boards may lead to a short-circuit of the Li-ion battery. It is recommended that the maintainer perform visual inspections of these components as part of the system's periodic preventive maintenance activity, to ensure this does not affect the BMS and battery's safety.

SAFETY DESIGN APPROACH AND DESIGN CONSIDERATIONS FOR LITHIUM BATTERY POWERED UNDERWATER SYSTEMS

The design of an underwater platform and the environment in which it operates present unique challenges that necessitate specific considerations to address hazards stemming from the use of Li-ion batteries. A systems safety approach of top-level hazard identification and how each of its effects can be mitigated or reduced to as low as reasonably possible are presented.

Top Level Hazard Identification

Thermal Runaway

Venting of enormous amounts of gases during thermal runaway within a water-tight pressure hull would lead to the build-up of internal pressure and could potentially rupture the hull. The key mitigation for this would be how to prevent catastrophic accumulation of internal pressure via, for example, *pressure-relief valves.*

Water Ingress

If water comes into contact with the battery, electrolysis could take place. This could lead to the generation of flammable hydrogen and oxygen in the vehicle, in turn making the system unsafe due to the risk of an explosion. The key mitigations for this would be to prevent water coming into contact with the battery *(watertight battery module),* to detect water in the underwater system *(water and pressure sensors),* and to implement appropriate intervention in the event that water is detected within the underwater system *(deliberate flooding).*

PLATFORM DESIGN TO MITIGATE HAZARD EFFECTS

Over and above recommendations in the earlier section to prevent thermal runaway, the team recognises that Li-ion batteries in underwater systems are also subject to hazards of water ingress. The team has consulted various guides[3] and best practices to recommend the following design considerations to prevent and mitigate the effects of water contact with the battery and also against the build-up of internal pressure during thermal runaway.

Pressure-relief Valves

Underwater systems are invariably watertight enclosures. As such, over-pressure due to venting of Li-ion batteries, electrolysis products, and heat build-up inside the underwater system can catastrophically overcome the system's yield strength, injuring personnel or damaging property nearby. The implementation of pressure-relief valves on the hull of the system allows one-way release of pent-up pressure to the environment, to prevent internal pressure from building up to unsafe levels. Such valves are designed to vent automatically when the internal pressure exceeds the external pressure by a pre-defined value (such as 0.5 or 1 bar).

Watertight Battery Module

If an underwater system experiences a collision or otherwise has its watertight integrity compromised, water can eventually come into contact with the battery cells. Even slow leaks over long periods of time can let enough water in for this to happen. This can be mitigated by incorporating watertight bulkheads within the UW system, although this might not be practical for small, compact systems, nor would it help if the battery module itself has a leak (in the event of a collision or poor waterproofing).

Water Leakage Sensors

Placement of water sensors in the battery module will help to detect the presence of water. The detection of water ingress will generate an alarm to alert users. Water sensors are preferably placed at the lowest possible location in the battery module, as water tends to accumulate in such areas, giving users more reaction time. Having multiple sensors in different positions and heights provides information about the water level and the rate of water ingress, thereby allowing users to assess the feasibility of repair or recovery.

Pressure Sensors

Underwater systems are typically filled to a slight over-pressure, and pressure sensors within the hull will be able to detect internal pressure drops through compromised watertight integrity. The pressure sensor will also be able to detect an increase in pressure in the event of battery thermal runaway and the associated venting of gases.

Deliberate Flooding of System

Displacing any accumulated or electrolysed gases within the vehicle with seawater through deliberate flooding can help to eliminate the risk of an explosion. Proper placement of scuttle valves is to be considered in the design in order to allow seawater to enter and gas to escape. It is especially important to consider any bulkheads or pockets where gas can accumulate. Once a system is fully flooded and its battery fully discharged, it is safe for recovery. Figure 2 illustrates an example of a sunken Autonomous Underwater Vehicle (AUV) in a rested position with scuttle valves opened to allow ingress of water. While it may seem counterintuitive to want to flood the vehicle, the design should consider a "point of no return" approach, where this deliberate flooding is only performed after a large amount of water (sufficient to come into contact with the battery cells, for example) has entered the vehicle. Strategically placed water sensors (near the battery cell terminals) can serve as the trigger point. By the time water has reached this point, the only remaining action would be to minimise the amount of residual gas within the system by flooding the vehicle. Note that there will be the risk of inadvertent activation of scuttle valves, leading to loss of system, which must be considered in the design.

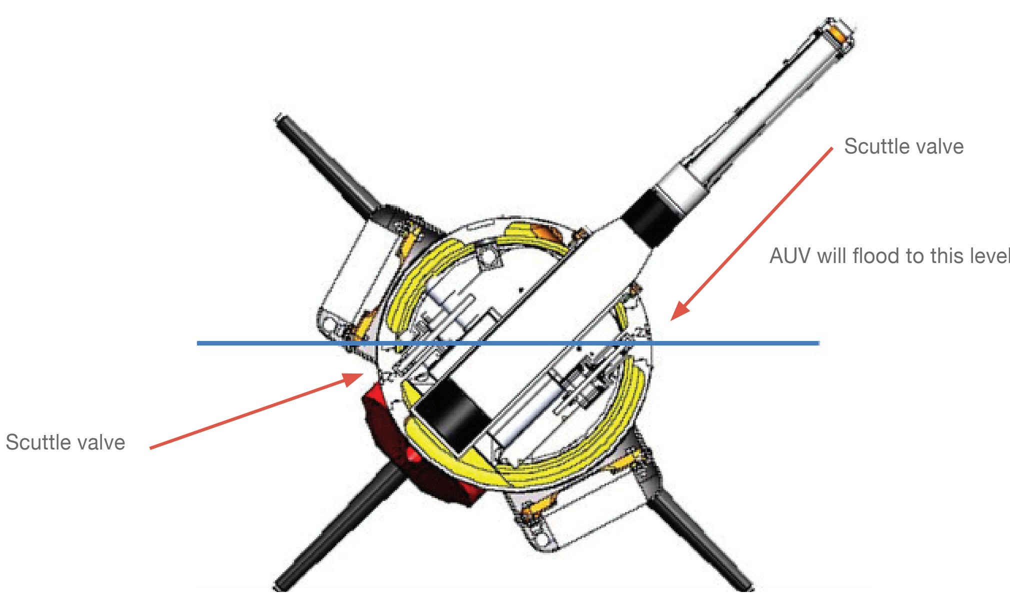

Figure 2. Internal free space of AUV for gas accumulation

SAFETY ASSESSMENT

The hazard of flammable gases from electrolysis of sea water can be better quantified through the following considerations that the team has developed to assess whether an underwater system is safe, should water enter the battery compartment.

Internal Air Volume

The system's internal air volume is used for positive buoyancy as well as convective heat transfer from the internal components to the AUV's hull and then to the surrounding water. This air volume also represents the enclosed space in which gases can accumulate (known as the residual volume). The residual volume within the system depends on the system design, final orientation, and the position of the leak (where water is entering the compartment). Since these cannot be known beforehand, the worst-case scenario should be used (i.e. scenario with the greatest residual volume). This can be calculated based on the position of the scuttle valves and, if there are no scuttle valves, the most likely point of water ingress (i.e. O-rings) in the system.

Amount of Gas Generated

The maximum theoretical amount of hydrogen which can be created through electrolysis when a battery is submerged in water is dependent on the amount of electrical charge, or Coulombs (C), present in the battery. This should be calculated based on the assumptions that: (1) all the cells are independently performing electrolysis, (2) all electrical charge goes into the electrolysis reaction, and (3) only hydrogen and oxygen are produced from the electrolysis reaction. These three assumptions create a worst-case scenario, as hydrogen and oxygen are the reactants that can form the greatest exothermic reaction (i.e., explosive effect).

During electrolysis, a reduction reaction takes place at the cathode (negatively charged terminal) to form molecular hydrogen (H_2) from water[4]. This reaction requires two electrons, shown below:

$$2H^{+}_{(aq)} + 2e^{-} \rightarrow H_{2\,(g)} \quad (1)$$

The number of moles of electrons per unit Coulomb is related by the Faraday constant, which has a value of 96,485 $Cmol^{-1}$. Assuming the battery contains X Coulombs of electrons, the number of moles of electrons in the system batteries is therefore $\frac{X}{96,485}$ moles.

Based on Equation 1, the maximum number of moles of H_2 produced is therefore $\frac{X}{96,485x2}$ moles. This is assuming ideal faradaic efficiency[5] and that the batteries are at maximum charge.

As stated earlier, this is a worst-case scenario, where only H_2 is produced at the cathode. In reality, seawater also contains a large variety of ions, such as chloride (Cl^-), bromide (Br^-), iodide (I^-), oxide (O^{2-}), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}). Each of these ions can be oxidised or reduced at the battery terminals, and preferential reaction is dependent on many chemical and kinetic factors. Oxidation and reduction of these ions generally creates less flammable products than H_2 and O_2.

With reference to project-related safety assessment efforts involving submergence of lithium-ion batteries in seawater, a relatively small proportion of energy actually goes into creating hydrogen and oxygen. During the submergence of the batteries, the following three phenomena were observed:

(1) Heating of seawater through the Joule effect[6] and electrical arcing
(2) Electrolysis of seawater into hydrogen and oxygen
(3) Oxidation of the battery terminals

These three phenomena represent different outcomes competing for the stored energy in the battery. The majority of the stored energy (approximately 80 – 90%) goes into the Joule effect and electrical arcing. In addition, the oxygen required for oxidation of battery terminals can only be drawn from that created by electrolysis[7]. This in turn leads to a dearth of oxygen through which combustion cannot occur. While this does mean that there is a non-stoichiometric mix of hydrogen and oxygen within the system in its steady state, opening the system on the surface could potentially introduce sufficient oxygen for a reaction to occur, albeit for a brief window of time[8]. If the team assesses that there are pockets of gas within which hydrogen can accumulate, sufficient care must be taken during the recovery process to vent this accumulated gas and prevent combustion.

Combustion Environment

Combustion requires all three sides of the fire triangle as shown in Figure 3 – oxygen, fuel, and heat, to be achieved. If the final environment in the system does not meet any of the following three conditions, combustion will not occur:

(1) Oxygen – The amount of oxygen in the system must be greater than 5% for combustion to occur.

(2) Heat – There must be heat within the system to ignite the gases. This can be due to a spark, or sustained heating to temperatures above 400°C. The team can consider stipulating the use of non-sparking tools during the recovery process, to avoid introducing this to the system.

(3) Fuel – Hydrogen is only combustible at concentrations between 5-96%. Outside these ranges, combustion will not occur.

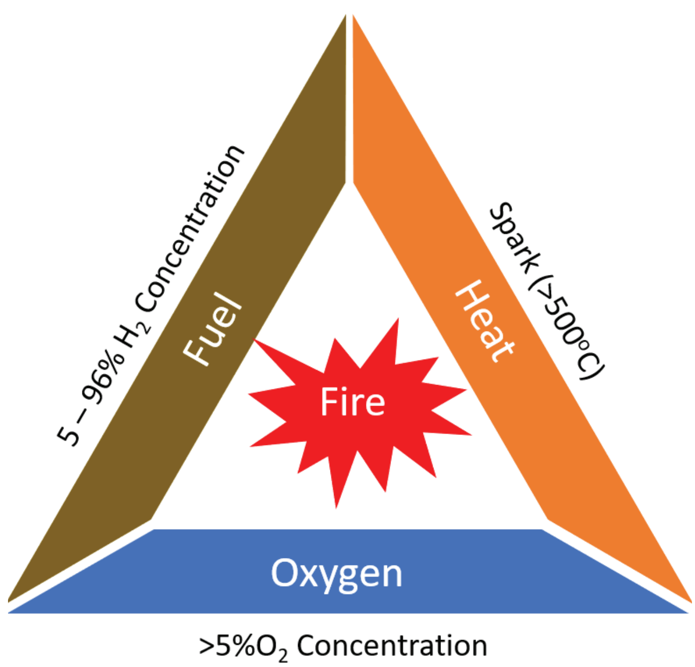

Figure 3. Fire Triangle Required for Combustion

Safe Stand-off Distance

The explosive equivalency between hydrogen and TNT can be calculated, which represents a theoretical maximum explosive force, and from there a safety stand-off distance away from the system can be determined. This recommended distance is typically observed for a duration of 24 hours from occurrence of the incident as it is assumed that by then, residual hazardous gas would have dissipated into its environment, the battery would have fully discharged into water, or the batteries contacts would have become corroded such that they can no longer discharge. The recovery team of the UW vehicle is recommended to observe this duration and stand-off distance before embarking on any salvage operations.

INSIGHTS AND LESSONS LEARNT

Battery Management System

The team considers certain BMS features to be useful if there are constant monitoring of battery health and are able to arrest any anomaly and provide feedback to the operator with an assessment about the state of the system, without the need to connect to any external monitoring device. Some battery systems incorporate a mechanical knocker, which would strike the hull of the UW system to alert the operator of any detected anomaly, rendering the UW system unsafe for deployment.

Deployment Considerations

The team considers the consequences of any potential hazards due to the battery to be more severe in a confined environment, in view of higher collateral damage due to fire and intoxication of dangerous fumes (for example, comparing an enclosed space in a submarine versus the open deck of a surface ship), and as such would not recommend charging of Li-ion batteries in confined spaces. The team also ensures that the stowage (including during transportation) of the UW systems is away from heat sources or solar radiation to maintain the correct operating temperature within the battery.

State of Charge

The team would additionally recommend that manufacturers furnish proof of battery qualification and testing certification with information to quantify occurrence of thermal runaway at different States of Charge (SOC) or level of charge of the battery. Passing safety certifications (e.g. UL164 – general Li-ion standard, UN38.3 – for transportation, SAE J2464 – for electric vehicles) is one of the ways of ensuring sound battery design. Performing tests such as the High Temperature Test or Nail-Penetration Test to incite thermal runaway conditions may reveal if the internal battery design is able to prevent sympathetic spreading of thermal runaway. These tests can also be performed at different SOCs to determine if there is a threshold below which thermal runaway will not occur, even under such extreme abuse levels. With this consideration, the user should consider safety vis-à-vis battery endurance at safe SOC levels to ensure operational success.

CONCLUSION

The recommendations put forth may also apply across domains such as land or aircraft systems, and are not necessarily limited to underwater systems. Utilising the standard hazard identification and risk management approach, the team has recommended approaches in managing the risk of powering underwater systems with lithium batteries. Safety calculations to quantify risks of flammable gases generated, and design considerations imposed on the UW platform may be used when applicable to enhance safe operations of the UW systems.

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ENDNOTES

[1] Intercalation is the reversible insertion of an ion or molecule into materials with a layered structure.

[2] Self-discharge refers to the internal chemical reactions in a cell which reduce the stored charge of a battery without any connection between its electrodes. Self-discharge rates are proportional to temperature, which is one of the reasons why controlled environments for batteries is important.

[3] American Bureau of Shipping guide for Use of Lithium Batteries in the Marine and Offshore Industries (Feb 2020) and DNVGL Rules for Classification: Underwater Technology – Autonomous Underwater Vehicle.

[4] Due to a process known as self-ionization, besides H_2O molecules, water contains also HO^- (hydroxide), H_3O^+ (hydronium), and H^+ ions. The inclusion of salts into water increases the likelihood of self-ionization.

[5] The faradaic efficiency of an electrochemical reaction is the efficiency at which electrons are transferred in a system. Faradaic losses include undesired chemical byproducts and heat. In this case, ideal faradaic efficiency means that no other elements are reduced at the cathode, and no heat is generated.

[6] The Joule effect is the generation of heat when an electric current flow through a circuit of finite resistance; in this case, the seawater through which the battery is discharging.

[7] Oxidation only occurs on an appreciable time scale when the terminals of a battery are submerged in water. The terminals will therefore not be exposed to any oxygen present in

the enclosed environment. In addition, most underwater systems will be filled with nitrogen (or a similarly inert gas) prior to operation.

[8] As hydrogen is much lighter than air, it tends to dissipate very quickly when the container is opened.

BIOGRAPHY

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EVOLUTION OF DSTA'S FRAGMENTATION LETHALITY ASSESSMENT

GOH Con Jun Roy, PHANG Wenfen, YAP Kah Leng, YUEN Ming Fatt

ABSTRACT

Since the early 1990s, in-house software tools have been developed to assist engineers with complicated and tedious fragmentation lethality assessment on warhead performance and training safety. Advances in computer technology allowed faster completion of these assessments and allowed the enhancement of tools with higher fidelity computation. For example, during in-situ disposal of war relics or terrorist bomb threats situations in urban areas, higher fidelity lethality assessment will allow operational planners to focus limited resources on high risk zones for crowd management and evacuation. This may be achieved by leveraging digital maps where accurate building information could potentially be used to analyse the shielding effects by the buildings. This article discusses the evolution of fragment lethality assessment capability, digital exploits and the way ahead for further enhancements.

Keywords: warhead, fragmentation, lethality, map data

INTRODUCTION

From small arms projectiles against infantry personnel to shaped-charge warheads against armoured vehicles, warhead design is largely influenced by the types of target it is intended to be used against. This leads to detailed studies of warhead terminal effects, or terminal ballistics, for warheads to be optimally designed. In general, there are three regimes of terminal ballistics, namely: (1) Penetration, (2) Blast, and (3) Fragmentation effects.

Penetration effects and blast effects are targeted at defeating building structures or armoured platforms such as main battle tanks and armoured personnel carriers. While these two effects also affect personnel, they are not as effective as fragmentation effects, which can neutralise a group of personnel further away from the explosion site. On a smaller scale, a fragmentation hand grenade is designed to defeat soldiers in a foxhole, trench or room. Examples of larger fragmentation warheads include mortar bombs, artillery shells and aircraft bombs.

This article focuses on the assessment of fragmentation lethality in order to provide the engineering analysis for the effectiveness and training safety of fragmentation warheads for the Singapore Armed Forces (SAF). It also discusses the various software tools developed in-house for different assessment scenarios back in the early 1990s. With the advancement of computer technology, older software tools had to be upgraded to avoid obsolescence and the result was the development of a new fragmentation assessment software named MAE3D that consolidates the functions and strengths of each preceding software tool.

FRAGMENTATION

Fragmentation warheads are usually designed as thick metal casings, also known as shells, packed with high explosives. Upon initiation of the explosive payload, the explosive presssures within the shells/metal casings expand and eventually break the casing into numerous fragments, each possessing energy to potentially incapitate the targets that they can reach.

The lethality of the warhead would thus depend on the warhead fragmentation characteristics such as fragmentation distribution, fragment shape, mass and velocity. These can be obtained from static fragmentation distribution tests known as Arena Tests. However, warheads are usually delivered over a certain distance, and thus lethality is also dependent on the warhead terminal conditions such as warhead velocity, angle of fall and height of burst (see Figure 1).

(2) US Damage Criteria – A study was conducted on human proxies to establish a relationship between personnel performing certain tactical roles (i.e. Assault, Defence and Supply) against specified time durations (e.g. 30 seconds, 5 minutes, half a day) before they succumb to injuries sustained from fragmentation effects. Results were then translated into equations and constants for each of the role-duration combination, which are then applied to fragmentation analyses on personnel.

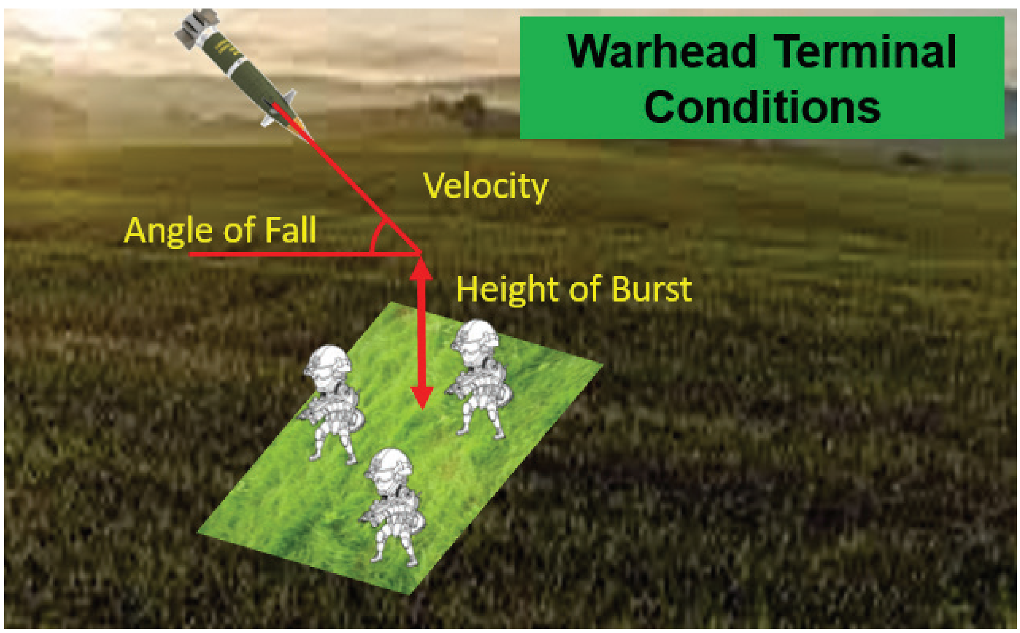


Figure 1. Warhead terminal conditions

These parameters are used to determine each fragment's trajectory by considering resultant fragment velocities (i.e. speed and direction) and air drag. With knowledge of fragment mass, speed and the direction they are headed towards, assessments can be done to see if the fragments are effective against the intended targets. Thereafter, depending on the type of target, different equations and considerations are applied to analyse if fragments are indeed hazardous or effective. These include:

(1) Energy Criteria – Similar to assessing injuries from a baseball impact (blunt trauma), there are standards and literature that propose a spectrum of injuries based on impact energies.

(3) Thor Penetration Equations – These are derived based on empirical data from trials that provide a deeper level of assessment on effects of steel fragments against different thicknesses of various materials. These are applicable for non-personnel targets only.

EARLY FORMS OF FRAGMENT LETHALITY ASSESSMENT

In the early years, engineering assessments were mainly focused on how well the warhead was able to neutralise the target and/or the safety distance required when training in proximity. However, computers then were not as advanced and the generation of results to assess performance or safety could take up to several hours or days. Hence, performance and safety simulations and calculations were to be executed separately, incurring more time and effort. The following paragraphs describe the three in-house developed software tools, namely Mean Area of Effectiveness (MAE), CONTOUR and FLAP3D, and the different scenarios they were each used for.

MAE was designed for near field effects on personnel targets in an area at ground level. Near field trajectory analysis focuses on fragments that are directed towards the ground upon warhead detonation. As fragments have high initial velocities, those directed to the ground are less affected by air drag and gravity, and thus were assumed to have linear trajectories (see Figure 2). Thereafter, lethality is assessed using the US Damage criterion. MAE is typically used for warhead performance assessments where the interest is on warhead effectiveness against personnel targets that are in close proximity to the warhead's detonation point. As MAE is mostly used for analysing terminal effects, at the end of a flight trajectory, the required angle of fall input is limited to downward pointing angles only rather than an upward pointing warhead at launch.

To assess for safety distances, CONTOUR used similar methods as MAE (i.e. fragment trajectory tracking) but it also considers fragments with parabolic trajectories in addition to linear trajectories. For safety considerations, the threshold of probability of personnel incapacitation can be as low as one in a million, as opposed to only one in a hundred for MAE calculations. In order to do so, there is a need to examine the trajectories of fragments that are not directed towards the ground and may fly further (see Figure 3). Other than assessments on personnel, CONTOUR is also able to simulate the fragments hitting metal plates of various thicknesses which are used as proxies for vehicular platforms. CONTOUR was also the only software that allows for warhead dispersion considerations, such as probable errors in range and dispersion, to be included in the assessment. Unlike MAE, CONTOUR allows upward pointing warhead angles to allow for simulations of warheads exploding during different phases of its flight trajectory. An example of using CONTOUR is illustrated in Figure 4. The fragmentation effects of an early burst warhead (probably due to a defective fuze that prematurely initiatied the warhead moments after launching) were simulated and clearly showed that most fragments would be directed forward and away from the firing position where personnel are located.

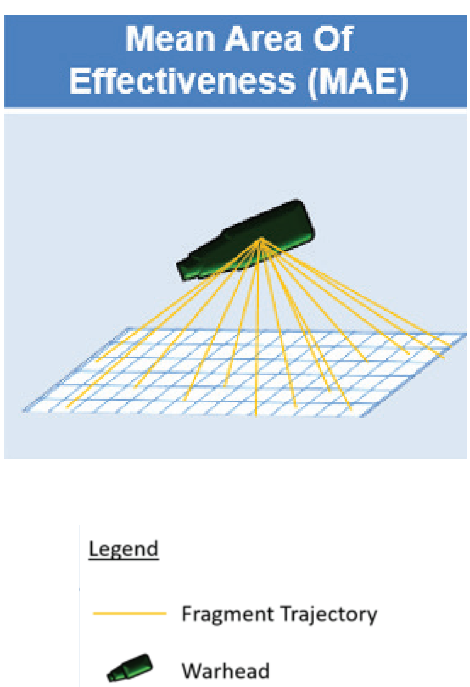


Figure 2. Fragment trajectories in MAE

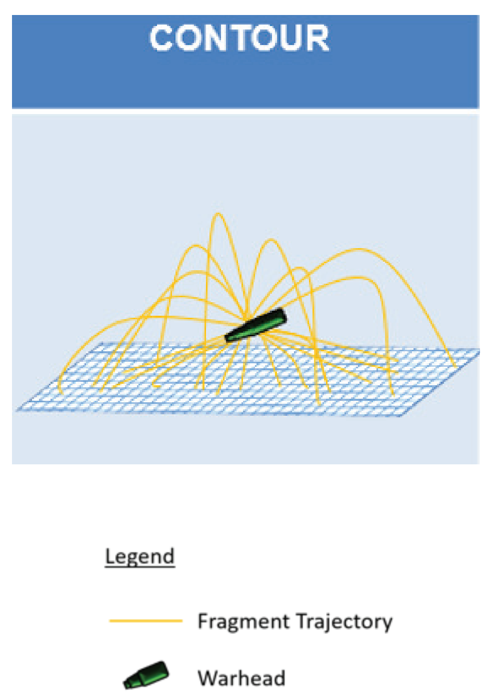


Figure 3. Fragment trajectories in CONTOUR

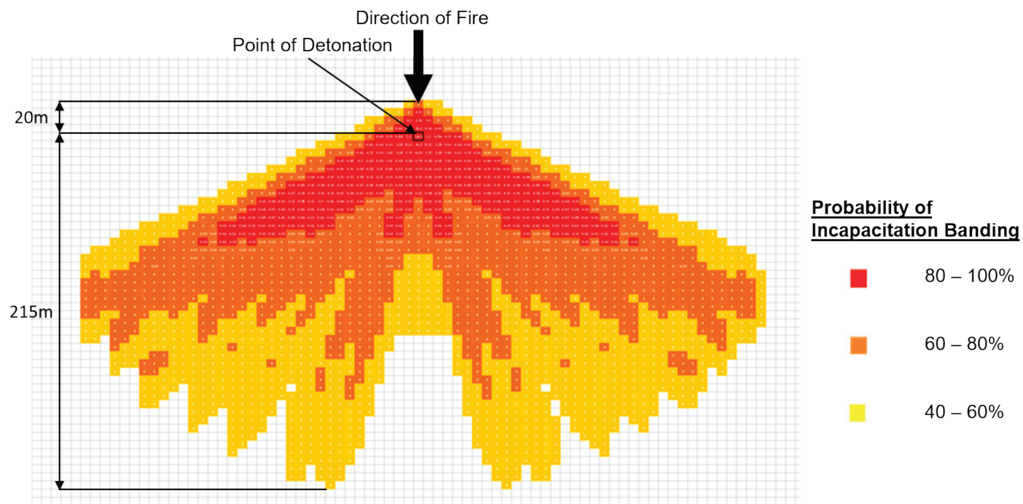


Figure 4. Early burst simulation

FLAP3D is similar to CONTOUR in terms of tracking fragment trajectories, but unlike CONTOUR that handles two-dimensional targets on the ground, FLAP3D is designed for three-dimensional targets anywhere in space such as air targets or even humans in elevated structures, such as fifth floor balcony (see Figure 5).

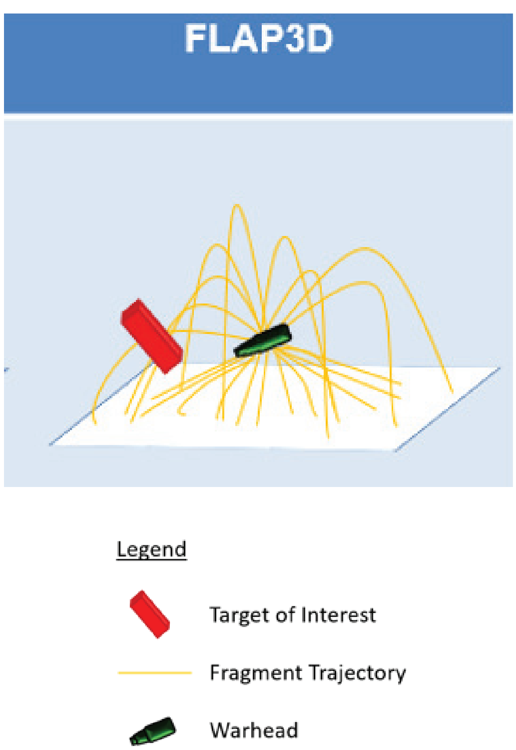


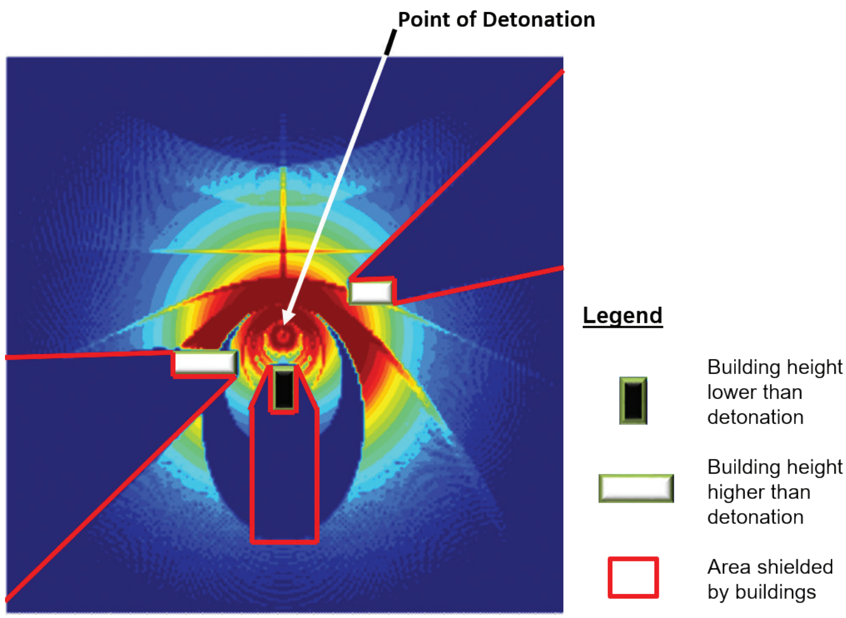
Figure 5. Fragment trajectories in FLAP3D

MAE3D

With the improvement of computer technology, computational timelines have shifted from days to minutes. At the same time, operating systems (OS) such as MS Windows were evolving quickly and soon there was a concern that the software would not be able to run on newer OSs. The team then embarked on converting the software using modern coding languages such as C++, and was able to combine all three software into a one-stop fragmentation assessment tool. The one-stop tool was named MAE3D as it combined the best features from its three software predecessors. In addition, new algorithms were added to enable the interaction with obstacles such as buildings and structures. With this important new feature, MAE3D was ready for further enhancements that would strengthen the engineering analyses and make it useful for field operations.

Obstacle Interaction

Previously, the area of assessment of both MAE and CONTOUR was limited to open ground. As the area of operations became more and more urbanised, the effects of shielding from obstacles such as buildings and structures became more significant. The ability for MAE3D to consider interactions with obstacles/buildings makes it more effective to assess real-world physical situations. An example of the interaction is shown in Figure 6 where the white objects represent extremely tall obstacles that are capable of preventing fragments from reaching beyond them, and the black object represents a shorter building where higher trajectory fragments are able to be lobbed past the building.

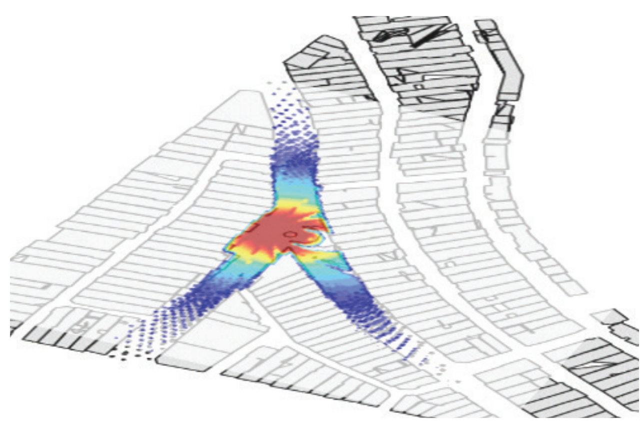


Note:
1) Different colour zones depict different bands of Probability of Incapacitation.
2) Dark red zone denotes very high probability while dark blue zone denotes very low or no probability.

Figure 6. Fragment-obstacle interaction in MAE3D

Map Reading Capability

The inclusion of obstacles was made possible with another input file where the basic shape of the building was defined with a few other parameters such as length, height and radius (for circular obstacle such as tree). In this example, only three obstacles were defined and illustrated. It would not be practical then for any user to have to create the obstacles input file for a dense urban terrain. Hence, the next enhancement would be to automate the generation of obstacles. This was achieved by reading building data that are embedded within digital maps. MAE3D incorporated Geospatial Data Abstraction Library, which is a free and open source tool, to enable MAE3D to extract the necessary data from different Geographic Information System map formats. Out of the many different map formats available, the team successfully tested MAE3D's algorithms to read and extract building info from three file formats (.geojson, .shp and .gdb). Figure 7 shows an example of the results from MAE3D's obstacle-interaction calculations overlaid back onto the map.



Note: Different colour zones depict different bands of Probability of Incapacitation.

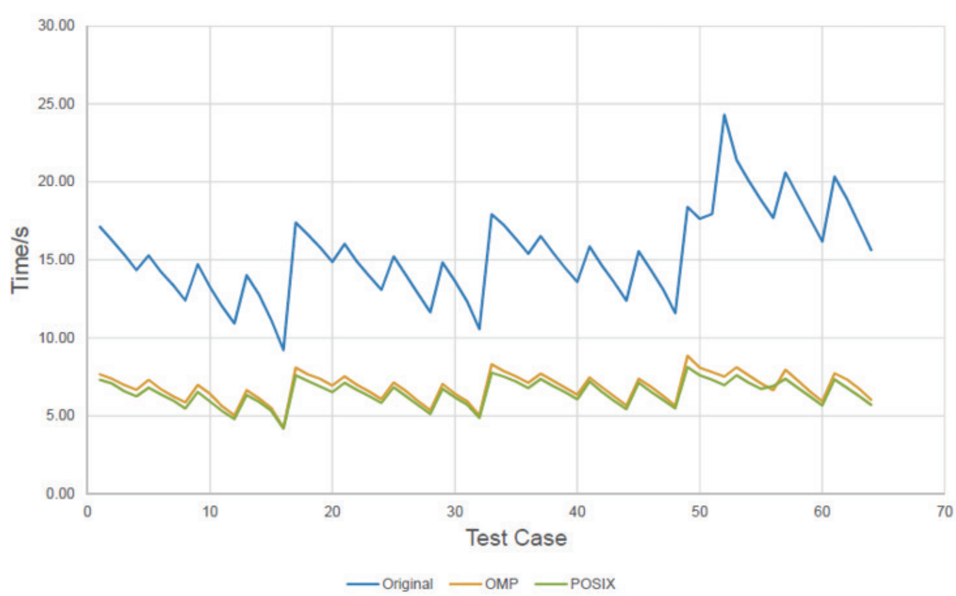
Figure 7. Results of obstacle-interaction overlaid onto map

Code Optimisation

As more features are implemented onto MAE3D, it may reach a point where there is a huge amount of data for MAE3D to process before it can generate the desired results. While a little increase in run-time is not a major concern for engineering analyses, it will become a significant issue if the capability is to be implemented in field operational systems. In view of this, the team began efforts to explore parallel processing methods. The basic idea is that while MAE3D has a lot of loops in its coding, such as tracking the trajectory of each and every fragment which generally takes the bulk of the processing time, it is possible to instruct a second processor core to perform part of the calculations. With two or more processors sharing the computational load, the time needed for generation of results is expected to be reduced significantly. On a duo-core laptop, the optimised code reduced the run-time by almost 50% (see Figure 8). While parallel processing wasn't implemented at this point of MAE3D's enhancement development, it proved that parallel processing harnessing multi-core computer technology was a viable option to implement on the code and to improve MAE3D's performance. In the future, if run-time shows signs of slowing down significantly, parallel processing can then be implemented.

Improving Fragment-Obstacle Interaction

The team is working on implementing suitable penetration equations into MAE3D, which would better determine if fragments have the energy to perforate the materials they impact, instead of assuming that fragments would be fully impeded. In the 1960s, the US Army conducted trials to determine the resistance of different materials to penetration by steel fragments. From the trials, empirical equations (later known as Thor Equations) were derived. However, as these are regressed equations based on empirical results, the usefulness is subjected to the boundaries of the experiments, such as limited types of material and material thickness being tested upon as well as the shape, size, material composition and impact velocity of the fragment. While the team has implemented the equations, and reference materials from the Thor study, the use case is restricted to assessing thin-walled obstacles. Work on studying and implementing more equations from other sources is required for scenarios involving thicker obstacles.

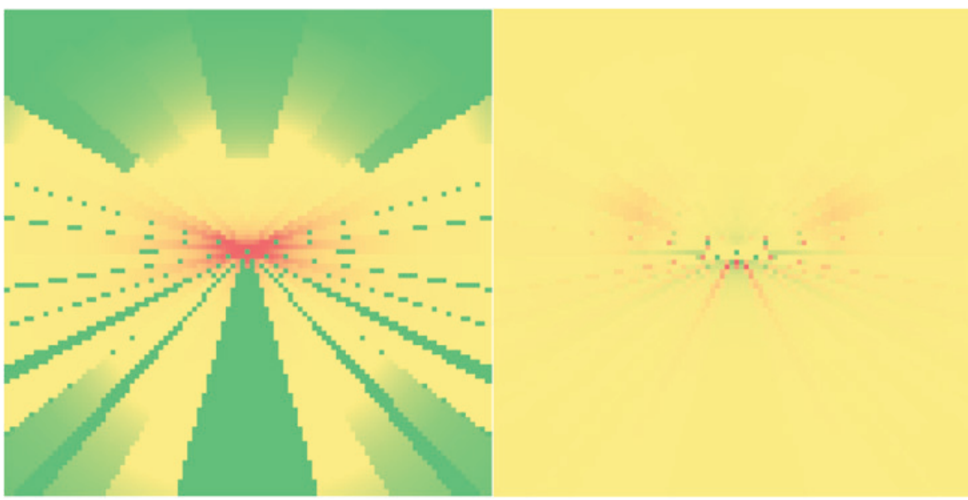


Note: OMP and POSIX are parallel programming methods that were explored during our optimisation study.

Figure 8. Time savings from parallel processing

Validating MAE3D

In order to ensure that MAE3D is working correctly, extensive trials and data collection on fragmentation would have to be conducted for comparison with simulation results. However, this is costly and time consuming. Another way would be to benchmark MAE3D against similar capabilities from foreign armed forces or weapons manufacturers when opportunity arises. Thus far, the team has benchmarked MAE3D with ammunition manufacturers. Figure 9 shows an example of the benchmarking were results between the two independent simulations are close.



Note:
1) For diagram on the left, different colour zones depict different bands of Probability of Incapacitation. Red refers to high probability of Incapacitation, green refers to low probability.
2) For comparison figure (i.e. the delta) on the right, green zones denote DSTA's results having lower incapacitation probabilities while red zones denote higher incapacitation probabilities compared to external results. Yellow zones mean little or no difference between the two.

Figure 9. Benchmarking results (Left: MAE3D, Right: Comparison Delta)
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APPLICATIONS

Explosive Storage Risk Assessment Tool

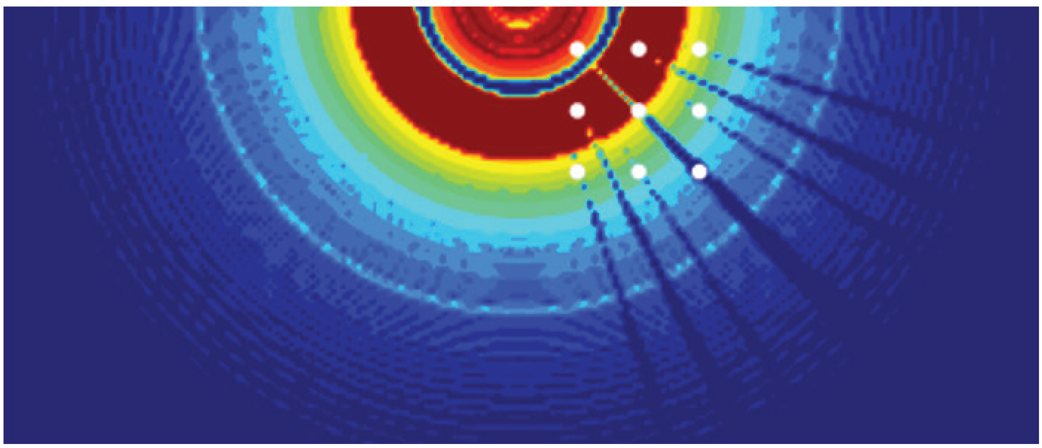
Safety Assessment For Explosive Risk (SAFER) is a software developed by the US for assessing safety of munition storage facilities and is useful for choosing storage location sites vis-à-vis the population demographics around the site of interest. SAFER considers the type of munition being stored, the type of storage facility, distance between the storage site and the exposed site as well as the nature of the exposed site, such as type of building and number of inhabitants etc. With the inputs entered, SAFER is able to advise on the probability of injury and death due to the blast, fragmentation, and from these analyses, a safe distance can be derived to reduce the risks to public from a storage facility accident. For example, during mobilisation exercises, open areas can be identified within the mobilisation centre or camp to become temporary ammunition storage locations. As SAFER is a US software, many of the parameters hardcoded within are based on US munitions and US buildings. This conservative approximations need to be applied to Singapore's context, such as the SAF's inventory of non-US origin warheads as well as different types of buildings found in Singapore. Using MAE3D to assess fragmentation effects of SAF warheads can help to better understand the safety of munition storage facilities.

Warhead Effectiveness in Plantations

In the past, when assessing warhead lethality in plantations, engineers had to superimpose the layout and spatial separation between trees in the plantation over the results generated by MAE. The main assumption for such studies was that the trees would be thick enough to stop any fragments. Thereafter, "straight lines" were plotted out from the detonation point towards the trees. Finally, any lethality effects "behind the tree" were assumed to be negated and removed manually. This was a tedious and inaccurate method but it provided a rough estimate of lethality degradation in a plantation. Now with the obstacle generation feature in MAE3D, the terrain details can be generated relatively easily and their effects are clearly shown on the plots (see Figure 10). This reduces the probability of human error when manually amending the lethality results affected by the plantation trees.

achieve this, MAE3D is not developed as a "plug-and-play" solution and integration uncertainties such as processing speeds, C2 workflows and availability of relelvant map data will challenge the integration efforts.

For instance, while most C2 systems have incorporated digital maps, some may not contain the necessary data for MAE3D to generate urban obstacles and analyse fragment-obstacle interaction. On the other hand, MAE3D has only been coded and verified to extract data from very limited range of map data



Note:
1) Different colour zones depict different bands of Probability of Incapacitation.
2) Plantation trees are represented by white circles in the figure.

Figure 10. Effects of plantation trees and warhead lethality

formats. Hence, more work is required to prepare MAE3D to read and extract from a wider variety of map data formats.

OTHER POTENTIAL FUTURE APPLICATIONS

Aside from consolidating three different programmes into MAE3D, the obstacle generation feature was a significant enhancement to the fragmentation lethality assessment capability. Subsequent enhancements such as the incorporation of digital maps for obstacle data also eased the obstacle generation process through automation. With these features, it is now possible to perform a wider variety of assessments and studies efficiently using MAE3D.

In addition to engineering studies, MAE3D can be further developed for implementation onto other systems. One possibility would be to implement MAE3D onto Command and Control (C2) systems to provide ground commanders with the fragmentation effects for collateral damage and/or target neutralisation assessments, so that more informed decisions can be made in the field. While there are ongoing efforts to

Another potential application is to implement MAE3D for crowd control during on-site war relic disposal. Singapore has seen quite a few war relics (especially WWII bombs) being unearthed at construction sites. Disposal is usually done on-site via controlled detonation and authorities have to cordon off large areas and build sandbag walls to contain the blast effects. Knowledge of the relic's fragmentation pattern can help to reduce the cordoning area and focus the crowd management efforts. There may even not be a need for the sandbag wall if the fragmentation distances are found to be limited through the use of MAE3D.

The main challenge of war relic disposal is that the warhead characteristics are often unknown and the disposal team will have to make conservative assumptions on the cordoning efforts. We may use proxies for the relic based on our knowledge of in-service warheads, and MAE3D can then be used to examine the potential fragment throw distances. Latest map and buildings data may also be unavailable for MAE3D to assess the obstructions to fragment trajectories accurately. A quick live scan of the construction site made using aerial drones to generate the map data may be explored to provide latest terrain information.

CONCLUSION

The development of MAE3D has been a fruitful and inspiring journey, allowing engineers to accomplish a stronger fragmentation lethality assessment capability beyond engineering studies. While the team may have achieved some MAE3D's enhancements in recent years, the work is far from over. There are still challenges and gaps, and further inputs should be sought from subject matter experts in areas such as C2 integration before other potential benefits such as near real-time visualisation of fragmentation effects can be realised. As the journey to improve MAE3D continues, the team will also continue to look for opportunities to proliferate MAE3D's capabilities.

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MANAGEMENT OF NOISE FROM LIVE FIRING ACTIVITIES

LIM Chuan Heng Kelvin, TAN Shi Bei

ABSTRACT

The Singapore Armed Forces regularly conducts live firing activities at designated sites, and the detonation sounds had alarmed residents in nearby populated areas. A task force was formed to investigate the key factors that affected propagation of detonation sounds from live firing activities and to establish noise mitigation measures. Root cause analysis and literature research revealed that the most likely causes were adverse atmospheric conditions and certain ammunition-related parameters. Sound trials were conducted to validate noise mitigation measures related to atmospheric conditions that were employed by Naval Air Weapons Station China Lake, USA and to explore other possible mitigation measures by adjusting ammunition-related parameters. Analyses of past year local atmospheric data and sound trials were conducted to quantify the effects of atmospheric parameters on sound propagation. Noise mitigation measures were developed after analysis of the results of sound trials which quantified the effects of ammunition-related parameters on detonation sound levels. The main highlights from the literature research, trials, analysis and recommendations for noise mitigation measures will be presented in this article.

Keywords: noise, sound, detonation, wind, live-firing

BACKGROUND

Due to the limited land space in Singapore, certain live firing activities are conducted on an offshore southern island. In 2017 and 2019, residents in the southern parts of Singapore provided feedback about loud sounds and vibrations, and these were traced to detonation sounds arising from the live firing activities on the southern island.

A technical study was conducted to identify the main contributing factors that enhance sound propagation and determine suitable noise mitigation measures in order to address public concerns.

The threshold for noise annoyance established by the American National Standards Institute is 120dB. While there is no annoyance threshold set by the local National Environment Agency (NEA) for impulse noises, NEA regulations on noise hazards dictate the permissible exposure limits to be at 115dB for up to 28 seconds per day. For the purpose of this technical study, 115dB is taken to be the reference sound level threshold.

ROOT CAUSE ANALYSIS AND LITERATURE RESEARCH

Root cause analysis and literature research were conducted and it was assessed that the most probable root causes identified were adverse atmospheric conditions and certain ammunition-related parameters.

Key Atmospheric Factors That Affect Sound Propagation

Based on literature research, the main atmospheric factors that affect sound propagation were identified as (1) Wind Speed and Gradient, (2) Wind Direction, and (3) Temperature Inversion.

(1) Wind Speed and Gradient - Sound waves move through mediums such as gases, liquids and solids. Wind is moving air caused by air pressure differences. When sound waves move through air, sound waves follow the direction of the wind.

The vertical wind gradient is defined as the rate of change of horizontal wind speed against the altitude above ground level. Vertical wind gradients cause sound to refract upwards or downwards (Wright, 1994). Stronger winds at higher altitudes and weaker winds at lower altitudes will create a positive wind gradient and thus cause sound to refract downwards (Figure 1) and cause a person standing downwind of a sound source to hear louder sounds due to the summation of the primary and the refracted soundwaves. Conversely, weaker winds at higher altitudes and strong winds at lower altitudes will cause sound to bend upwards and away from the ground.

Larger differences in wind speed across altitudes also contribute to greater vertical wind gradients and thus intensify the refraction of sound either towards or away from the ground (Wright, 1994).

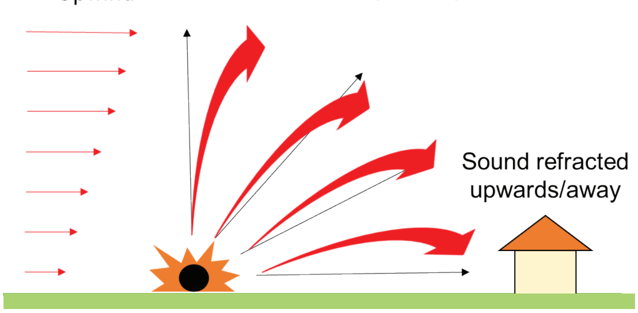


Figure 1. Downward refraction of sound

(2) Wind Direction - Since sound propagates through the air, the wind direction affects the propagation of sound by refracting the soundwaves towards the direction of the wind.

(3) Temperature Inversion - Temperature inversion is the phenomenon that occurs when the normal air temperature gradient in the atmosphere is reversed (Naval Air Weapons Station China Lake, 2013). Air temperature typically decreases with height as the sun heats up the ground, which heats the air directly above it first. This occurs most often on clear nights when the ground cools off rapidly by radiation. In the mornings following these clear nights, the cold ground temporarily keeps the air at lower altitude at a lower temperature than air at higher altitudes (Figure 2), resulting in temperature inversion. This layer of warm air forms a boundary which traps air pollutants and reflects sound waves downwards back to the ground (Parnell, 2015), causing the soundwaves to travel further and be heard over larger distances.

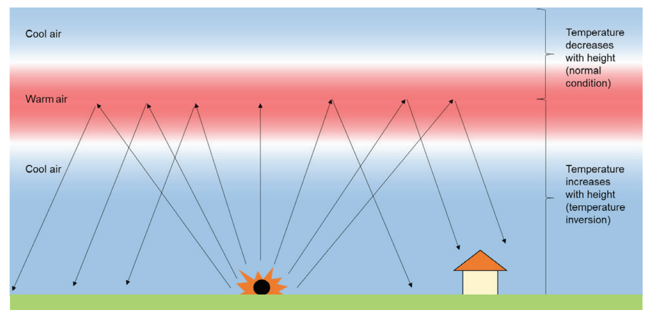


Figure 2. Sound is reflected back towards the ground when there is temperature inversion

Key Ammunition-Related Parameters That Affect Sound Propagation

The ammunition-related parameters of interest are as follows:

(1) Net Explosive Quantity
(2) Cased versus uncased ammunition
(3) Detonation method
(4) Hazard Division
(5) Detonation pit layout

(1) Net Explosive Quantity (NEQ) - An ammunition with a larger NEQ will produce higher blast overpressure (higher sound level) as compared to one with a smaller NEQ.

(2) Cased Versus Uncased Ammunition - A trial conducted previously for 155mm artillery shells found that there was significant reduction in blast overpressure of a cased charge due to energy lost in breaking the casing and propulsion of fragments. The trial results showed that the 155mm artillery shell produced about 50% to 65% lower blast overpressure compared to a bare charge of equivalent NEQ. The noise incident that occurred in Apr 2019 revealed that not only were the atmospheric conditions unfavourable, there were large amounts of uncased charges used. This could have been a significant contributing factor that resulted in the excessive sound produced.

(3) **Detonation Method** - Three methods of detonation are of interest in this study, namely surface, sub-surface, and overburden. For surface detonation, ammunition are placed on bare ground and detonated. Sub-surface detonation requires pits to be dug beforehand for placement of ammunition in the pits. Overburden detonation requires pits to be dug, placement of ammunition in the pits, followed by covering of the pit with soil before detonation.

(4) **Hazard Division (HD)** - Ammunition are classified into different HDs. It was postulated that the blast overpressure generated could vary for different HDs given the same NEQ.

(5) **Detonation Pit Layout** - It was hypothesised that a single pit of 200kg NEQ will produce a higher blast overpressure as compared to two pits of 100kg NEQ each. This could be due to the separation distance between the pits, slight difference in detonation timing due to varying detonation cord lengths as well as the cancellation of some of the sound waves due to wave interference from the two sound sources.

METHODOLOGY OF TECHNICAL STUDY

Conduct of Sound Trial to Validate Effectiveness of Atmospheric Criteria and Ammunition-Related Parameters

Atmospheric Conditions

The trials were conducted to validate the set of atmospheric criteria and quantify the effects of atmospheric parameters on sound propagation.

There are however challenges faced in relying solely on atmospheric conditions as the only means of sound mitigation to determine if live firing activities can proceed. The allowable time window for live firing activities is between 10am to 6pm. However, data for the atmospheric parameters of interest used to determine the atmospheric condition across the day are only available twice daily at 8am and 8pm when meteorological balloons are released by Meteorological Service Singapore. There is a risk of atmospheric conditions changing during the period between 8am and 8pm. While real time ground level atmospheric data are available, they are inadequate as the parameters of interest require data across different altitudes.

Additionally, live firing activities may be aborted in the event that atmospheric conditions are unfavourable. Logistics costs will thus be incurred to bring the ammunition back to mainland Singapore. This will impact operations and training as the detonation will have to be postponed until another slot for live firing activities is available.

Ammunition-related Parameters

It is therefore important to also explore ammunition-related noise mitigation measures to be less reliant on favourable atmospheric conditions, so that noise mitigation can be tailored for live firing configurations during seasons with generally unfavourable atmospheric conditions. Hence, sound trials were also designed to explore and quantify the effects of ammunition-related parameters on detonation sound levels.

Data Visualisation and Analysis

A data visualisation tool was used to visualise the sound data for ease of gleaning insights into the effects of atmospheric and ammunition-related parameters. Analysis of the data and trial results will enable the implementation of suitable noise mitigation measures for live firing activities conducted on the island.

SOUND TRIAL

Design of Sound Trial

One sound meter was placed at the source of the sound which is on the island where the detonations take place, and another was placed at the sound receiver on mainland Singapore. Sentosa was chosen as the location for the sound receiver as it is the nearest residential area to the island where the detonations take place.

Set of Atmospheric Criteria

To continue with live firing activities and proceed with sound trials while maintaining an acceptable level of noise that will not raise public concerns, a set of atmospheric criteria was devised to determine whether live firing activities should proceed or not. The set of atmospheric criteria consists of restrictions in terms of (1) wind gradient, (2) wind speed, and (3) wind direction.

The criteria were adapted from the criteria used by Naval Air Weapons Station (USA) to our local context after reviewing past year local atmospheric data. Since literature studies indicate that the likelihood of occurrence of temperature inversion is low during summer and from late morning onwards due to warm conditions (Naval Air Weapons Station China Lake, 2013), it is assessed that temperature inversion can be omitted from the atmospheric criteria considering our local weather and that usual live firing activities' start from 10am onwards.

To validate the atmospheric criteria, a preliminary trial was conducted from August to September 2019. The highest detonation sound recorded during this period at 92.4dB on mainland Singapore was attributed to a considerably large NEQ under near unfavourable atmospheric conditions with medium wind blowing towards Singapore and negative wind gradient. 92.4dB is more than 20dB below the public annoyance threshold of 115dB, which translates to the sound being four times softer. It was thus validated that the atmospheric criteria are adequate to address concerns of detonation sounds.

Calibration Blow

In the event of unfavourable atmospheric conditions, live firing activities and sound trials would have to be cancelled and ammunition would be brought back from the island to mainland Singapore. This will impact operations and training. Furthermore, sound trials will not be able to take place in the event of unfavourable atmospheric conditions, as the range of atmospheric conditions suitable for data collection is limited.

In order to continue with the live firing activities and proceed with sound trials to collect data during unfavourable atmospheric conditions, calibration blows were conducted when atmospheric conditions were unfavourable to assess if the live firing activities and sound trials can proceed.

From the preliminary trials, a low NEQ that consistently generated sound levels of 30dB below the annoyance threshold of 115dB upon detonation was identified and assessed to be a suitable NEQ for calibration blows. In addition, an estimation of sound levels from detonations of various NEQs and types of ammunition were made possible with the results from the preliminary trials. The sound level from the calibration blow measured on mainland Singapore would serve as a baseline. If the estimated sound levels of the planned live firing activities based on this baseline and results from preliminary trials are assessed to be suitable, the live firing activities can proceed.

Trial Objectives and Plan

The main aim of the sound trial is to explore and quantify the effects of atmospheric factors and ammunition-related parameters to develop noise mitigation measures that allow continuation of live firing activities while addressing public concerns.

Since atmospheric conditions are uncontrollable, a fixed live firing configuration was selected for each day of the trial period to collect sound data under different atmospheric conditions. The trial objectives are listed in Table 1 below in priority.

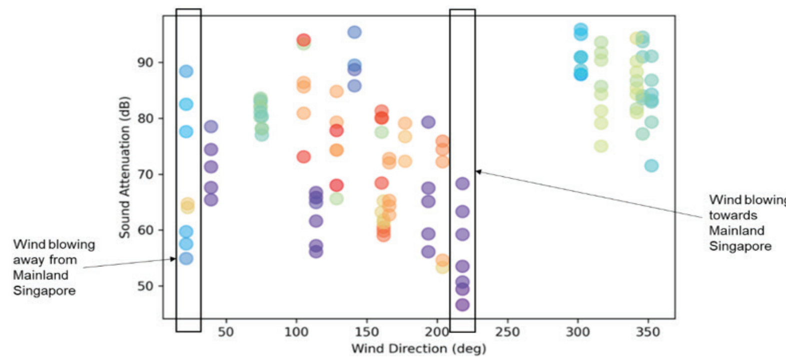
S/N	Trial Objective
1	To quantify the increase in sound level due to unfavourable atmospheric conditions.
2a	Find out the difference in sound level arising from different NEQ of uncased charges via sub-surface detonation.
2b	Find the NEQ limit for detonation of uncased charges that will give a reasonable sound level buffer before reaching sound levels that cause public disturbance.
3a	Find out the difference in sound level arising from different NEQ of cased charges via sub-surface detonation.
3b	Find the NEQ limit for detonation of cased charges that would give a reasonable sound level buffer before reaching sound levels that cause public disturbance.
4	Find out the difference in sound level arising from cased and uncased charges via sub-surface detonation.
5	Find out the difference in sound level arising between surface and sub-surface detonations of uncased charges.
6	Find the effect of breaking a pit into smaller multiple pits on sound level.

Table 1. Sound trial objectives

EFFECT OF KEY ATMOSPHERIC FACTORS

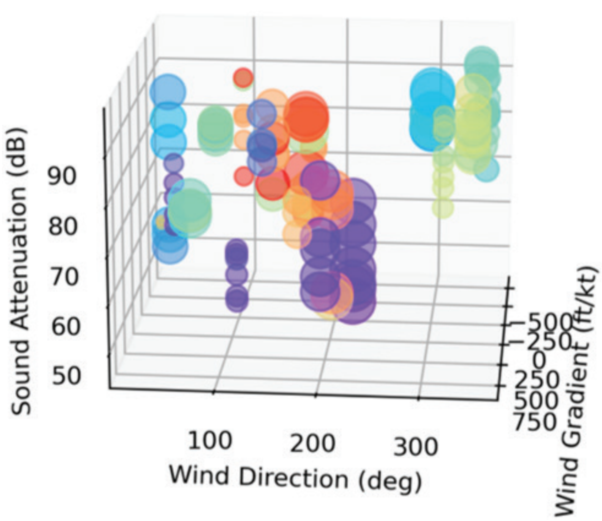
Lower Sound Attenuation in Direction of Wind

Figure 3a shows a three-dimensional scatter plot of the sound attenuation from the sound source to mainland Singapore at 226° against the three atmospheric parameters of interest. The valley around 226° in Figure 3a where the wind direction would be blowing directly towards mainland Singapore demonstrated that sound attenuation is generally lower in the direction of wind. For better illustration, a two-dimensional scatter plot (Figure 3b) based on data from Figure 3a was plotted to highlight the valley described.



Note: Different colours represent different live firing configurations.

Figure 3b. Effect of wind direction on sound level attenuation



Note: The size of data points indicate wind speed (kts). Different colours represent different live firing configurations.

Figure 3a. Effect of wind conditions on sound level attenuation

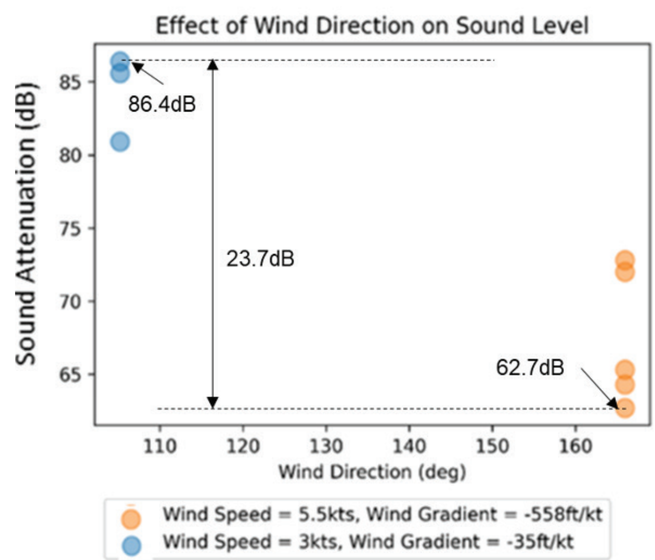


Figure 3c. Consistent trend of lower sound attenuation when wind blows in the direction of mainland Singapore (226°). All points are of the same pit layout, detonation method, main HD total NEQ, uncased ammunition NEQ and item.

To isolate the effects of wind direction, a range of wind direction with similar wind speed and gradient will be required over the course of the trial. Sound attenuation on such days were plotted for detonations with the same detonation configurations. A consistent trend of lower sound attenuation was observed when the wind blows in the direction towards mainland Singapore. As illustrated in Figure 3c, the largest difference between the sound attenuation when the wind blew towards and away from mainland Singapore was 23.7dB, where the sound level attenuation was 62.7dB for the former and 86.4dB for the latter. This difference of 23.7dB demonstrates that the effect of wind direction can have a very significant impact on sound attenuation.

Effect of Wind Speed and Wind Gradient

Literature research has shown that wind speed and wind gradient will further increase or reduce sound attenuation when the wind is blowing away or towards the "target of interest" respectively (Naval Air Weapons Station China Lake, 2013).

In order to measure the effects of wind speed, a range of wind speeds with similar wind gradient and direction will be required over the course of the trial. However, there was a lack of such wind conditions during the trial period. There was also a lack of a range of wind direction with similar wind speed and gradient on the trial days. Hence, the effects of wind speed and wind gradient on sound attenuation could not be quantified conclusively.

Assessment on Key Atmospheric Factors

Wind direction was assessed to have a significant impact on sound attenuation. Although the effects of wind speed and wind gradient were unable to be quantified conclusively, literature research has shown that these atmospheric factors do affect sound attenuation. It was thus assessed that all three atmospheric factors should be part of the atmospheric criteria to determine whether live firing activities should proceed or not.

INSIGHTS ON EFFECT OF AMMUNITION-RELATED PARAMETERS

Effect of Detonation Method

Results from trials conducted using uncased ammunition only (Figure 4) showed that overburden detonation at 400kg NEQ (two pits of 200kg each) resulted in significantly softer sound (by around 20dB) than sub-surface and surface detonations of up to 200kg NEQ. It is thus validated that the overburden detonation method is an effective means for sound attenuation.

The trial results in Figure 4 demonstrate that there is little or negligible difference in sound attenuation between surface and sub-surface detonation of uncased ammunition. A summary of the trial results in Figure 4 is shown in Table 2 below.

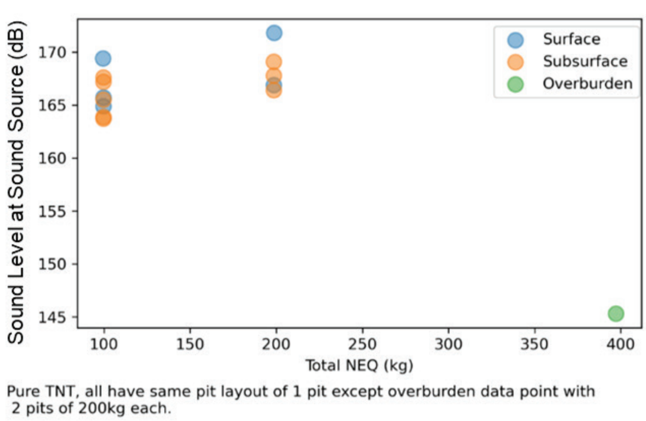


Figure 4. Effect of detonation method on sound level

Effect of Type of Ammunition Detonated (Cased versus Uncased)

Trial results of surface detonation of cased ammunition (using 155mm standard projectile) and uncased ammunition (TNT blocks) demonstrated that detonation of uncased ammunition generates louder sounds than that of cased ammunition by up to 9.5dB for the same total NEQ (Figure 5). This finding corroborates with our literature research which show that the percentage of total blast charge energy converted into sound energy decreases with increasing case thickness (Oei & Chua, 1998).

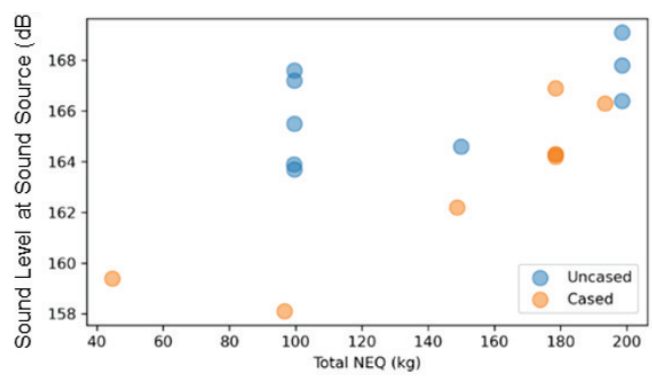


Figure 5. Effect of cased compared to uncased ammunition on sound level at source of sound

All trials were conducted via sub-surface detonation method only, with same pit layout (1 pit).

NEQ	Average Detonation Sound Level at Sound Source	
	Surface Detonations	Sub-surface Detonations
100kg	165.6dB	166.7dB
200kg	167.8dB	166.9dB (single data point)

Table 2. Summary of differences in sound attenuation between surface and sub-surface detonation of uncased charges.

Effect of NEQ Amount of Uncased Ammunition

Trial results demonstrated that reducing the uncased ammunition from 200kg to 100kg can reduce the sound level by around 2 to 3dB (Figure 5).

The highest detonation sound level observed during favourable atmospheric conditions for 100kg NEQ of uncased ammunition is 86.2dB (Figure 6). Since wind direction may affect the sound level by up to 23.7dB, the worst-case scenario during unfavourable atmospheric conditions for 100kg NEQ could be around 110dB, which is still below the 115dB threshold.

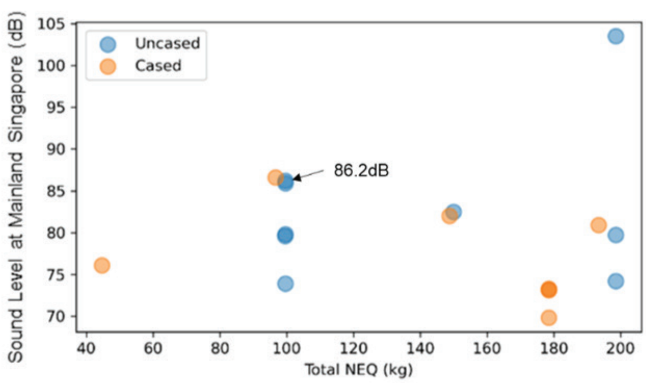


Figure 6. Effect of cased compared to uncased ammunition on sound level at mainland Singapore

All trials were conducted via sub-surface detonation method only, with the same pit layout (1 pit).

It was also noted that the sound levels on mainland Singapore of all uncased ammunition trials up to 50kg NEQ were approximately 30dB below the 115dB threshold. Out of which, the highest sound level of 85.4dB recorded at Sentosa was when all three atmospheric conditions were unfavourable.

Moreover, sound data collected from trials using uncased ammunition (TNT blocks) with varying NEQ demonstrated that reducing the total NEQ from 100kg to 50kg reduces the sound level by around 3dB (Figure 7).

It is thus assessed that a 50kg uncased ammunition limit will be suitable to provide sufficient sound buffer from the worst-case scenario.

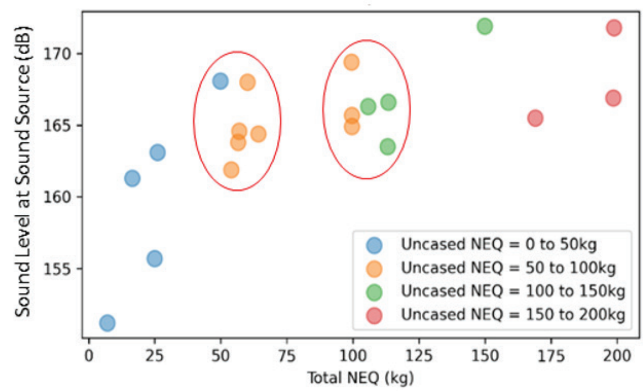


Figure 7. Effect of total NEQ on sound level. All data points are of TNT only with same pit layout, detonation method, and main HD

Effect of Number of Detonated Items

Trial results also demonstrated that detonation of a single large NEQ item resulted in louder sound than multiple small NEQ items that add up to the same total NEQ. Sound levels from detonation of a single large NEQ item per pit (two pits of 144kg NEQ each) were around 10dB higher on average compared to multiple small NEQ items that add up to the same NEQ (Figure 8). This affirms our understanding that detonation of single large NEQ items would generate higher blast overpressure than a pile of smaller NEQ items adding up to the same NEQ as a single charge detonates all at once compared to multiple smaller detonations in succession. This single detonation will generate a single uniform shockwave outward whilst multiple detonations will generate multiple shockwaves that might not merge together due to the slight time difference in detonation.

Moreover, sound levels from detonation of a single large cased NEQ item were higher than that of multiple small uncased NEQ items despite the latter having a larger total NEQ than the former (400kg compared to 288kg). It is thus assessed that the effect of detonation of a single large NEQ item has larger impact on sound level than the effects of uncased versus cased ammunition.

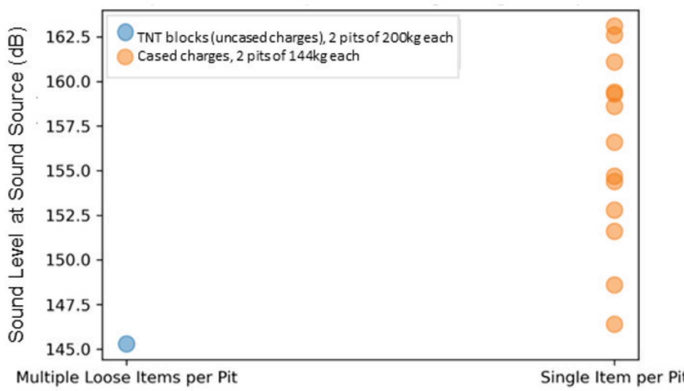


Figure 8. Effect of detonation of multiple small items per pit compared to single large item per pit adding up to same NEQ

Effect of Pit Layout

Breaking a pit into smaller pits has little or no effect in noise mitigation. Results from TNT trials of 200kg NEQ detonated using different pit layouts demonstrated that there was no clear trend of the effect of splitting pits on detonation sound levels (Figure 9). The average detonation sound level of one pit of 200kg is 167.7dB, and the detonation sound levels for 200kg split into two, three, and four pits are 166.7dB, 167.6dB and 169dB, respectively. It is thus assessed that splitting pits will have little or negligible effect in noise mitigation.

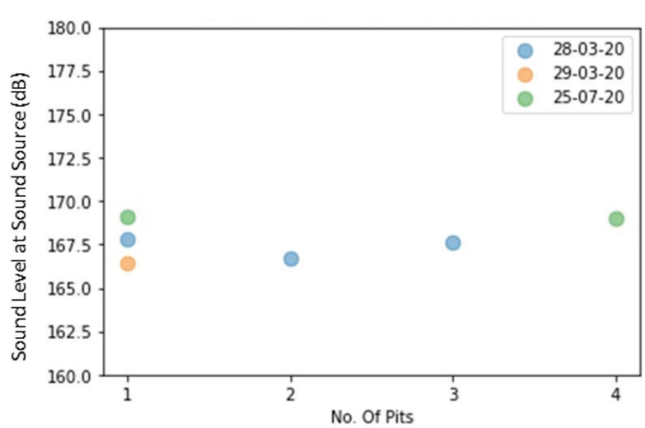


Figure 9. Effect of pit layout on sound level observed over three different days

All trials used TNT only, have total NEQ of 200kg, and were conducted via sub-surface detonation method only.

Effect of Explosives HD

There were insufficient data points collected to observe differences due to effect of main HD of the charges on sound propagation (Figure 10).

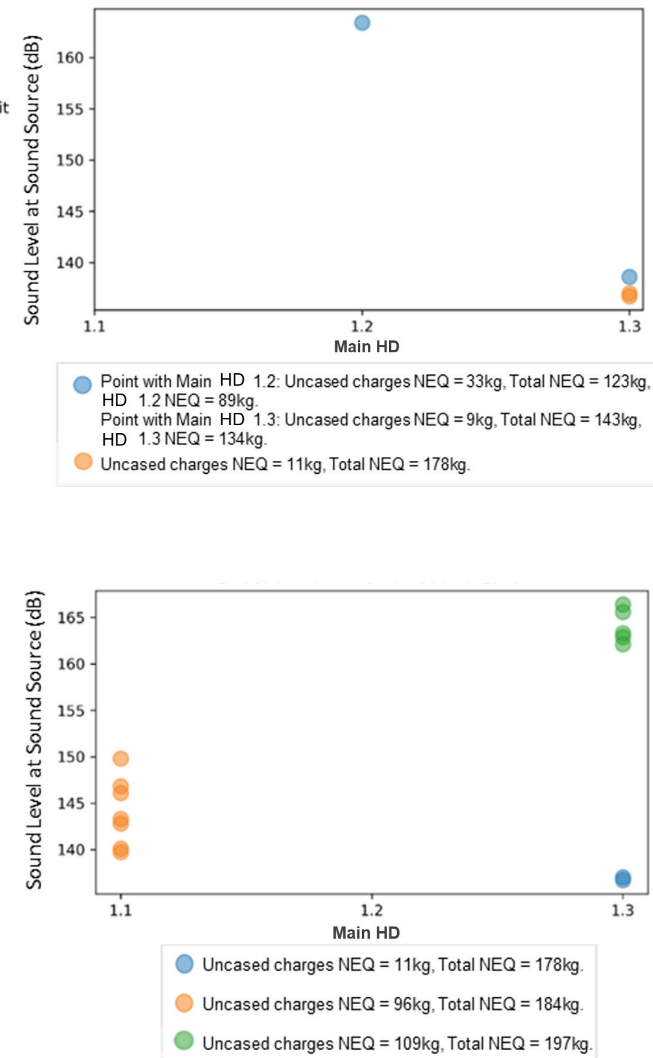


Figure 10. Effect of main HD on sound level

All data points are of same pit layout and detonation method, and have total NEQ of between 150 to 200kg.

SUMMARY OF INSIGHTS

A summary of insights from the sound trials are listed in Table 3 below.

S/N	Atmospheric and Ammunition-Related Parameters
1	Reduction in sound attenuation from sound source to mainland Singapore when wind blows towards versus away from mainland Singapore
2	Lower sound levels for overburden detonation versus surface/sub-surface detonation
3	Lower sound levels for detonation of cased versus uncased charges
4	Lower sound levels of 100kg NEQ versus 200kg NEQ detonation of uncased charges
5	Lower sound levels of multiple versus single items adding up to same NEQ
6	Little or no effect of the following: - Surface versus sub-surface detonation - Pit layout
7	Insufficient data to conclude effects of the following: - Wind speed - Wind gradient - Hazard Division

Table 3. Summary table of insights from sound trials

RECOMMENDATIONS FOR WAY AHEAD

The insights gained from the sound trials are translated into our recommended noise mitigation guidelines stated in Table 4.

S/N	Ammunition-Related Parameters	Noise Mitigation
1	Surface/sub-surface detonation of large NEQ	Should only be allowed when prevailing winds are north-easterly.
2	Amount of uncased ammunition via surface and sub-surface detonation	Should be limited to 50kg. The rest of the detonation pit should only comprise cased ammunition of up to 150kg NEQ. This may however result in the need to split certain configurations into several detonation pits in order to keep the amount of uncased ammunition to below 50kg per pit.
3	Single large NEQ item	Should be detonated via overburden method only, unless assessed as unsafe for overburden detonation. If overburden detonation is not possible, then live firing activity should only be allowed when prevailing winds are north-easterly.
4	Overburden detonation of single large NEQ item	Should subject to atmospheric criteria (and calibration blow) or allow live firing activity of such items when prevailing winds are north-easterly.

Table 4. Noise mitigation guidelines

In order to determine a suitable period when prevailing winds are north-easterly, wind roses showing the frequency and speed of wind from all directions across the years of 2017 were plotted and analysed (see wind roses from 2017 in Figure 11). The labels on the concentric circles indicate the frequency of the specified wind speed and direction in terms of percentage of the whole month. The different colours in the legend represent the wind speed in knots.

Based on the wind roses plotted, it was noted that the months with prevailing north-easterly winds are typically from December to March. Noise mitigation guidelines that are recommended for the conduct of live firing activities when the prevailing winds are north-easterly would thus be recommended for the period of December to March.

Figure 11. Wind roses from each month in 2017 showing the frequency and strength of winds from all directions

CONCLUSION

The analyses and results from this technical study are valuable in contributing to the understanding of the effects of atmosphere and the parameters of live firing activities on sound attenuation. The noise mitigation measure of using atmospheric criteria to determine if live firing activities should proceed was validated and adapted to our local context. Further noise mitigation measures by adjusting ammunition-related parameters for live firing configurations were newly developed to be less reliant on favourable atmospheric conditions, so that live firing configurations can be tailored during seasons with generally unfavourable atmospheric conditions. With these noise mitigation measures in place, the likelihood of public disturbances due to live firing activities on the southern island will be reduced significantly. The insights gained can also be used for future studies on noise mitigation for other applications involving live firing activities to benefit the larger community.

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DIGITISING BACKWARD CONTACT TRACING

MEO Kok Eng, SIN Daren, CHEW Weng Kit Aaron

ABSTRACT

On 11 March 2020, the World Health Organization declared COVID-19 a global pandemic. To manage the situation, Singapore established a Multi-Ministry Taskforce to coordinate the national response against the outbreak, with contact tracing as one of the national strategies to curb the spread of the virus. In early 2020, a contact tracing centre was stood up to manage the increasing number of daily cases and clusters.

A multidisciplinary DSTA team was embedded in the contact tracing centre to provide engineering support to strengthen and augment Singapore's contact tracing effort. This article describes the team's experiences and considerations in delivering the Network Analysis Tool that supported epidemiology investigations to identify sources and clusters of infection.

Keywords: contact tracing, network analysis, cluster discovery, text search, geo-spatial analysis

INTRODUCTION

The coronavirus (COVID-19), first detected in December 2019, was declared a global pandemic by the World Health Organization (WHO) on 11 March 2020. At the time of writing, there were more than 175 million cases of COVID-19 and more than 3.7 million deaths globally (WHO, 2021).

Containing the virus would require intervention measures such as contact tracing – a known infection containment strategy recommended by the WHO – and isolation of suspected or confirmed cases. In Singapore, contact tracing is one of our strategies and is led by the Ministry of Health (MOH) with support from various government agencies.

In March 2020 when Singapore experienced multiple new clusters and an increasing number of unlinked cases daily, MOH reached out to DSTA for engineering support to strengthen and augment MOH's contact tracing effort.

This article describes the key considerations behind the Network Analysis Tool developed by the multidisciplinary DSTA team that was embedded in MOH's contact tracing team. It also explains how the tool helped to streamline and improve the contact tracing process.

UNDERSTANDING CONTACT TRACING

The contact tracing process can be segregated into forward and backward contact tracing (see Figure 1).

Forward contact tracing focuses on identifying close contacts to whom COVID-19 positive patients could have passed the virus to during their infectious period. The purpose is to anticipate and break the transmission cycle by isolating the close contacts. Forward contact tracing looks at the activities of infected person three to five days before the onset of symptoms until the person is admitted to hospital/community care facility (CCF) for isolation, as the infected person could already be transmitting the virus before experiencing any symptoms.

On the other hand, backward contact tracing focuses on establishing the source of infection and identifying clusters. It aims to remove the source of transmission and prevent further infection. For example, a restaurant may have asymptomatic staff who are unaware that they were infected and continue to infect others while working. Through backward contact tracing, such locations are identified for further investigation to establish the source of infection. Backward contact tracing looks at the activities of the person up to 14 days prior to the onset of symptoms.

This article focuses on backward contact tracing as the team's work centred on identifying sources and clusters of infection for epidemiology investigations.

Besides the challenge of analysing the large amount of information, some of the data in the activity maps were in free text and there was a need to search through and analyse this information efficiently. There was also a need to visualise geospatially where the potential COVID-19 hotspots were.

These challenges drove the requirement to digitise the process and incorporate data analytics which could elucidate the interactions among the thousands of cases more efficiently.

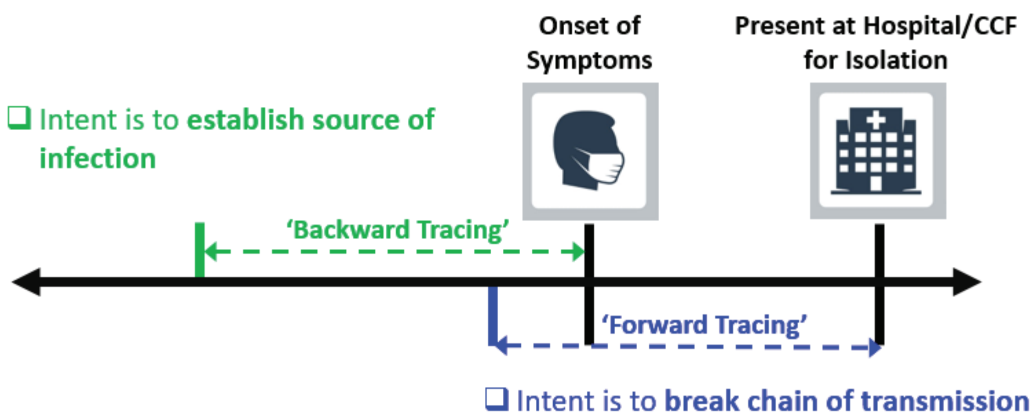

Figure 1. Forward and backward tracing

CHALLENGES IN BACKWARD CONTACT TRACING

Initially, backward contact tracing was done by a team of epidemiology officers who would run through the "activity maps" of the infected cases, and try to correlate multiple branches of information across the different cases to establish linkages. Before being tested positive, each patient could typically have up to 100 close contacts and visited more than 30 locations over the 14 days.

This process was manual and memory-intensive. The rapidly increasing cases in the early stages of the pandemic worsened the problem, as there was a surge in the amount of data to be analysed, making this manual process unmanageable.

THE BACKWARD CONTACT TRACING TOOLKIT

Overview of the Toolkit

The challenges identified in backward contact tracing were multi-faceted and required a multi-pronged approach to handle the operational needs. This section describes the various components of the toolkit (see Figure 2), and explains how each component tackled different issues as well as how the team put them together to tackle backward contact tracing.

Four key components were developed – (1) a Network Analysis component for relationship analysis between COVID-19 cases and contacts, (2) a Text Search component to search through text-based activity data efficiently, (3) a Geo-Spatial component to aid in the analysis of the cases' geo-spatial movement and (4) a data pipeline to ingest and process the data into databases for analysis by the Network Analysis, Text Search and Geo-Spatial components.

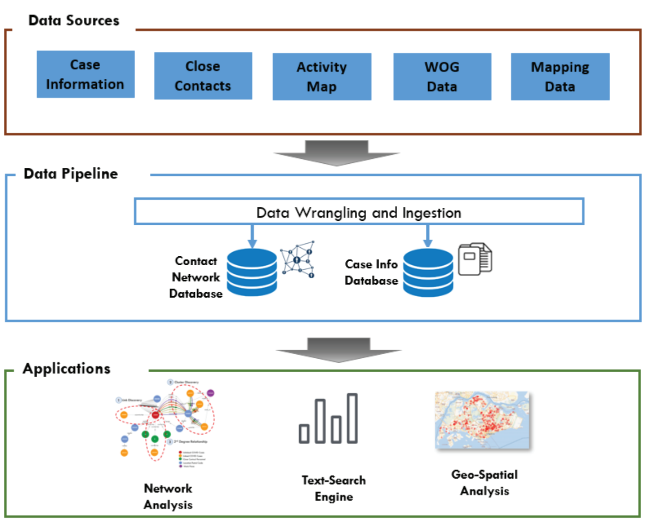

Figure 2. Overview of the backward tracing analysis toolkit

Network Analysis Component

Narrowing Down to Network Analysis

Backward contact tracing requires the extensive analysis of interactions between individuals across space and time. Network analysis was identified as the natural fit for modelling the complex interactions between infected cases. Besides its visual intuition, concepts and algorithms stemming from graph theory could be used to analyse trends and clusters and have been applied in various government and commercial products (Zagalsky, 2020) (Jain, Liu, Sarda, & Molino, 2019).

In addition, the team had experience in applying the network-based analysis approach in other domains such as identifying terrorism threats within the shipping community. These experiences and tacit knowledge enabled the team to deliver a minimum viable product quickly within weeks to support contact tracing operations.

What is Network Analysis?

In Network Analysis, information such as locations, activities, close contacts and case details are fused together and presented in visual network graph to help identify links between cases and uncovering clusters of infections.

In order to form the network representation efficiently to support real-time analysis, the data needs to be properly structured and stored. In this aspect, transactional (row-wise) data structures using Structured Query Language (SQL) database would be sub-optimal. SQL queries would be ill-fitting and more prone to errors. For example, if one needed to know the contacts of cases who had visited a specific location at a particular time, transactional data structures would require complex SQL joins across multiple tables which can be computationally intensive and slow. In contrast, a graph database stores the relationship(s) between cases, contact and locations optimally, and provides natural graph queries to map out the COVID-19 transmission landscape which can identify links and emerging clusters more easily. In view of these considerations, the graph database was selected for Network Analysis.

The diagram below shows the three main outputs of the Network Analysis component (see Figure 3):

(1) Link discovery: Cases that are directly connected
(2) Cluster discovery: Cases that are in close proximity
(3) 2nd degree relationship: Identification of potentially infected, asymptomatic person

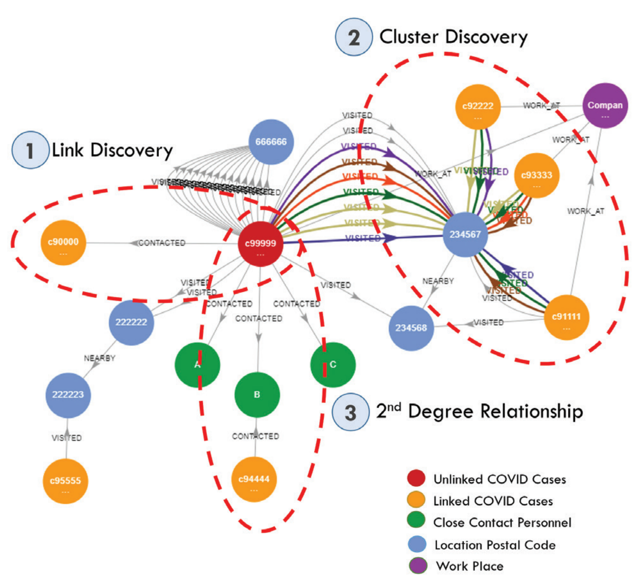

Figure 3. Network analysis component

Incorporating Data Analytics

Analytic algorithms were also incorporated into the tool to detect clusters automatically by analysing links between cases who had visited a common location in a particular timeframe. The algorithms enabled the tool to highlight overlaps in time and location between unlinked and linked cases, thereby uncovering hidden links between cases. Besides shortening the contact tracing process, they allowed contact tracers to sieve out potential commonalities such as locations visited which were crucial in finding potential clusters.

Well-known graph-based algorithms were also applied for analysing the data:

- Community detection algorithms such as the Louvain algorithm[1] (an algorithm to extract communities from large networks) were applied to detect denser subgraphs where nodes have larger number of connections between each other thus forming potential COVID-19 clusters.

- Centrality analytics such as the PageRank algorithm[2] (an algorithm used to measure the importance of nodes based on a node's position and its neighbours in the graph and used in Google to rank web pages in its search engine) was used to detect potential "super-spreaders" who could have been asymptomatic cases that went undetected.

However, these existing algorithms were unable to handle temporal aspects such as time comparison for the purpose of contact tracing. For example, a person who was flagged out by a centrality detection algorithm (because he/she was in contact with two confirmed cases) might not be the link between the two cases if the time he/she interacted with the two cases was too far apart.

Thus, on top of using well-known algorithms, the team developed specialised routines for handling time comparison. One of such routines – Time and Space Analysis – detected clusters by looking at common locations (space) visited by cases in a particular timeframe (time), thereby linking them together.

This analysis was done by taking advantage of linkages between cases and locations. Linkages are represented by edges in the graph and the times where a case visited the location are stored as properties of the edge. For example, this query[3] lists down pairs of cases (c1, c2) that visited the same place p:

```
MATCH path=(c1:Case)-[v1:VISITED]->(p:PLACE)<-
                [v2:VISITED]-(c2:Case)
RETURN path
```

To find cases which visited a place during the same time, the results from the query above were further refined by filtering the time-visited property of the edges to those whose start and end time overlapped.

Text Search Component

Need for Text Search

The data found in activity maps collected from interviewing the cases was text-based. They were rich sources of information that described what the places the cases visited and the types of activities there. Contact tracers needed to be able to search through this information efficiently.

One straightforward solution was to directly search the raw text/CSV files. However, with the burgeoning amount of data, this became increasingly slow and inefficient. Furthermore, there was also a need to filter the textual search results with additional constraints such as date/time, case number and cluster. An example of such a query might be to list down all the cases who had visited a specific location (Location A) from within a certain date range (e.g. 1st to 15th May).

Moreover, due to misspellings and spelling inconsistencies, doing a manual search meant that one had to consider different spelling permutations of a word. This was unreliable and inefficient. Hence, there was a need for a tool that could first perform a search and return the results quickly, then perform a fuzzy search to accommodate for spelling inconsistencies.

Use of Elasticsearch as a Search Engine

Elasticsearch is a scalable NoSQL database (this is a non-tabular database which stores data in a format different from relational tables. In Elasticsearch, data is stored in a document format.) based on the Lucene library that provides scalable, near real-time, full-text search. It is built upon JavaScript Object Notation (JSON) documents that are optimised for full text search capabilities and data aggregation.

Elasticsearch is commonly used in the industry. For example, search engines at Yelp (crowd-sourced business reviews) use Elasticsearch (Dangat, 2017). Furthermore, Elasticsearch was chosen as one of the databases as the developers had some expertise and knowledge in using it in the Singapore Armed Forces Web Intelligence for counter-terrorism (Ng, Sharma, Loke, & Lee, 2020).

Whenever a piece of text is ingested into Elasticsearch, analysers which make use of Natural Language Processing techniques are applied to them, and this makes the text searchable. Furthermore, Elasticsearch is able to perform fuzzy searching, which addresses the spelling inconsistencies, and is able to perform relevance-based searching such that search results are sorted according to its relevance to the query.

Geo-Spatial Component

The Geo-spatial component was developed to help contact tracers analyse the geo-spatial trends and relationships between cases (see Figure 4). Two sub components were developed, namely Heat Map Visualisation and Spatial-Temporal Analysis, and these are described in the sections below.

Heat Map Visualisation

Adjacent locations between cases were analysed to narrow down geographical clues to where transmissions were likely to occur. Heat mapping is a useful visualisation tool that plots the density of visits by positive cases to an area and provides the team with additional information. The application was able to identify high-risk locations where transmission was prevalent. Cases were plotted against known clusters and confirmed cases to identify the possibility of exposure to existing clusters. This helped contact tracers identify potential location clusters such as supermarkets and eating places which were high-risk focal points for transmissions. This approach also helped to verify the centrality analysis on the network database where multiple cases were centrally linked by common location nodes. This information aided policy makers in making data-driven decisions to control the transmission in such places.

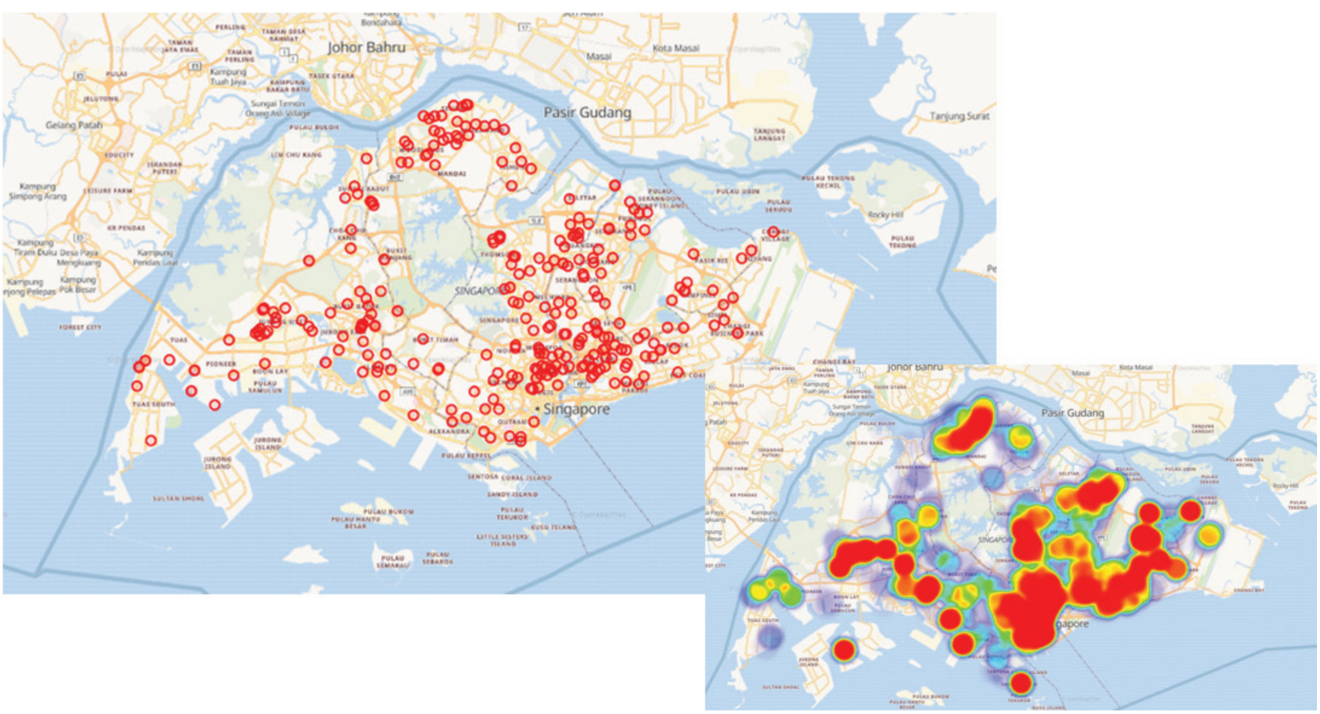

Figure 4. Geo-Spatial Component (simulated data for illustration purposes)

Spatial-Temporal Analysis

To identify potential high-risk areas where transmission between cases was likely to occur, the users wanted to find locations where there were frequent interactions. The spatial-temporal application allows the users to filter positive cases in proximity with each other over a time span. Its objective was to uncover overlapping visits across locations and time. Locations visited by cases were converted to latitude and longitude coordinates and plotted onto the map. Matches were flagged out when the haversine distance between a pair of coordinates was within a threshold proximity and fell within a specified time window. This allowed the contact tracers to identify possible links between cases immediately based on their movement history. The temporal window included time overlaps between two cases, and scenarios where, say, case A could have arrived before case B and left or vice versa. Potential matches were returned to the analyst as a list for further investigation on the movement history of each case.

Putting Everything Together - Data Pipeline

With the rising number of COVID-19 cases, there was a surge in the volume of raw data. The team had noticed data quality deteriorating as the volume increased and this created downstream issues for the system, such as duplicated cases. During the same period, as operations evolved, new data sources were identified. This led to the need for a central Data Pipeline to clean, wrangle and structure the data into a Contact Network and Case Information Database (see Figure 2) to support analysis by the Network Analysis, Text Search and Geo-Spatial components.

The design considerations for the Data Pipeline include:

(1) Independent components – To cater for new data sources and new formats of data which changed frequently due to the dynamic nature of the operations during the early stages. Each module (e.g. data ingestion, data processing) was built separately with an internally defined format so that external changes, e.g. changes in case information format etc, would not affect the internal data processing pipeline.

(2) File-based exchange of data between components – For the purposes of data recovery, a file-based approach was adopted for data exchange instead of passing data via Application Programming Interface[4] calls. Saving the raw data files also allowed the team to re-ingest the data in the future when better pre-processing scripts were developed.

(3) Data Fusion – Data from various sources are fused to produce a more accurate and consistent information. For example, the address of a case might be missing in the case details information but can be retrieved from other government databases. Data fusion also helped in generating richer datasets for analysis. An example was when the team wanted to be more thorough in the analysis of the locations where a case visited. There could be a lapse in memory in the individual's account of where he visited or he could have unknowingly interacting with other people in the vicinity. To this end, the pipeline expanded the COVID-19 dataset by fusing each location postal code with its nearby postal codes. This allowed the analysis to have a more comprehensive picture of where the cases might have visited.

DEPLOYING FOR OPERATION

In early April 2020, the first prototype was deployed for field trial after just one week of development. To validate the tool, the team compared the results against previously identified and confirmed links involving several cases that had visited locations such as Mustafa Centre in Little India, the Project Glory construction site and migrant worker dormitories. The tool substantiated the findings and additionally found more cases connected to the clusters. Subsequently, new cases were linked to the mall (Mustafa Centre) to the construction sites and dormitories, thereby demonstrating the effectiveness of the first prototype.

During its initial use, the early prototype successfully resolved multiple unlinked cases and also identified new clusters at the Marina Bay Sands and massage parlours in the East Coast. It also associated new cases to the initial Mustafa Centre cluster in Little India.

LESSONS LEARNT

Working Alongside Users

The key to delivering a working tool quickly in a fast-paced and ever-changing environment was for the software development team in DSTA to work closely alongside operational users at MOH. This close relationship exemplified the importance of ops-tech integration. The developers and epidemiology teams were stationed physically at the same place, and the constant communication between the users and the developers allowed the entire team to be aware of what everyone else was doing. It accelerated the speed of development. An example was when overlapping data requirements for different analysis required by the epidemiology teams were quickly sieved out which reduced the duplication of efforts. Development was also sped up through constant data clarifications with the ops team, and this led to fast development of the data processing pipeline to form a single source of truth.

Establishing Quick Feedback Loops

One major challenge was the evolving situation where policies and requirements were changing by the day, and therefore forcing the models to adapt in parallel. Agile development was practised in order to keep pace with the changing environment. Once a certain feature of the tool was ready, it was deployed immediately to complement the existing contact tracing workflow in order to get early feedback. Bugs and fixes were addressed immediately and redeployed in the next sprint. This methodology allowed the tech team to prioritise the development tasks with the ops team, to ensure that the tool remained relevant and useful in a rapidly evolving situation.

Another merit of adopting agile development was the ability to conduct in-depth investigation of actual data using exploratory approaches in an operational environment. This brought about three positive outcomes. First, the software development team was able to uncover actual human errors in the large volume of information by using artificial intelligence techniques. Second, complex features could be derived quickly from the actual data, which was critical in a fast-spreading epidemic. Lastly, the operational users and the software development team could boldly adopt a fail-fast approach to evaluate ideas and identify promising ones for future development.

CONCLUSION

With the Network Analysis Tool, contact tracers were able to map out a visual network representation of the cases, linking them through activities, locations and time. Besides shortening the contact tracing process, the tool allowed contact tracers to apply data analytics to identify linkages and sieve out potential commonalities which were crucial to finding potential clusters. The geo-spatial heatmap supported the identification of high-risk locations where transmissions were prevalent for public health actions.

Since its deployment, the tool has enabled faster and more accurate linking of cases. Most importantly, significant clusters such as shopping malls, restaurants, shops, and work sites were identified and closed off promptly by authorities to prevent further transmission at these locations.

The tool has streamlined and improved the contact tracing process and has been transited to the MOH team for operations and support since August 2020.

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ENDNOTES

[1] The Louvain algorithm is a hierarchical clustering algorithm that recursively merges communities into a single node and executes the modularity clustering on the condensed graphs (Neo4j, n.d.).

[2] The PageRank algorithm measures the importance of each node within the graph, based on the number of incoming relationships and the importance of the corresponding source nodes. The general underlying assumption is that a page is only as important as the pages that link to it (Neo4j, n.d.).

[3] This query was used on the Graph Database that was used: Neo4j. It is written in Cypher, which is Neo4j's graph query language.

[4] Application Programming Interface, which allows for software or applications to communicate with each other.

BIOGRAPHY

MEO Kok Eng is a Senior Principal Engineer (C3 Development). He is currently leading the development of artificial intelligence and data analytics capabilities for decision support in Command & Control (C2) Systems. He has previously led teams in the development of strategic C2 systems for the Joint & Navy domain. Kok Eng graduated with a Bachelor of Computing (Computer Engineering) from the National University of Singapore in 2006.

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CHEW Weng Kit Aaron is a Senior Engineer (Digital Hub). He currently works on translating new language processing technologies to C2 applications. Aaron graduated with a Bachelor of Information Engineering and Media from Nanyang Technological University in 2019.

A JOURNEY OF INNOVATION – DEVELOPING A ROBUST AND ACCURATE TEMPERATURE SELF-CHECK KIOSK

LAW Teck Hiang, CHAN Shi Jie Donovan, CHEN Mingyi Edmund, YONG Seng Choon

ABSTRACT

When the COVID-19 pandemic spread in Singapore in 2020, fever continued to be one of the symptoms for people potentially infected with the coronavirus. To screen people for fever, while commercially off-the-shelf contactless thermometers were available, they were not automated and required manpower to conduct individual temperature screening at entry points to buildings. The Infrared Fever Screening System (IFss) on the other hand, was employed for mass temperature screening during the Severe Acute Respiratory Syndrome outbreak in 2003, had a large deployment footprint and was much more costly than contactless thermometers. To overcome these challenges and allow individuals to check their temperatures easily, DSTA worked with the Ministry of Culture, Community & Youth, Land Transport Authority and industry partners to develop the Temperature Self-Check Kiosk (TSCK). The TSCK was accurate, 70% cheaper than the IFss, had a small deployment footprint and was easy to use. They were placed at train stations and bus interchanges and deployed at Army camps to facilitate temperature checks. This article shares the authors' experience in the development of the TSCK.

Keywords: COVID-19, temperature, screening, fever

INTRODUCTION

During the COVID-19 pandemic, there was a need for temperature screening systems to be deployed in public areas, where individuals could check their temperatures quickly, conveniently and accurately. The system would require a small deployment footprint, be contactless and intuitive for individuals to use without assistance. DSTA worked with industry partners who had experience in infrared technology, as well as the capability to scale up prototyping to production rapidly and provide downstream maintenance support. To diversify options and increase chances of delivering a viable solution quickly, DSTA engaged multiple industry partners, including ST Engineering and HOPE Technik, to develop and test their respective prototypes.

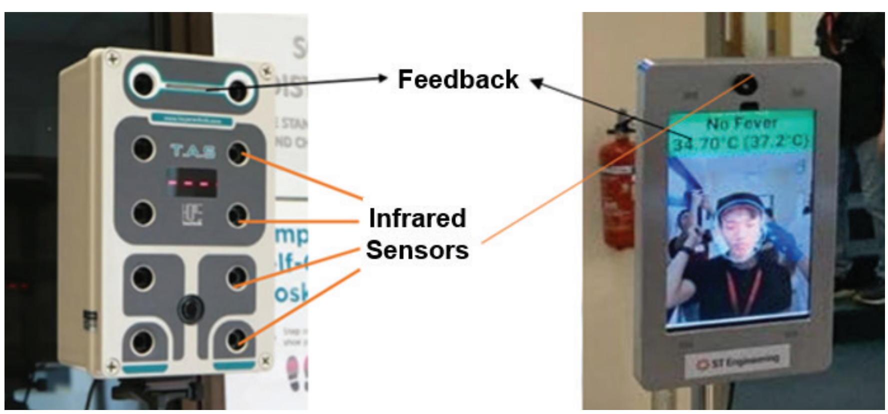
In developing the Temperature Self-Check Kiosk (TSCK), the team had the following considerations: (1) user centricity in system design and development, (2) need for accurate measurement of physiological body temperature, (3) data-driven approach towards setting the fever detection threshold, and (4) ease of system deployment.

SYSTEM DESIGN AND DEVELOPMENT CONSIDERATIONS

The design concept behind the TSCK was for an easily deployed, fast and contactless means of determining if a subject was potentially febrile[1] by sensing the skin temperature. The TSCK was to serve as the first layer in the temperature screening process, for subjects to be flagged as potentially febrile for subsequent confirmation of a fever with a clinical thermometer.

Design thinking was applied throughout the development process to ensure that the system's design goals were met. The first prototypes were developed within two weeks, and consisted primarily of infrared sensors sensitive specifically to the range of temperatures between 30-40°C, with visual indications to feedback to the user as shown in Figure 1.

The prototypes had to be calibrated so that they could detect potentially febrile persons. To calibrate the prototypes, data collection for febrile and non-febrile subjects was necessary. While data collection was ongoing, the team also deployed the prototypes at public areas, such as MRT stations and bus interchanges (See Figure 2 and Figure 3). This allowed the team to observe whether the system design was intuitive to first-time users and to gather valuable feedback on the product design. Some of the feedback pointed to the light-emitting diode (LED) indicators being too small and not prominent enough; while others highlighted that they would want to see a temperature readout. It was observed that people tended to stand too close to the TSCK, as they were used to commercial handheld infrared thermometers, which had an operational range of five centimetres. Hardware and software changes based on the feedback and observations were implemented iteratively in the improved versions of the prototypes. For example, a proximity sensor was included in the final system design to enable temperature readings only when users were standing at a correct distance from the sensor. This reduced user error when taking temperature measurements.



Note: Feedback for the device on the left in was in the form of a LED light bar while feedback for the device on the right in was in the form of a coloured display as well as words indicating if the user had a fever or not.

Figure 1. Prototypes that were developed
Reprinted with permission from The Singapore Army (left image)

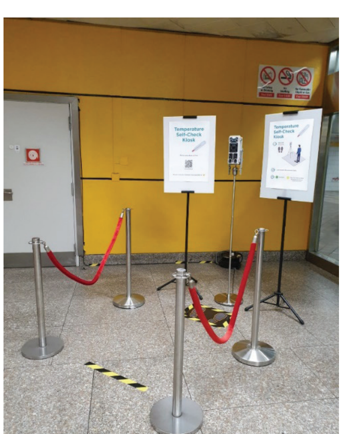


Figure 2. Prototype trial at Toa Payoh MRT

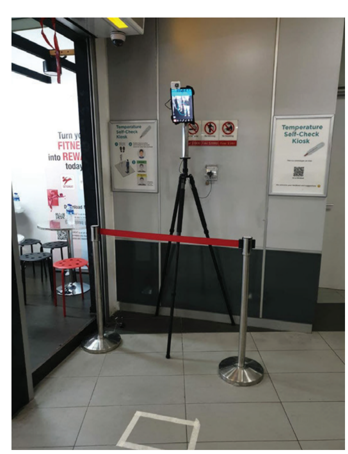


Figure 3. Prototype trial at Serangoon bus interchange

Apart from being user-friendly, it was also important for the TSCK to maintain its accuracy, repeatability over different ambient conditions and temperature stability over time. For one of the prototypes, a proprietary solution was engineered and implemented to ensure that the TSCK could maintain its temperature reading stably without the need for a blackbody cavity (see Figure 4), which greatly reduced the cost. To test this, a calibrated blackbody cavity (see Figure 4) was used as a reference heat source at different pre-set temperatures to verify the system's accuracy and stability over an extended period of time. The temperature drifted over an extended period of time for one of the prototypes was found to be less than +/- 0.04°C from the mean value.

Figure 4. Example of a Blackbody Cavity

HUMAN PHYSIOLOGICAL CONSIDERATIONS

Skin Versus Core Temperature

The core or internal body temperature is generally considered to be the temperature of the blood in the heart and the brain. However, this is not easily measured, unless an invasive catheter is inserted. Therefore, other body sites are typically used as proxies to assess human core temperature (American Society for Testing and Materials, 2003). There are four common methods for the measurement of the core body temperature (McCallum & Higgins, 2012): (1) rectal thermometer, (2) oral thermometer, (3) ear thermometer, and (4) axillary (armpit) temperature. Methods 1 to 3 provide accurate measurements of the core body temperature, while method 4 is an unreliable site (Sund-Levander & Grodzinsky, 2009) for estimating core body temperature due to the absence of main blood vessels around the area. However, all four methods require contact with the body. For contactless means, measurements of the skin temperature are primarily used as a gauge of core body temperature.

Empirical data collected has shown that there is no independent correlation between skin temperature and the core body temperature of a person. Skin temperatures are also found to be easily affected by ambient conditions (Liu, Wang, Liu & Di, 2013) and fluctuate across different times of the day (Morf & Schibler, 2013), with the highest at between 4pm to 6pm and lowest in the early morning.

As the TSCK was a newly-designed system, there was a need to determine the most suitable temperature threshold for fever as measured by the TSCK. While the Infrared Fever Screening System (IFss) had collected data during its development in 2003, these were not applicable to the TSCK for two reasons. First, as the TSCK used a different infrared sensor from the IFss, it was therefore important to collect fresh data to characterise the TSCK's sensors accurately and ensure its efficacy. Second, the TSCK was meant for individual use and, hence, had a much shorter measuring distance compared to the IFss used for screening larger groups at a further distance. The team adopted a data-driven approach, using the methodology published in the Society of Photo-Optical Instrumentation Engineers proceedings (Tan, Teo, Ong & Tan, 2004) from the development of the IFss, to collect temperature measurements from both healthy and febrile populations and establish the threshold at which to detect febrile persons.

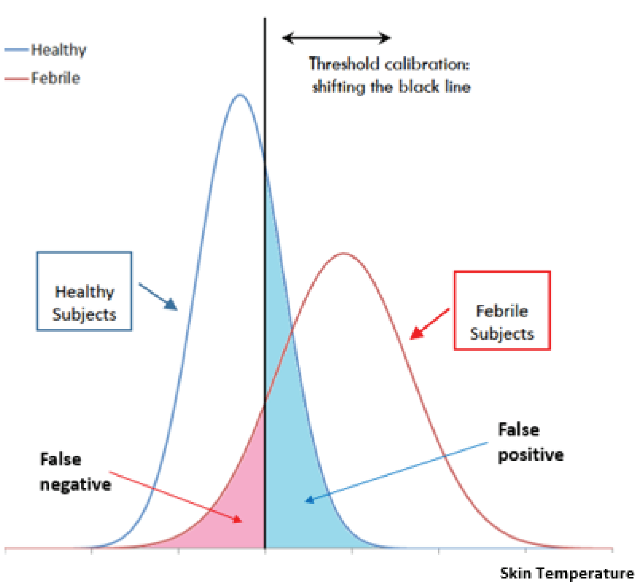
METHODOLOGY FOR THRESHOLD SETTING

The threshold setting of the TSCK is the level that is used to indicate to the user if they might have a fever. The aim was to derive a linear classifier to categorise a subject undergoing screening into either a febrile or healthy class based on the subject's skin temperature, while minimising the impact of errors. There are two types of errors: Type I error – a false positive result in which a healthy subject is classified as febrile; and Type II error – a false negative result in which a febrile subject is classified as healthy.

Two sets of data are required to determine the threshold setting: (1) the core and skin temperature of a healthy population, and (2) the core and skin temperature of a febrile population.

The core temperature was measured using a tympanic (ear) thermometer while the corresponding skin temperature is measured using the TSCK. A febrile subject is defined as having a core temperature of equal to or more than 38°C.

The data collected was then plotted to understand the distribution of skin temperature of healthy and febrile populations as shown in Figure 5. The blue curve represents the healthy population and the red curve represents the febrile population. The black line in the plot represents the threshold that was being defined based on the data collected. The blue shaded area in the curve represents the false positive errors, which means healthy subjects were being misclassified as febrile subjects. The pink shaded area represents the false negative errors, which means febrile subjects were being misclassified as healthy subjects. The threshold setting was therefore a trade-off between the proportion of false positive and false negative errors. For example, if the black line was shifted to the left, the false negative percentage would decrease while the false positive percentage increased. In the ideal scenario, the two sets of data would have minimal overlap, such that the shaded blue and pink regions could be minimised with a given threshold. In reality, however, the two sets of data had significant overlap, thus making it impossible to reduce either the false positive or false negative without increasing the other. Given that false negative was less desirable compared to false positive, the threshold for the TSCK was optimised for an acceptable ratio of false negative to false positive errors, based on risk tolerance level and deployment scenario.



Note: The data points are generalised and smoothened into a curve for illustration.

Figure 5. Healthy versus febrile population for threshold setting

Process of Data Collection

Febrile data collection trials were conducted in medical facilities, including hospital and private clinics, to collect the skin and core temperature of febrile subjects. See Figures 6-8 for the data collection process. The TSCK prototypes were set up in similar air-conditioned environments. The core temperature of each patient would first be measured using the clinic's tympanic thermometer. For measurement consistency, the same tympanic thermometer was used throughout the trial. The patient was then directed to the prototypes to measure his/her skin temperature. Visual markers were placed on the floor and on the prototype to guide the patients on where to stand and use the prototype. Personnel were also on site to record the temperature measurements and observe the patient's behaviour when using the prototypes.

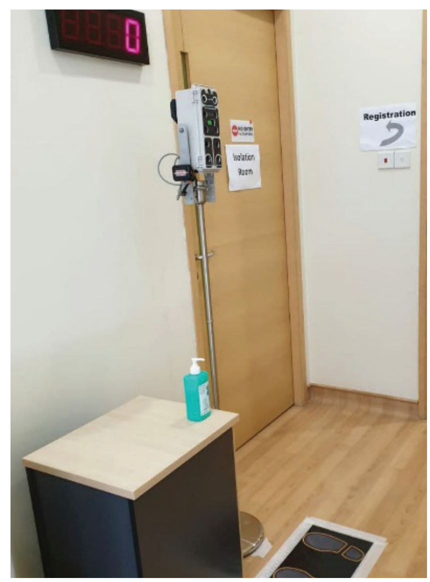


Figure 6. Prototype deployed in medical facility to collect febrile data

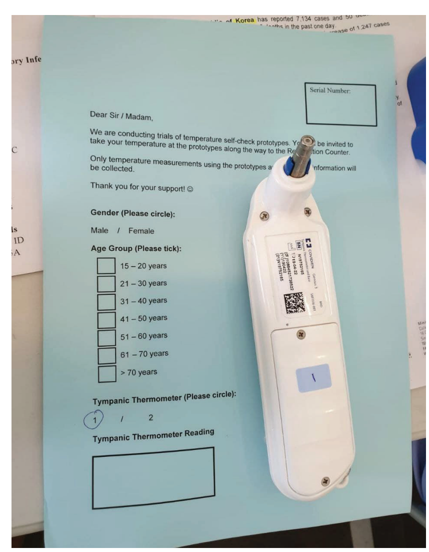


Figure 7. Form to record temperature measurement

Healthy data collection trials were subsequently conducted using the TSCK prototypes. The prototypes were set up in air-conditioned environments similar to those used for febrile data collection. The core temperature of each subject was measured using a tympanic thermometer, followed by his or her skin temperature using the prototypes.

Figure 8. Healthy data collection trials

Setting the Threshold Temperature

A non-parametric distribution fitting (histogram) was used to determine the threshold temperature as the febrile patient data points were limited. Figure 9 shows an example of data plot used to assess the threshold setting of a prototype. The vertical black dotted line represents the threshold setting. In these particular examples, a threshold setting at 33.8°C would give a 48.3% false positive and 5.0% false negative while a threshold setting of 34.6ºC would result in a 1.9% false positive and a 27.5% false negative. Therefore, it can be seen that there will always be a trade-off in choosing a low false negative number which will result in a high false positive number and vice versa.

SYSTEM DEPLOYMENT CONSIDERATIONS

To conduct proper temperature screening, the TSCK should be placed in temperature-controlled surroundings, such as in an air-conditioned environment and facing away from direct sunlight or high heat sources. See Figure 10 for an example of a correct system deployment and usage of the TSCK at a bus interchange. This would minimise the ambient effects on

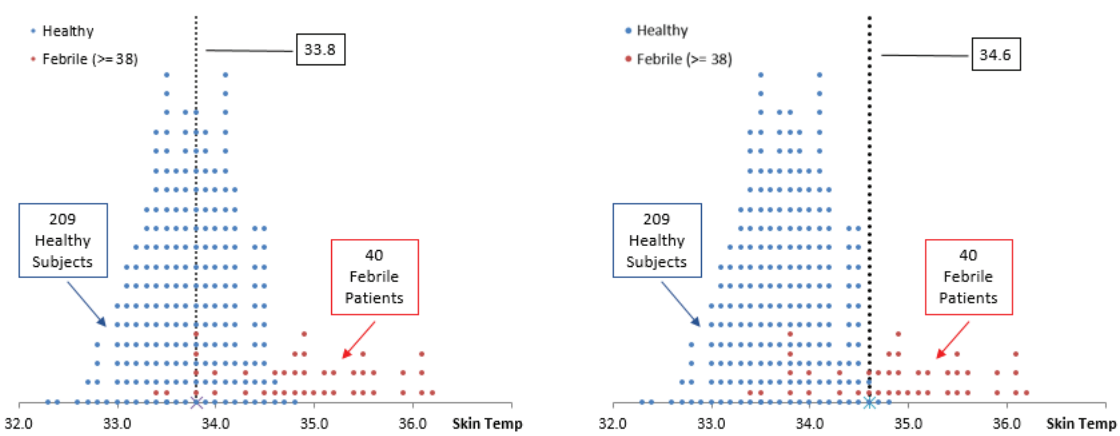


Figure 9. Threshold temperature setting collection trials by DSTA

the human physiology. It was observed in trials conducted under uncontrolled ambient conditions that high ambient temperatures led to higher skin temperature of subjects resulting in a higher number of false positives i.e. where healthy individuals were flagged out to be potentially febrile during screening.

Figure 10. System deployment at a bus interchange

As part of the workflow, guideposts should be used to control the flow of people using the TSCK. A person flagged out as potentially febrile by the TSCK should use a clinical thermometer to confirm his or her temperature. As such systems were expected to be operated continuously for long periods, regular maintenance and technical support would have to be planned accordingly to ensure high availability and ease of maintenance.

CONCLUSION

The TSCK was designed to provide a quick and contactless means to determine if a subject was potentially febrile by sensing the facial skin temperature. Using a data-driven approach, the threshold temperature setting for fever was statistically determined based on the healthy and febrile data collected through trials, with associated trade-offs in false positive and false negative errors.

The team eventually selected the temperature self-check system of local firm HOPE Technik for production. The first system was deployed at MINDEF Pass Office on 23 April 2020. The systems were subsequently deployed at MRT stations, bus interchanges and other Singapore Armed Forces (SAF) camps. This has reduced the reliance on the IFss as well as enabled deployment of the TSCK in areas which are spatially constrained, saving manpower for the SAF by removing the need to man the TSCK.

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ENDNOTES

[1] Febrile: Having or showing the symptoms of fever.

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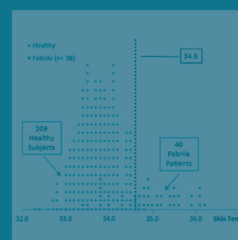

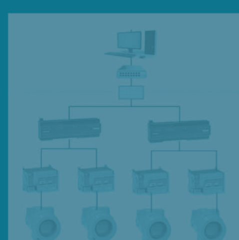

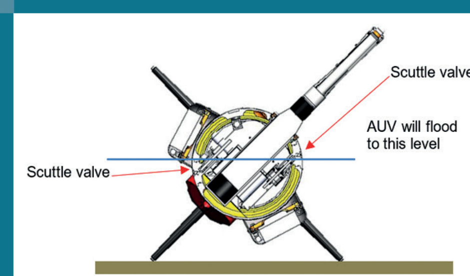

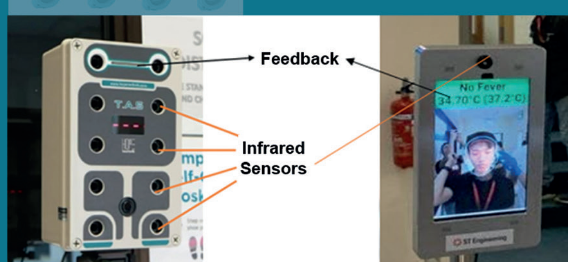

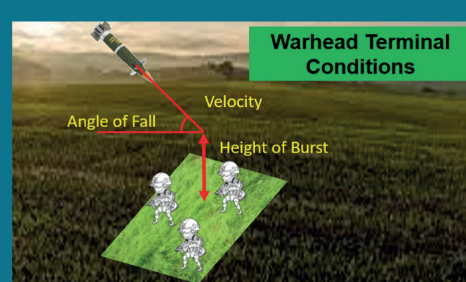

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