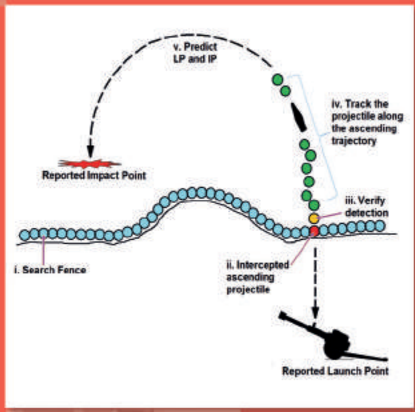
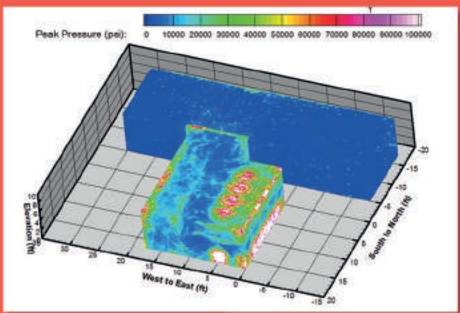
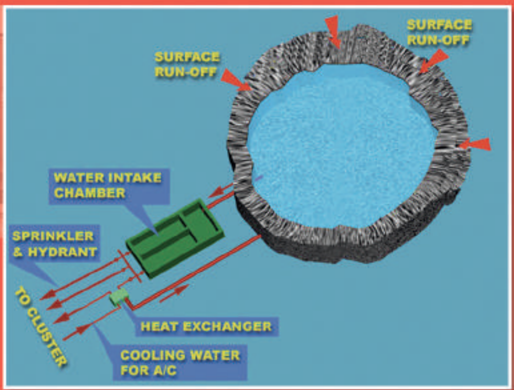
DSTA HORIZONS

2020







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CONTENTS

EDITORIAL

Tan Yang How
President
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This special year marks DSTA's 20th anniversary. It is also one of unprecedented change due to the COVID-19 outbreak where amid new crises and challenges, DSTA has continued to provide engineering support and innovative solutions to the nation. The 15th edition of DSTA Horizons thus puts forth eight articles carefully curated to show the diverse competencies and expertise within DSTA that enable it to develop and implement cost-effective systems solutions for the defence and security of Singapore.

The first article **'Designing the Hunter Armoured Fighting Vehicle (AFV)'** discusses new design approaches in the development of the Hunter AFV to address resource constraints while realising the next bound of networked warfighting capabilities for the Singapore Army. It also highlights innovations in the systems engineering process to develop a more comprehensive suite of design tools and testing methodologies, for agility in verifying and validating complex systems. This is followed by the article '**Achieving Environmental Sustainability for MINDEF and the SAF'** which outlines how DSTA contributes to Singapore's sustainable future by being early adopters of innovative green technology, delivering sustainable camps and bases, implementing initiatives in a broad-based manner, and promulgating good practices through projects and developments.

Providing an overview of DSTA's data-centric strategy to help the Ministry of Defence (MINDEF) and the Singapore Armed Forces (SAF) achieve data-enabled transformation is the article **'Towards a Data-Enabled Organisation'**, which also covers the Fleet Management System initiative that demonstrates the exploitation of instrumentation data and data analytics on military platforms to improve the readiness of platforms, streamline maintenance, and reduce operating costs. Following which, **'The Development of a Synthetic Battlespace'** explores the approach in developing a synthetic battlespace to support new capability development. It shares how DSTA leveraged modelling and simulation technology to create a digital twin of the battlespace to support System-of-Systems and new Concept of Operations development.

The fifth article **'Hybrid Approach for Cost-Effective Development of Explosive Storehouses'** shows how our project management teams strive for continuous improvement in their support for MINDEF and the SAF. It covers a systematic effort to develop new explosive containment facilities that have the capability to mitigate fragment and debris hazards, by tapping knowledge in using a combination of small-scale explosive testing and numerical modelling of large-scale structures. **'Operating and Supporting Three Generations of Weapon Locating Radars (WLR)'** traces the evolution of radar technologies, capabilities, as well as operations and support practices over three generations of WLRs. It also identifies the trade-offs as operational and maintenance support practices evolve. **'Design and Integration of the Littoral Mission Vessels' Launch and Recovery System (LARS) for Fast Response Craft'** compares the designs of LARS and outlines the integration process for stern ramp LARS applicable for multi-role naval vessels. Future directions in continual design improvements and incorporation of emerging technology to enhance safety and operability are also discussed. The last article **'Review of Underwater Blast Safety Criteria'** examines past developments in underwater blast safety criteria and compares the associated experimental results with safety standards from various sources. While studies in the field are ongoing, it is critical to stay up-to-date with international researchers and developments to enhance the understanding of underwater blast effects on divers and the associated underwater blast safety criteria.

We hope readers find this issue of DSTA Horizons informative and interesting. The compilation of articles offers insights into the various fields of technology, both defence-related and otherwise, that DSTA is involved in. It also reflects the passion and commitment of the authors and reviewers inspired to share insights into their endeavours. We hope that DSTA Horizons will continue to be an integral platform for learning and sharing within the defence technology community, for many issues to come.

DESIGNING THE HUNTER ARMOURED FIGHTING VEHICLE

PEH Boon Pin William, WONG Ying Tat, WONG Sai Hong Caleb, NG Kin Loong Bryan

ABSTRACT

As militaries around the world continuously modernise their warfighting machines and equipment, there is an impetus to be innovative in the way systems are designed and built, to stay at the forefront of technology and engineer a new generation of capabilities that provides a force multiplier effect at reasonable cost. As budget, manpower and time are finite, system requirements need to be cautiously balanced with the availability of such resources.

Beyond the traditional focus on safety, quality and total life cycle support, this article discusses new design approaches in the development of the Hunter Armoured Fighting Vehicle to address resource constraints commonly faced by other militaries while realising the next bound of networked warfighting capabilities for the Singapore Army. The article also highlights innovations in the systems engineering process to develop a more agile and comprehensive suite of design tools (e.g. design innovation, 3D Computer-Aided Design modelling) and testing methodologies (e.g. systems integration lab, progressive testing methodology) for verifying and validating complex systems, as well as expediting the deployment of new capabilities.

Keywords: Hunter AFV, design approaches, systems engineering, systems integration

INTRODUCTION

The Hunter Armoured Fighting Vehicle (AFV) was designed and developed by a multi-disciplinary team in DSTA in collaboration with the Singapore Army and defence partners, to replace the ageing fleet of Ultra M113 AFVs. As the Army's first fully digitalised platform, it provides Singapore's armoured forces with enhanced lethality, protection, mobility and networked capabilities. It comes with advanced fighting capabilities that allow a four-fold increase in its area of operations with 20% less manpower. The Hunter AFV was designed with logistical considerations upfront in the system design to enable approximately 40% reduction in operations and support (O&S) costs as compared to existing armoured vehicles.

As the overall systems integrator, the team introduced new design approaches to incorporate the latest technologies and operational concepts for the Hunter AFV, while ensuring that its underlying architecture remains agile in responding to the rapidly changing technology landscape and shortening the time to field future capabilities. The Hunter AFV made its public debut during the system commissioning in June 2019 and was showcased at National Day Parade 2019 (see Figure 1).

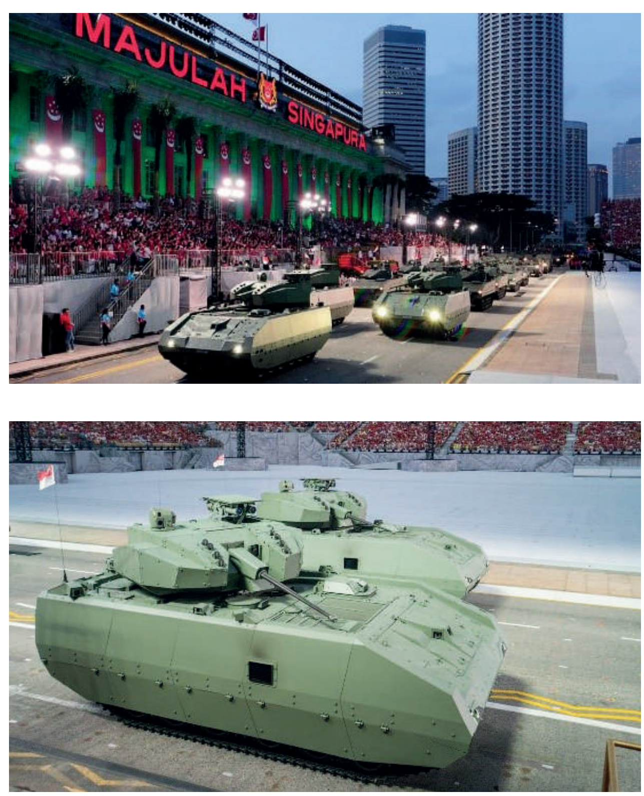


Figure 1. Hunter AFVs on display during National Day Parade 2019

KEY ENGINEERING CHALLENGES

In the journey to design the complex Hunter AFV, the team faced four key challenges:

(a) Engineering a new generation of capabilities to maintain an operational and technological edge, which often meant there is limited reference
(b) Dealing with decreasing manpower due to Singapore's declining birth rate
(c) Rising operational costs as systems become more complex and expensive to maintain, which is unsustainable in the long run
(d) Managing increasing systems integration complexity as many capabilities had to be integrated within a small footprint that was just slightly bigger than a parallel parking lot

A pressing but not commonly known challenge was to design, build and develop a new AFV that would set itself apart significantly from the current generation of AFVs – the Bionix. This was an internal challenge that the team embraced throughout the design process. The general outlook of an AFV was probably the only similarity the Hunter shared with the Bionix. The team made deliberate efforts to ensure that the Hunter AFV would present leaps in capabilities and provide a brand new user experience.

At the early stage of development, the team spent considerable time on the transmission and suspension systems to ensure that these new sub-systems are safe and reliable for operations. Partnering the defence industry, the team designed and built a compact and digitalised transmission system that is capable of generating a high power to weight ratio to provide greater mobility for the Hunter AFV. Equipped with a 'drive-by-wire' capability akin to the 'fly-by-wire' system of airplanes, the transmission system also has the ability to control acceleration, braking and steering functions of the vehicle via electrical signals (see Figure 2). This provides greater operational flexibility as it removed the constraint of driving functions residing solely with the driver.

The new suspension system is an upgrade from the Bionix with significantly enhanced reliability, resulting in lowered maintenance cost. This is one example of the team taking the initiative to examine the maintenance cost drivers of the Bionix, and making deliberate efforts to pursue design enhancements in the Hunter AFV to drive down O&S costs.

Figure 2. Driving by wire

To overcome the challenges mentioned, the team collaborated with stakeholders and tapped the collective expertise to venture into unchartered areas and deliver the next-generation AFV that is stronger and smarter.

DEFINING DESIGN PRINCIPLES

Beyond the traditional focus on total life cycle support, interoperability and integration, new design approaches were introduced throughout the development process to tackle key challenges. The new design paradigm (see Figure 3) ensured that the systems were designed for support, data-enabled and cyber-safe, designed to cost, and ready for growth.

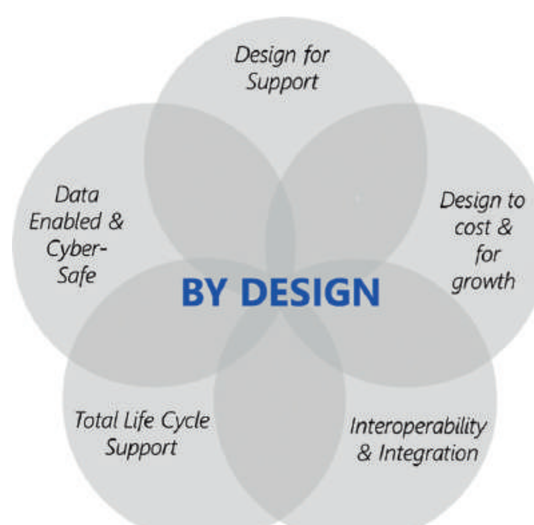


Figure 3. New design paradigm

Design for Support

The team adopted three guiding principles to meet the goal of design for support.

Easy to Operate

The Hunter AFV's integrated combat cockpit (see Figure 4) is the main user interface for the combat systems and designed to enhance collaboration between the crew, with the Army Tactical Engagement and Information System (ARTEMIS) at its core. An apps-based architecture was adopted, with platform, weapon, and Command, Control, Comunications and Computer (C4) apps integrated into the user terminals.

To enhance operational effectiveness and intuitiveness of the apps, a design innovation approach was used. The team interviewed users and conducted rapid prototyping for every app, to sieve out latent user needs and streamline workflows. This included innovative workflows such as Touch-to-Aim (see Figure 5), where the smart algorithm would automatically find the optimal aim point and initiate tracking of the target through a single touch on the screen, reducing target engagement time by about 90%.

Figure 4. Hunter AFV's integrated combat cockpit

Terrain analytics features such as area-of-sight analysis and auto-routing reduce the cognitive load on the operator and enable better decision-making. The fighting experience is further enhanced through the first-of-its-kind video-based Battlefield Management Suite (BMS) (see Figure 6), where the intersection of Command and Control (C2) and sighting system capabilities enables the overlay of tactical C2 information on weapon and commander sights to achieve a leap in situational awareness during combat.

Figure 5. Touch-to-Aim

Figure 6. Video-based BMS

Figure 7. AR for maintenance training

Easy to Train

To minimise training for ARTEMIS, its design was validated through objective usability trials with full-time National Servicemen in the systems integration lab (SIL), where they were given common tasks to execute with no prior exposure to the system. A 100% task completion rate was achieved. With the use of automated processes and smart algorithms such as automated target detection and tracking as well as Touch-to-Aim, gunnery operations can be executed effectively with less reliance on operator proficiency and training. Augmented reality (AR) (see Figure 7) was adopted for maintenance training to enable self-directed learning and to reduce the number of instructors, while virtual reality was used to reduce training for recovery operations by 20%.

Easy to Maintain and Configure

Built-in tests and Diagnostic Expert Systems (DES) (see Figure 8) were incorporated in the vehicle to isolate system faults and provide guided step-by-step troubleshooting instructions to aid the technicians in identifying and replacing the faulty components. The Health and Utilisation Monitoring System (HUMS) was developed to instrument platform, combat systems and training systems. The collected data can be loaded seamlessly into the Vehicle Status Management System (VSMS) for centralised fleet monitoring. The App Store (see Figure 9) and Common Configuration Application enable the automatic proliferation of software patches, configurations and C4 data through an integrated Digital Vehicle Key (DVK), to reduce force preparation timings significantly by about 80%. To improve spares inventory management, reduce procurement lead time and better manage obsolescence, selected vehicle components were specifically designed to be producible by 3D printing.

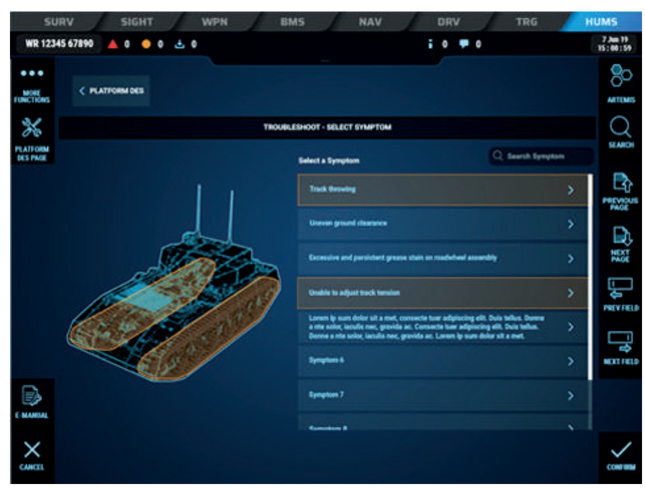


Figure 8. DES

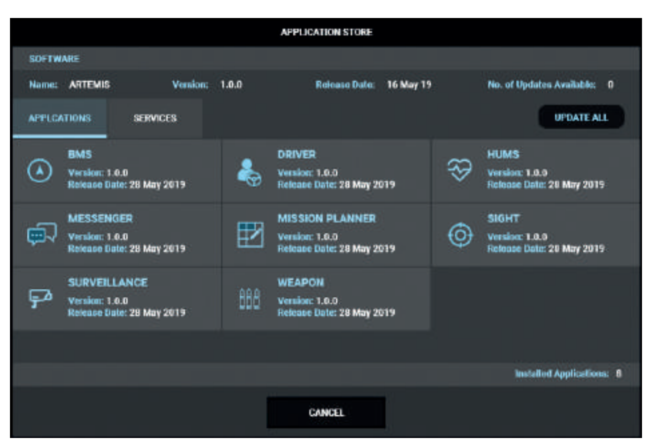


Figure 9. App Store

Data-Enabled by Design

The Hunter AFV's platform, Remote Controlled Weapon Station (RCWS) and C4 systems were instrumented with digital sensors to publish health, utilisation, faults, and event data. These data are logged by the HUMS (see Figure 10), which would notify the user in the event of anomalies on the platform. The crew can rely on the HUMS to identify and troubleshoot faults within seconds, which would otherwise have taken hours in the past. Besides digitalising the Hunter AFV's operations, its pre- and post-mission tasks were digitalised as well, from filling in vehicle logbooks to fault reporting.

To enable the seamless extraction of data, the DVK was conceived to store data automatically and upload them to the VSMS. With more than 1000 parameters being logged, data across the fleet can be aggregated and data analytics tools can be employed to aid fault trend analysis and facilitate condition-based maintenance to drive down operating costs.

Figure 10. HUMS

Cyber-Safe by Design

It is essential to ensure that the Hunter AFV is cyber-safe by design as it is a digitalised platform. The team adopted the 'Protect, Detect, Respond and Recover' framework and designed a multi-layered approach from application to communication security. The past focus on inter-vehicle transmission is now extended to intra-vehicle – the protection of data buses such as the Ethernets and Controller Area Network-Buses in the vehicle. The team built anomaly detection algorithms and integrated a first-of-its-kind cyber-guard module to scan all data traffic, alert the crew of cyber anomalies, and recommend possible response and recovery actions in the event of a cyber-intrusion on the platform.

Design to Cost

The team capped the total cost of ownership of the Hunter AFV fleet to be no more than the current generation's. Despite having more capabilities, the Hunter AFV's maintenance cost is expected to reduce by 40% compared to existing armoured vehicles by considering the supportability needs of the Hunter AFV upfront in the system design. For example, the maintenance demands of the Hunter AFV were reduced by designing for higher equipment reliability (120% increase in guaranteed Mean Time Between Failures), incorporating smart diagnostics (e.g. the HUMS and DES) to troubleshoot faults, and pursuing hardware commonality such as using three identical screens in the cockpit.

Furthermore, high cost drivers in Bionix were identified and efforts were made to drive down the O&S costs of these components in the design of Hunter AFV. Long-cycle maintenance for the platform was stretched to reduce maintenance cost as well. The suspension unit for the Bionix was one of such components identified for enhancement due to prolonged exposure of the piston to the environment. By sealing and enclosing the In-Arm Suspension (ISU) of the Hunter AFV, the reliability of the ISU increased and was validated during the reliability growth demonstration. With all the reliability improvements implemented for the Hunter AFV, the overhaul interval stretched by 30% leading to significant reduction in the O&S costs.

A performance-based logistics approach was adopted in the contracts with Original Equipment Manufacturers (OEM) to lock down the maintenace cost per utilisation rate for sustainable O&S while guaranteeing a certain system availablility, and to incentivise the OEMs to design for reliability and maintainability upfront in order to reduce downstream maintenance cost.

To ensure cost effectiveness, the team separately acquired the various combat systems such as the RCWS and tactical radios through competitive tenders, and managed their complex integration with the platform. This approach enabled the integration of best-of-breed systems and led to significant cost savings in acquisition.

Design for Growth

The team designed and implemented an open and modular vehicle electronic architecture (VEA) based on NATO's Generic Vehicle Architecture (GVA). This architecture minimises systems integration risks and eases the insertion of future technologies to remain relevant in evolving operational environments. This is essential as military platforms are expected to last for 30 years with multiple upgrade cycles. The VEA (see Figure 11) forms

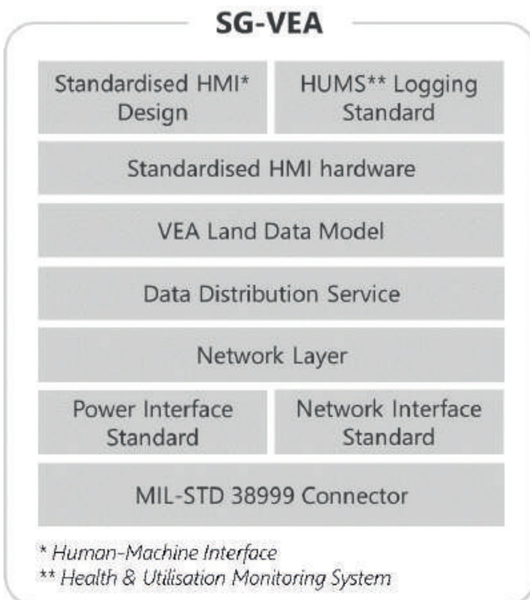


Figure 11. SG-VEA

the backbone of the digitalised Hunter AFV and expedites the integration of new capabilities. Coupled with the model-based systems engineering approach (discussed in the following section), the team delivered the first vehicle ahead of schedule despite making extensive enhancements to the combat systems since the end of the full-scale development phase.

In the VEA, the 'Standardised Human-Machine Interface (HMI) Design' and 'Land Data Model' were adapted from NATO's GVA. On HMI, the team further refined GVA's definitions to focus on HMI design for better user experience. For example, more soft buttons were added on the screen to create a familiar smartphone-like experience for the younger generation and minimise the need for training. Once this was achieved, common HMI was applied across every crew station so that they are unified. On the data model, GVA's data model for common sub-systems such as navigation was used, but was expanded to include features for the unique weapon, sensor and C4 suite.

On system interfaces, the team adopted open and non-proprietary standards. For example, they converged to IP interface for data and USB for peripherals. To take that one step further, the connector was standardised as the MIL-STD 38999 series with the pin-out for Ethernet and USB defined in accordance with GVA standards. In addition, they used HD-SDI as a standard for digital video. To exchange data, they followed the data model and leveraged a data distribution service (akin to Singapore Post) to ensure that messages are routed to the right recipients among the on-board sub-systems. On power infrastrucutre, similar to what was done for Ethernet and USB, both the connectors and pin-out were standardised. Each device must comply with MIL-STD 1275 and be able to operate using 28Vdc.

These were done to enable continuous improvement and technology insertion at lower integration risk, facilitating future readiness. For example, a GVA-compliant sub-system can be replaced with new hardware via plug-and-play. Even non-GVA-compliant hardware can be integrated with minimal effort as long as it conforms to the required power and network interface standard as well as the data model.

Space, weight and power for growth were also catered for in the platform and the RCWS to house new capabilities without requiring significant modifications to the vehicle. The team considered ease of future retrofitting to be carried out on-site instead of moving it to the depot to minimise vehicle downtime and cost. In terms of software growth capabilities, the team worked with the defence industry to establish an App Store concept for ARTEMIS, similar to Google's Play Store or Apple's App Store, which would ease the insertion of new apps and support third-party app deployment on the Hunter AFV.

DESIGN TOOLS AND VERIFICATION

Adopt Model-Based Systems Engineering

The Hunter AFV packs many capabilities in a small form factor. As systems integration for land platforms has become increasingly complicated over the years, a new approach is needed to balance the performance of many sub-systems and achieve an optimal overall system performance. To do this well, the team spearheaded model-based systems engineering (MBSE) within DSTA and developed in-house 3D Computer Aided Design (CAD) modelling capabilities (see Figure 12) to facilitate the integration of capabilities across multiple OEMs. This also provided the means for the team to dissect the integration complexity, and enabled stakeholders to better visualise capabilities, optimise system performance and importantly to iterate the design in a virtual world to get the design right prior to production so that the team could minimise downstream modifications, which would be costly and time consuming.

The Hunter AFV is the first Army programme where 3D CAD models were extensively used in the design process. Previously, mock-ups and prototypes had to be built, and multiple iterations with users were required before arriving at the final design, with each design iteration typically months apart. Now, the models provide greater fidelity and clarity for

Figure 12. 3D CAD Modeling for systems engineering

stakeholders visualising the detailed design, enabling them to make informed decisions during technical reviews and helping the team to get the design right from the start. This reduced integration time and downstream integration risks. The maintainability of the systems can also be assessed by visually showing the technicians the accessibility of certain areas, such that the placement of the various equipment can be studied and optimised upfront.

The team has since expanded the use of 3D CAD models to visualise future capabilities in a cost-effective manner without the need to build prototypes.

Leverage Design Innovation Methodology

Design Innovation was adopted in the design of the Hunter AFV, which involved discovering the user's latent needs and operating environment, defining the problem statements, developing operating concepts and ideas, and delivering prototypes for feedback and iteration. User interviews were extensively conducted to better understand their needs, while the SIL and MBSE were used to facilitate rapid prototyping sessions with them to obtain feedback. This resulted in the design of novel user-centric features such as the integrated combat cockpit, 'Touch-to-Aim' and the use of AR to overlay C2 data on the video of the sighting systems.

Define Progressive Systems Verification Milestones

Owing to the highly interconnected nature of the various sub-systems in the Hunter AFV, the team developed a set of progressive integration milestones (see Figure 13) during engineering development, as a structured approach to manage integration testing.

In Integration Review (IR) #1, the preliminary Interface Requirement Document (IRD), Interface Design Specification (IDS) and Interface Control Document (ICD) are generated. In IR #2, the final IRD, IDS and ICD are required to proceed with the preliminary interface test (PIT). The team adopted a progressive testing approach for the subsequent major milestones such as the software acceptance test and systems integration lab test (SILT). During PIT, the focus would be on the message level while during the software acceptance test, the focus is on functionalities. During SILT, the focus is on scenarios and workflows. The IRs after PIT and SILT would be used to address the issues arising after each test.

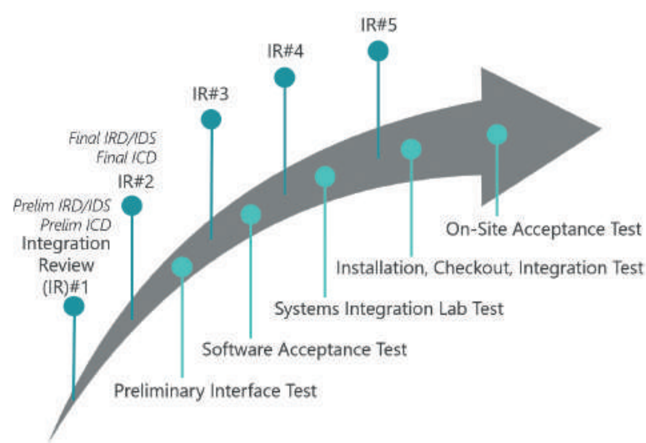


Figure 13. Progressive systems integration milestones

Establish Systems Integration Labs

To integrate the various sub-systems well, the team set up a SIL for more efficient and cost-effective testing. Traditionally, multiple field trials were conducted to integrate and test systems, which were costly and time-consuming. A lab makes it easier to identify and troubleshoot faults, especially for complex systems.

Dedicated SILs (see Figure 14) were established by the team to test and validate the system progressively at the component and system level before installation on the platform. This

Figure 14. Hunter AFV's SILs

allowed integration issues to be identified and rectified as early as possible and greatly reduced the time and resources needed for testing on the platform. The SIL also allowed users to experiment with workflows and provide their feedback on the system design.

Automation tools (e.g. MicroFocus' Unified Functional Testing, Microsoft's Perfmon and Jperf) were used to expedite the testing process by 70% and enable less engineering resources to be employed. This significantly reduced the testing time and facilitated regression testing during continuous improvement of the system. In the O&S phase, the SIL will continue to be used for testing of subsequent software releases to shorten the time-to-field new capabilities, which will be a key enabler to staying agile in response to the rapidly changing technology landscape.

EMBRACE 4th INDUSTRIAL REVOLUTION TECHNOLOGIES

The Hunter AFV is the first Army platform to include 3D-printed metal parts (see Figure 15) in its production build, via the establishment of 3D models and a digital part library. DSTA

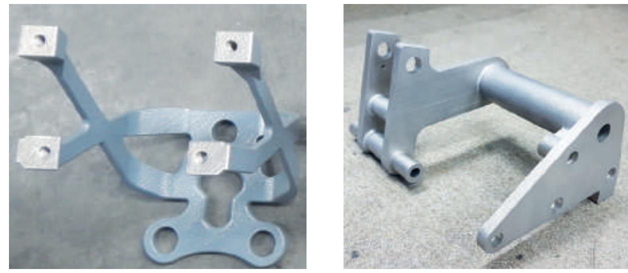


Figure 15. 3D-printed metallic parts:
MFCH bracket (left), ramp lock linkage (right)

collaborated with the Army, the defence industry, and the Singapore University of Technology and Design to implement additive manufacturing (3D printing) for certain production parts. The team leveraged this opportunity to optimise the design of selected parts, namely the multi-functional control handle (MFCH) bracket and ramp lock linkage, which reduced assembly complexity by consolidating multiple parts into a single component and facilitated corrective maintenance. The initiative to introduce additive manufacturing as part of Hunter AFV's production also aimed to chart out the implementation process of 3D printing for future land systems.

As part of the drive for consistent quality, the team partnered the defence industry to incorporate automation into the production line (see Figure 16). A robotic welding system was introduced into the production line to automate the fabrication of hull modules. Apart from achieving consistency in production quality and minimising workmanship issues, production automation also allows the programme to reduce its reliance on manual labour, and keeps the production system versatile for future projects.

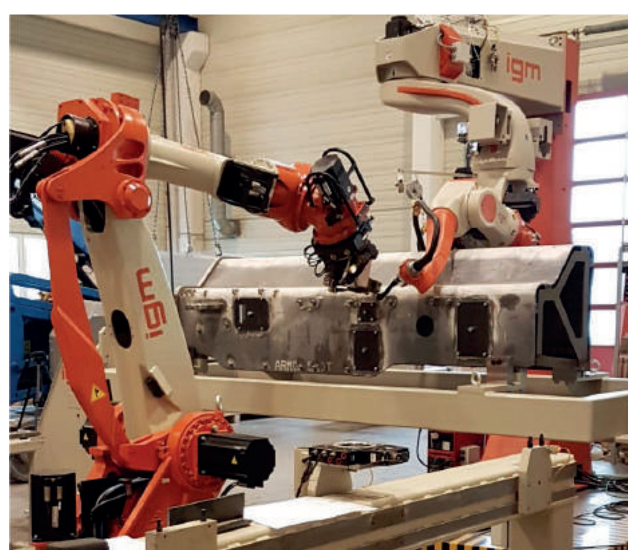


Figure 16. Robotic automation in hull fabrication

As discussed earlier, the team leveraged AR for maintenance training. This enables self-directed learning by bringing the expert to the trainee – all trainees have access to the master trainer – and allows for a larger student-instructor ratio. The trainees can also receive immediate feedback on their actions which are recorded for further review. During operations, the team exploited AR to augment the videos of sighting systems with critical battlefield information such as blue and red forces for rapid situational awareness. Commanders no longer have to correlate information from multiple screens as they now have one integrated view for a new fighting experience.

CONCLUSION

The traditional, tried and tested systems integration methodology and processes employ a total life cycle management approach to achieve optimal integrated performance within the programme schedule and budget. These provide the foundation for engineering and delivering defence capabilities within the typical 25 to 30 year life cyle of military platforms.

A more agile approach based on new design concepts such as design for support, design for growth and design to cost was adopted in the development of the Hunter AFV to augment the systems integration methodology, to address the perennial challenges of decreasing manpower and rising operational costs, and to ease the incorporation of future technology. Beyond the design process, the team also embraced 4th Industrial Revolution technologies in partnership with the defence industry to improve production quality, reduce spares inventory and achieve more effective maintenance training. As platforms become more connected and integration complexity continues to increase, the engineering initiatives employed by the Hunter AFV will be the new norm in the design and development of future generations of fighting vehicles.

BIOGRAPHY

PEH Boon Pin William is a Programme Director (Land Systems). He is responsible for leading a multi-disciplinary team to design and develop the Hunter Armoured Fighting Vehicle (AFV). His experience includes combat systems integration and development of Command and Control (C2) systems for the Singapore Army's AFVs. William graduated with a Master of Engineering (Electrical and Electronic Engineering) from Imperial College London in 2010.

WONG Ying Tat is a Senior Programme Manager (Land Systems). He is currently responsible for the combat systems integration for the Hunter AFV. He was previously involved in the integration of the 30mm Remote Controlled Weapon Station for the Hunter AFV. His past work includes the mid-life upgrade of the Landing Ship Tank and the acquisition of naval guns for various naval platforms. Ying Tat graduated with a Bachelor of Engineering (Mechanical and Production) from Nanyang Technological University (NTU) in 2004.

WONG Sai Hong Caleb is a Senior Programme Manager (Land Systems). He leads the platform development efforts for the Hunter AFV and its support variants. Prior to this, Caleb was part of a programme team that led the refurbishment and subsequent upgrading of the Leopard 2 Singapore Main Battle Tanks for the Singapore Army. Caleb graduated with a Bachelor of Engineering (Mechanical and Production) from NTU in 2004.

NG Kin Loong Bryan is a Senior Programme Manager (Land Systems). He leads the development of the Battlefield Management System for the Hunter AFV, to deliver networked warfighting capabilities for Army's tactical echelons. Bryan graduated with a Master of Engineering (Electrical and Electronic Engineering) from Imperial College London in 2013.

ACHIEVING ENVIRONMENTAL SUSTAINABILITY FOR MINDEF AND THE SAF

LEE Eng Hua, TAN Tze Leng, KUEK Choon Han, CHUNG Yee Peng Jolene

ABSTRACT

Singapore has seen bouts of high temperatures and intense rainfalls that led to flash floods. The city-state's vulnerabilities to the impact of climate change are real. There is an urgency to sharpen the action plan to build a climate-resilient nation and to recognise that everyone needs to contribute towards a sustainable future. Delivering green and sustainable buildings is one of the most effective ways to reduce Singapore's overall carbon footprint, as the built environment is the second largest carbon emitter in Singapore. DSTA's strategy in delivering sustainable buildings has been to prioritise design strategies and adopt best-in-class technologies that are cost effective and impactful in reducing operational carbon emissions, while still meeting the SAF's needs. Recently, DSTA has also started to focus on carbon neutrality in the built environment, including the reduction of embodied carbon emissions. This article outlines how DSTA contributes to Singapore's sustainable future by being an early adopter of innovative green technology, delivering sustainable camps and bases, implementing initiatives in a broad-based manner, and promulgating good practices through projects and developments where feasible.

Keywords: environmental sustainability, carbon emission, water conservation, waste reduction, green buildings

INTRODUCTION

Climate change is a global phenomenon caused by increasing levels of greenhouse gases (GHG) emissions into the earth's atmosphere. As an island city-state, Singapore is particularly vulnerable to the impact of climate change and there is strong recognition that everyone needs to contribute earnestly towards a sustainable future. Singapore has committed to take steps that combat climate change. The greening of buildings is one of the key ways to reduce Singapore's overall carbon footprint, as the built environment sector is the second largest contributor of the projected business-as-usual GHG emissions in 2020[1]. In particular, building construction and operations have both direct and indirect impact on the environment in terms of energy use, atmospheric emissions, raw materials usage, waste generation, and water usage.

DSTA is cognizant of the importance of its role in Singapore's sustainable future. In partnership with MINDEF and the SAF, DSTA has put in place a suite of cost-effective measures over the years to build low-carbon and climate-resilient infrastructure which minimises environmental impact, while ensuring that the SAF's operational needs are met.

SUSTAINABLE CAMPS AND BASES DEVELOPMENT

DSTA aims to develop camps and bases that are sustainable and benchmarked against the Singapore Building and Construction Authority's (BCA) Green Mark Scheme wherever appropriate, in the context of defence infrastructure developments. This is especially so for developments that are conventional in nature, like office-type buildings. Besides reducing carbon emissions, the Green Mark Scheme's benchmarks on Indoor Environmental Quality, Wellness and Health, Water Conservation, Waste Reduction, and Sustainable Construction Materials and Products are adopted whenever feasible.

Figure 1. Examples of MINDEF and the SAF buildings which attained Green Mark certification

Delivering Green Mark Certified Buildings

Since 2011, DSTA has delivered 19 projects under the BCA's Green Mark Scheme. In 2017, DSTA attained the BCA Green Mark Champion award, marking a milestone in the journey of sustainability. Moving forward, DSTA is looking into building more Super Low Energy Facilities and where possible, Net Zero Energy and Net Positive Energy Buildings (PEB) with cost-effective green solutions for MINDEF and the SAF (see Figure 1).

The next section illustrates the key features of the first Net Positive Energy Aircraft hangar in Singapore.

Positive Energy Building at Changi Air Base

The maintenance hangar constructed in Changi Air Base is the SAF's first PEB. Photovoltaic (PV) panels on the roof are estimated to generate at least 30% more energy than what the hangar consumes annually. The estimated yearly energy savings through more energy efficient building design is about 0.43 GWh, and PV energy yield is close to 1.23 GWh. In total, this is equivalent to powering about 370 4-room HDB apartments a year. Rainwater is also harvested and recycled for non-potable water usage. Through the upcycling of construction waste, the hangar is also constructed with green concrete[2] consisting of 10% recycled concrete aggregates and 8% washed copper slag. This reduces the overall utilisation of natural sand.

In the construction of the widest hangar in the Republic of Singapore Air Force (RSAF) thus far, a safer and more efficient construction method of using hydraulic jacks to erect the large-span roof was adopted, to improve construction work productivity and quality with minimal wastage of resources. Technologies such as Building Information Modelling and virtual reality were used to obtain more accurate user feedback on workflows and operations, which aided in design iteration and development. This also minimised rework and wastage, and improved the overall outcome for users of the facility (see Figure 2).

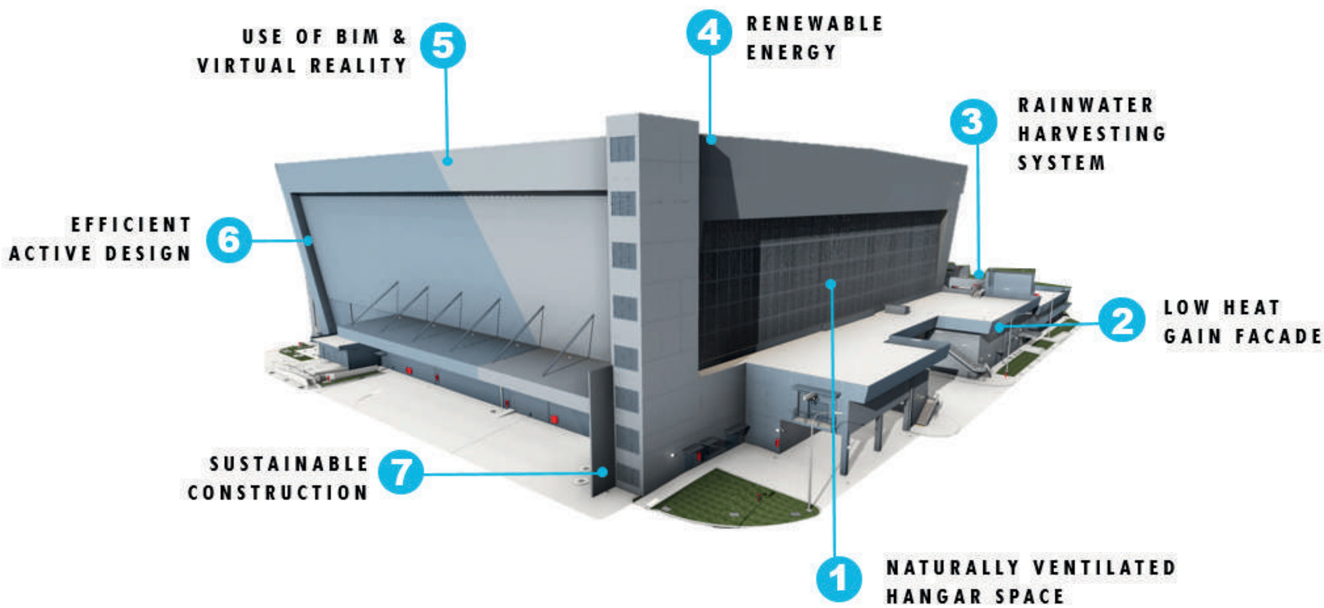


Figure 2. Design features of maintenance hangar in Changi Air Base

BROAD-BASED IMPLEMENTATION OF IMPACTFUL SOLUTIONS

DSTA partners MINDEF and the SAF to deploy impactful green initiatives and best practices in a broad-based manner, so that the benefits are scaled up consistently and extensively across all camps and bases, for both existing and new developments.

Demand Aggregated Contract for LED Lighting

As lighting systems are major contributors to the energy consumption of the SAF's camps and bases, effort was made to deploy LED for all lighting systems. For new buildings, this requirement is incorporated into the design and contractual specifications upfront. For existing buildings, a demand aggregated period contract was established to ensure competitive pricing for the replacement of all major fluorescent light fittings to LED types. The replacement of fluorescent lights involved a one-to-one replacement of lights with minor electrical works required, without altering the main lighting circuit. This results in expeditious and cost-effective implementation in existing facilities.

Guaranteed Performance Contracting with Modifications for Chiller Replacements

Chilled water plants constitute a big percentage of large air-conditioned buildings' energy consumption. Their inherent efficiency is thus important in managing and reducing energy usage. It is also critical that the energy efficiency system designed upfront is adhered to throughout the entire life cycle. An area of focus is to rectify the shortcomings of conventional maintenance contracts, which typically do not address the degrading operating efficiencies of chiller plants. In addition, the designers and implementers of the systems tend to be more concerned about upfront efficiency and capital outlay, and neglect subsequent maintenance outcomes. These often cumulates in a system that may deteriorate prematurely and accelerate the increase of operational and maintenance costs as the system ages.

To align all parties to a common interest and outcome, a single contract encompassing design to maintenance was established for a chiller plant modernisation project at the Defence Technology Tower B (DTTB). The contract is governed by consistent performance indicators throughout the lifespan of the system, including the requirement for an efficiency performance guarantee. The efficiency guarantee was translated into expected savings and these savings were taken into consideration as part of the evaluation criteria, to promote a balanced design approach and ensure competitive pricing. This unified contract imposed a cost ceiling for the life-long operational and maintenance costs of a chiller plant. The total cost of ownership is determined upfront and guaranteed for the duration of the contract. This amalgamation of requirements also spurred competitive pricing among tenderers and delivered better overall value for MINDEF and the SAF. Following the success of DTTB, this effort will be promulgated to future air-conditioning modernisation efforts whenever possible.

Applying the '3Rs' for Water Conservation

Singapore has Four National Taps[3] to ensure a sustainable and reliable water supply for the nation. In the same vein, best practices were put in place to save water. A '3Rs' approach – Reduce, Reuse and Recycle – was adopted to reduce the reliance on and demand of potable water from the Singapore Public Utilities Board (PUB). To reduce water usage, water fittings with the 3-tick ratings under the Water Efficiency Labelling and Standard Scheme (WELS)[4] are used for the toilets and pantries across all projects and developments in MINDEF and the SAF. Where feasible and when there is a NEWater source near developments, NEWater will be used for non-potable usage such as toilet flushing, cooling tower consumption for the air-conditioning system and irrigation, as well as at water points for the washing of boots by soldiers. To reuse water, the air-conditioning systems' condensate water is collected for cooling tower top-up, and rainwater is collected for toilet flushing and irrigation. To facilitate water recycling, the vehicular and aircraft washing facilities in MINDEF and the SAF are designed and equipped with a water recycling system that cycles used water through a filtration system for reuse. These reduce the amount of potable water used.

Use of Sustainable Green Certified Products

In addition to the main building materials such as reinforced concrete, DSTA has also standardised the use of main building finishing products (e.g. drywalls, partition boards, solid timber doors, mineral ceiling boards and carpet tiles) certified under the Singapore Green Labelling Scheme and Singapore Green Building Product. These products and equipment are independently certified through a methodology with criteria such as energy, water and resource efficiency as well as environmental protection. They are also benchmarked against similar products in their categories.

EARLY TESTING AND ADOPTION OF INNOVATIVE GREEN TECHNOLOGY

In the push to be more sustainable in the built environments for MINDEF and the SAF, a key focus is to test innovative green technologies and strategies quickly. Whenever there are opportunities, pilot testing of emerging products, solutions, and approaches will be performed with the intent for small-scale trials and subsequent scaling up.

Immersion Cooling for Data Centres

The new information economy triggered by the 4th Industrial Revolution will increase the demand for higher power density servers. Hence, more efficient cooling solutions are required. Immersion cooling technology (see Figure 3) offers the potential for a leap in efficiency in the cooling of data centers, where high density servers are fully immersed in a dielectric fluid. The heat generated by the servers is transferred directly to the dielectric fluid and removed through heat exchangers without the use of mechanical chillers or refrigerants. A study conducted with Nanyang Technological University (NTU) showed that immersion cooling could outperform air-cooled solutions by three times or more, without affecting performance. As the team awaits the maturity of local IT vendor support for immersed servers, immersion cooling remains a viable option for high density cooling of data centres as demand continues to grow.

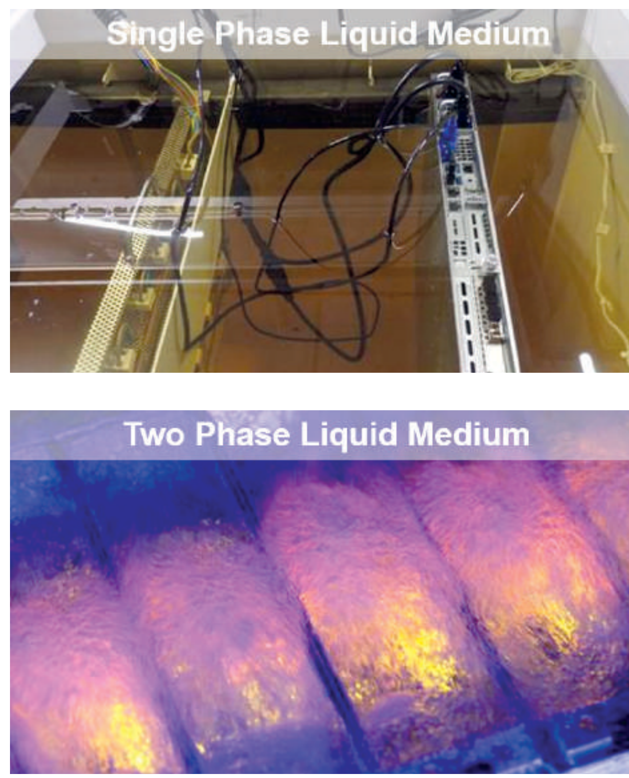


Figure 3. The immersion cooling study compares the performances of single phase and two phase liquid mediums against a conventional air-cooled design

Machine Learning for Chiller Optimisation

With more than half of a building's electrical energy consumed by the cooling plant, finding optimisation opportunities to improve cooling efficiency will unlock huge potential energy savings. The complexity of various cooling equipment coupled with the dynamic behavioural characteristics of the building means that traditional cooling optimisation strategies that rely on static set points will not be optimal. The team used over 20 machine learning models to model the cooling plant. The cooling load profile was forecast while key parameters were dynamically optimised and updated every five minutes, resulting in a 5% improvement in energy efficiency to an already well-performing Green Mark Platinum certified chiller system. Following this pilot trial, there are plans to conduct further fine-tuning of the algorithms and site calibrations, before deploying the solution on a larger scale.

Mass Engineered Timber[5] for Accommodation Building

Mass Engineered Timber (MET) was used as a material to build an accommodation building in a SAF Camp, the first for an accommodation building in Singapore (see Figure 4). Besides lowering the carbon footprint and net carbon emissions as compared to steel or concrete constructions, MET is also a renewable material harvested from sustainable managed forests where new trees are planted to replace harvested trees. This prevents the depletion of mature trees, thereby limiting the emission of carbon back into the atmosphere[6]. In addition, a boost in construction productivity of at least 80% with 35% less manpower was achieved for this accommodation facility. As this material has not been widely adopted in the industry, factors from material sourcing to facilities maintenance were considered for a holistic solution. This will ensure operational sustainability is achieved through cost-effective strategies. This MET implementation provided DSTA with first-hand knowledge in terms of installation, and the opportunity to examine the potential challenges during the operational stage, before potentially scaling up its use.

Building Integrated Photovoltaic System in Changi Naval Base

During the early 2000s, DSTA implemented a Building Integrated Photovoltaic (BIPV) trial where 72 solar panels were integrated into building elements such as glass canopy panels (see Figure 5) to harness solar power while allowing for daylight penetration. At that time, the solar power generated was able to power approximately 100 downlights. The BIPV continues to draw attention as it has the potential to push the envelope of renewal energy generation in land-scarce Singapore, and is continually monitored for larger scale implementation when the opportunity arises.

Pond Water for Cooling and Firefighting in the Underground Ammunition Facility

The development of the Underground Ammunition Facility (UAF) encompassed massive engineering studies in rock caverns and tunnelling. Along with the development in rock, the site presents an opportunity to channel nearby pond water

Figure 4. Use of MET for accommodation building in Kranji Camp

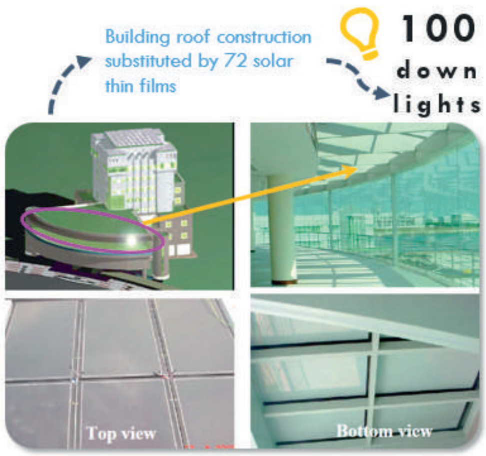


Figure 5. Use of BIPV as a source of renewable energy in Changi Naval Base

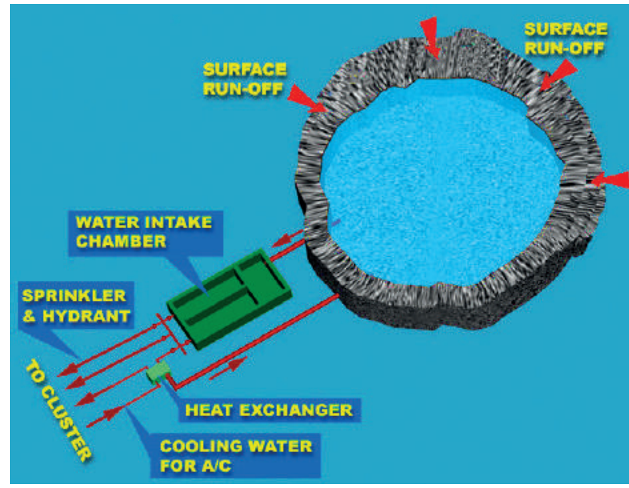


Figure 6. Use of pond water for cooling and firefighting purposes

to the chilled water supply network used to distribute cooled air into the storage facility (see Figure 6). The water from the pond is also used for an active firefighting system in the UAF. This enables the recycling of water, minimising the impact to the environment, and enhancing system survivability due to the readily available source of on-premises water supply.

Indirect Sea Water Cooling and Thermal Ice Storage System

In the early 2000s, several economically efficient and innovative measures were deployed in Changi Naval Base (see Figure 7). Leveraging the close proximity to the sea, seawater was tapped for a water-cooled chiller system. This being a nascent application of indirect seawater cooling technology, engineering studies (e.g. corrosion and marine growth control assessment, and district cooling system performance) were conducted. Simulation studies on the district cooling system and thermal storage were also performed to evaluate the system performance and effectiveness. This use of seawater channelled through the seawater intake chamber for heat exchange at the cooling plant (before distribution to the base network through a separate fresh water network) allows for water conservation of up to about 140 Olympic size pools of water per year. With seawater being an abundant resource, this has enabled the cooling of the base to achieve an increased level of resiliency.

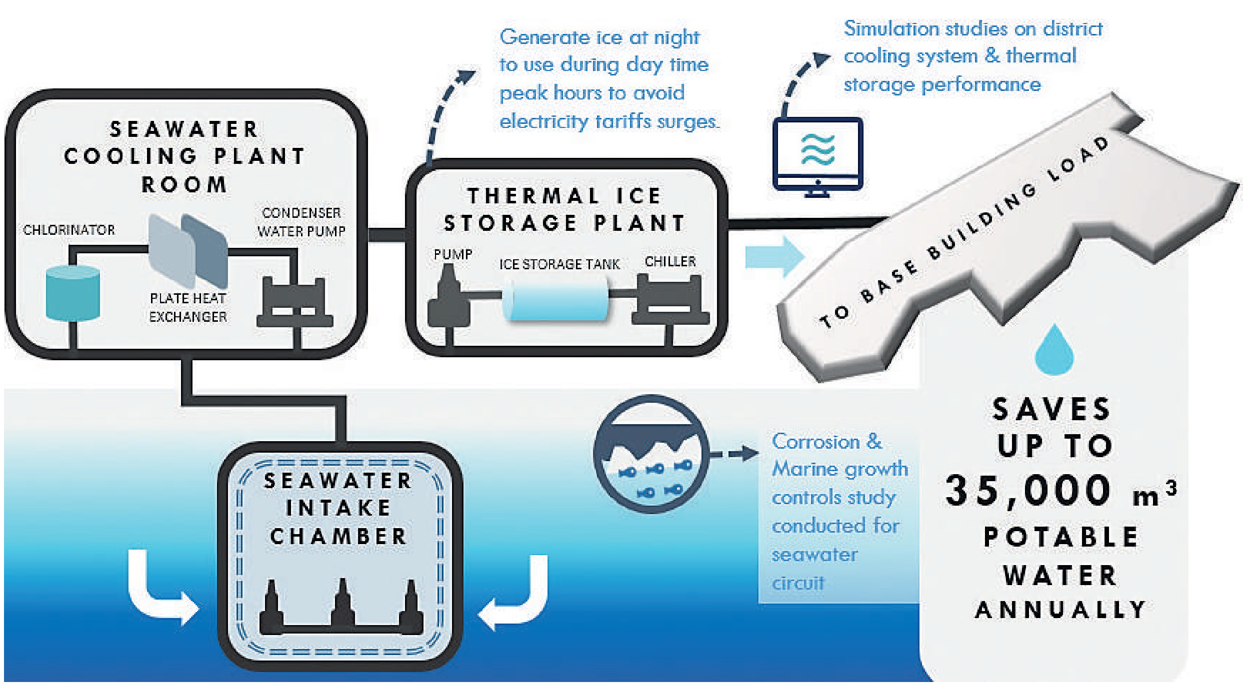


Figure 7. Indirect seawater cooling and thermal ice storage system used in Changi Naval Base

GOOD PRACTICES IN GREEN BUILDING DESIGN

Underpinning the broader strategies and push for innovation is a foundation of good practices in green building design, which is continually updated and deployed to all developments in MINDEF and the SAF. The sustainable building design approach aims to support an increased commitment to environmental stewardship and conservation. This is done by achieving an optimal balance of costs from the total life cycle perspective, environmental benefits, and improved wellness of users while meeting the intended function of the facility. The green building solutions in mitigating climate change encompasses suites of strategies deployed to target three areas – Energy, Water, and Waste (see Figure 8).

Energy

A three-step strategy was adopted to drive energy conservation, as shown in Figure 9.

The passive design strategy is the first step towards reducing the energy demand of a building as it has the largest impact on building energy consumption in the long run. Initial site planning establishes the orientation and massing which affect the usage of and set the parameters for passive design strategies. The suite of passive design strategies adopted is summarised in Table 1.

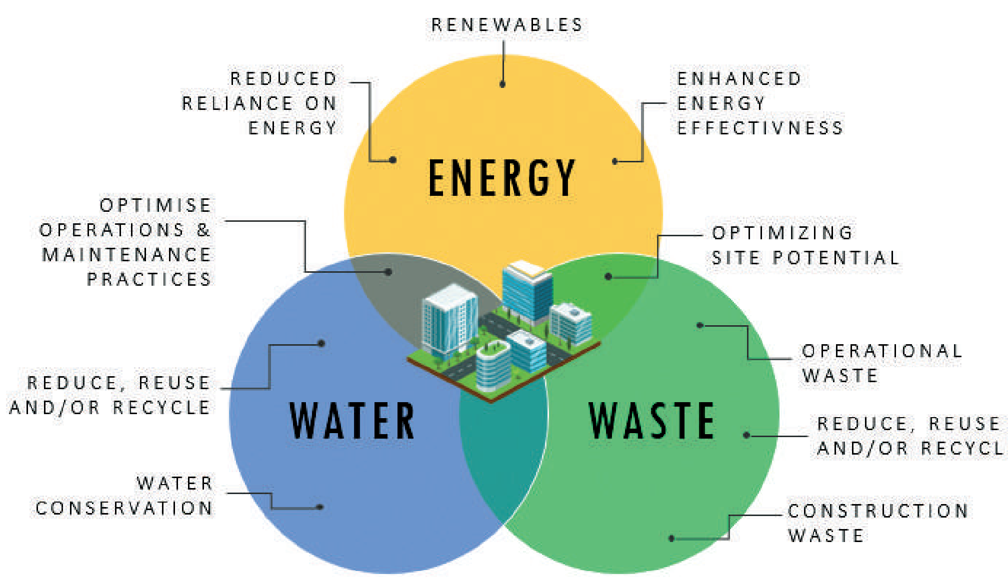


Figure 8. Illustration of the design approach for Green Building Design

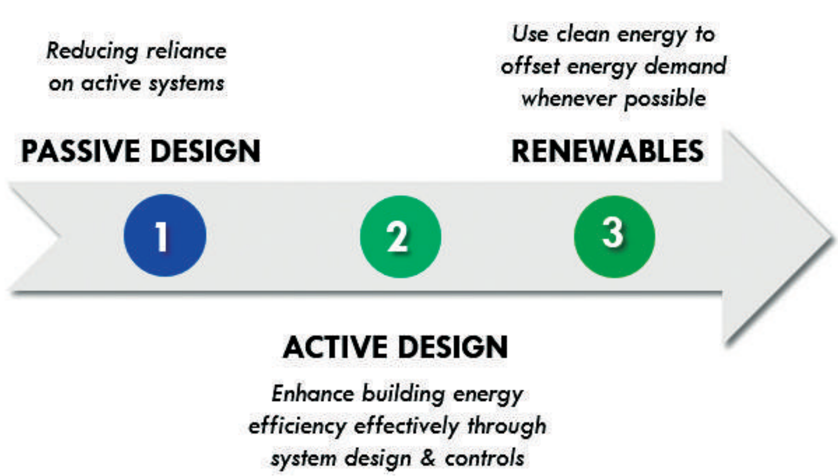


Figure 9. Illustration of three-step approach to energy conservation

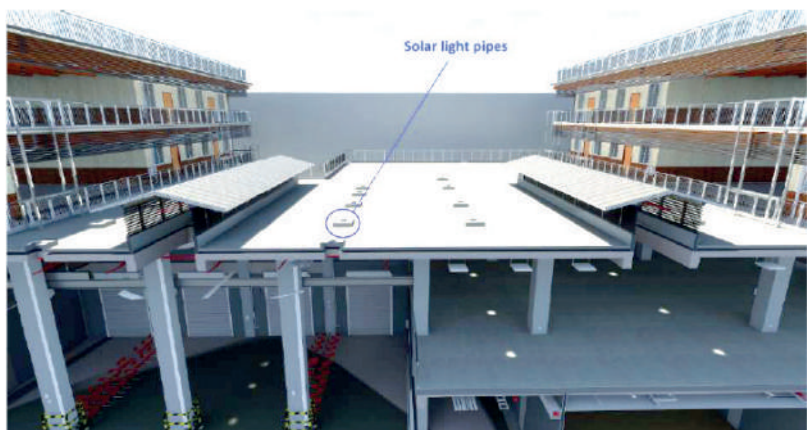
Passive Design Strategies	Impact	Applications
Natural ventilation	Maximising the amount of space to be naturally ventilated helps to reduce energy demand.	• Use of wind turbine ventilators in Paya Lebar Aircraft Hangar to draw warm air out of the hangar space. • Use of Computational Fluid Dynamics to optimise the cross-ventilation performance of the accomodation block in Kranji Camp.  *Location: Kranji Camp Building*
Daylighting	Good daylighting design helps to improve the well-being of occupants and reduces reliance on artificial lighting.	• Use of solar light pipes to channel daylight effectively into the area beneath the canopy of Kranji Camp Building.  *Location: Kranji Camp Building* • Use of solar-powered Global Positioning System motor as a sunlight harvesting system, to track the sun path and harvest natural light into the hangar space in Paya Lebar Air Base. • Use of translucent material for the maintenance hangar door, to allow daylight to penetrate the maintenance space and reduce reliance on artificial lighting in hangars. This has been used in Paya Lebar Air Base and Changi Air Base.
Landscape design	Greeneries of hardy species are used due to their adaptability to climate fluctuations throughout the year. Robust landscape management plan supported by auto-irrigation design is adopted to combat the threats to green plots due to dry spells.	

Table 1. Passive design strategies and their applications

Active design involves the pursuit and application of technology in system design. To reduce operational carbon emissions associated with the energy used to operate the building, DSTA seeks to improve system efficiencies by design, careful selection, and control of equipment for optimum performance (see Table 2 for examples).

Active Design Strategies	Impact	Applications
Air-conditioning and mechanical ventilation design	Employing the right design upfront ensures that the systems perform at the most energy efficient manner throughout the life span, to reduce the carbon footprint.	• DSTA benchmarks its design targets against the industry's top 25th percentile and seeks to improve the chiller system design and controls continually. An example is a chiller plant operating at an average of 0.54kW/RT in Depot Road Camp.  *Location: Depot Road Camp* • An automatic tube cleaning system is used to improve heat exchange properties within chilled water network and also to prolong the life span of the water pipes. • Electronically Commutated DC brushless motors for fan coil units and air handling units (AHU) are largely used to allow the precise modulation of motor speed corresponding to the demand required. This optimises the system performance at varying and low occupancy loads. • Non-conventional air distribution systems are used for better efficiency. An example is the DSTA office space which uses an active chilled beam system to deliver treated cool air via more compact ceiling space to building occupants, resulting in 60% more efficiency compared to the conventional AHU.
Lighting design	As a complement to natural daylighting, energy efficient artificial lighting systems are always designed upfront to reduce the operational energy demand.	• As many of the SAF's facilities are naturally or mechanically ventilated, majority of the energy used is from the lighting system. • Extensive use of LED lighting that is controlled with photocell sensors and motion sensors to optimise daylighting and reduce operational energy consumption across MINDEF and the SAF.
Smart energy management	In order to utilise the building energy more efficiently, energy management systems are installed to help the user to understand the energy consumption behaviours and implement techniques for enhanced conservation efforts.	• Energy monitoring with demand controls, maintenance planning, and defect and incident reporting is enabled through the IT-enabled Facilities Management platform to ensure building system performance sustainment with preventive maintenance practices.  • The system also alerts the maintenance crew through notifications to rectify anomalies in consumption, to help in optimising the operation and maintenance practices for the building.
Renewable energy	The use of clean energy helps to offset the energy demand of the building from the national grid.	• DSTA is in the process of deploying PV panels nationwide, across MINDEF and SAF camps. The harnessed solar power will be used to offset the operational energy demands in new and existing facilities. • An example is the maintenance hangar in Changi Air Base, which maximises the roof area for PV panels' installation and any additional energy harvested will be used to supplement the air base energy demand.

Table 2. Active design strategies and their applications

Water

The ‘3Rs’ approach is used in water conservation. Besides installing efficient water fittings for the toilets and pantries, rainwater is harvested in some areas for non-potable uses like toilet flushing, general washing, or auto-irrigation for landscape management. For water intensive activities like vehicle washing, on-site water recycling and filtering systems are designed to reduce potable water consumption and greywater discharge (see Figure 10).

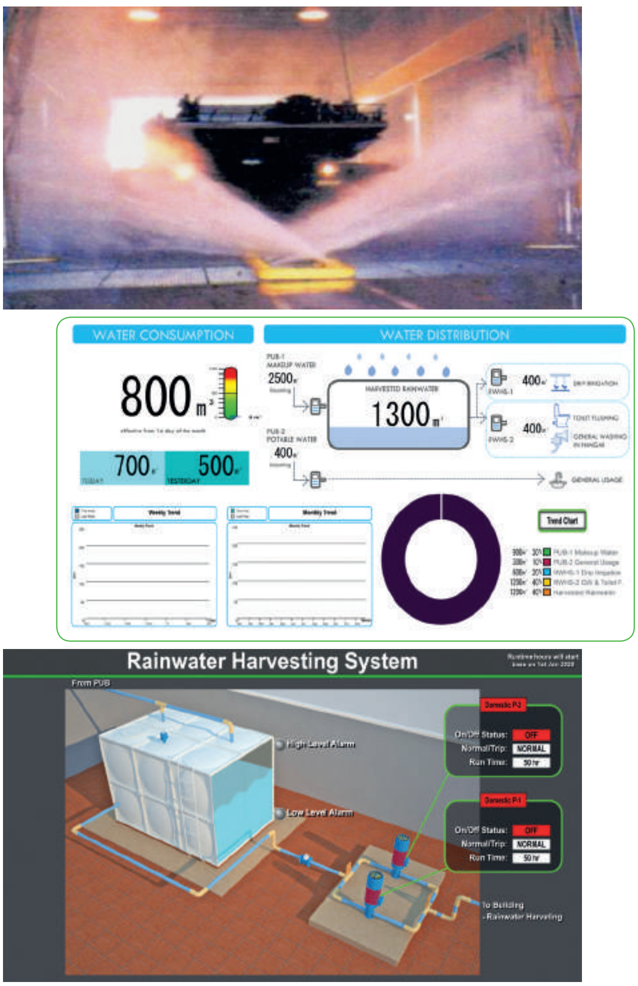


Figure 10. Automatic vehicle washing using recycled water in Kranji Camp and use of rainwater harvesting system for auto drip-irrigation, general washing, and toilet flushing in Changi Air Base

Waste

The waste generated in the built environment can be broadly categorised as construction and operational waste.

Construction Waste

The main contributors to embodied carbon in the built industry are building materials and elements (e.g. concrete, steel, and glass primarily from the production and manufacturing process). Hence, DSTA strives to adopt sustainable construction processes to reduce on-site wastage, and for better material utilisation by using materials that are sustainable, taking into account the life cycle costs and technical implications. This can be effectively achieved through the careful selection of construction materials; accounting for the embodied carbon content in the production of the materials; planning of construction methodology to reduce wastage, improve construction quality and on-site work productivity (see Table 3).

Materials		Embodied Carbon ($kgCO_2/kg$)
Cement		1.0
Concrete *(16/20MPa)*		0.1
Steel		2.7
Glass		0.9
MET *(including carbon storage)*		-1.0 *(1.5 $kgCO_2/kg$ constitutes carbon storage of timber)*
Green Concrete *(16/20MPa)*	40% Fly Ash	0.08
	50% Blast Furnace Slag	0.06

Table 3. Summary of embodied carbon of construction materials (Hammond & Jones, 2011)

The selection of sustainable materials and products has a large impact on upfront embodied carbon emissions of the building cycle. Sustainable materials (e.g. MET and green concrete) and construction processes (e.g. Prefabricated Prefinished Volumetric Construction and off-site prefabricated plants for on-site installation) are increasingly employed to reduce potential wastage and embodied carbon emissions during construction.

Operational Waste

The day-to-day operations in the building generates operational waste, which can be segregated into organic and non-organic waste. In order to cultivate a green culture by design, recycling bins are deployed strategically to help reduce downstream efforts in waste segregation, which can be laborious or ineffective due to contamination. For organic waste, DSTA has tested an on-site food digester system to process food waste into sludge and non-potable water (see Figure 11). In partnership with MINDEF and the SAF, there was also an active

Figure 11. On-site food waste digester in the DSTA Integrated Complex to generate non-potable water from organic waste

effort to eliminate food waste through participation in an off-site food waste treatment administered by the Singapore National Environmental Agency[7]. This initiative reduced operational waste through the delivery of food waste from the food halls of a few major camps to the off-site co-digestion facility, for further processing into biogas for energy recovery.

CONCLUSION

DSTA's sustainable development for camps and bases supports an increased commitment to environmental stewardship and conservation. This is achieved through an optimal balance of costs from the total life cycle perspective, while meeting the intended operational functions of the building infrastructure and facilities for MINDEF and the SAF. DSTA will continue to stay vigilant and watch for technologies, new solutions, and innovations to reduce whole-life carbon emissions in the built environments of MINDEF and the SAF.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the Project Management Teams who delivered the cited projects.

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ENDNOTES

1 The National Climate Change Secretariat projected that business-as-usual emissions from 2005 will reach 77.2 million tonnes in 2020. The building and construction sector contributes to 13.8% of total projected emissions.

2 Green Concrete is defined as concrete which uses waste material as at least one of its components and does not lead to environmental destruction or has high performance and life cycle sustainability.

3 The Four National Taps is branded by the Public Utilities Board, Singapore's National Water Agency. In integrating the water system and maximising efficiency of each of the four national taps, Singapore has overcome its lack of natural water resources to meet the needs of a growing nation. The Four National Taps include water supply from our local catchment areas, imported water from our geographical neighbours, NEWater source from our NEWater plant and desalinated water sources.

4 The Water Efficiency Labelling and Standard Scheme is a scheme developed by PUB to rate the efficiency level of a sanitary fitting.

5 Highly renewable engineered wood with improved structural integrity that can be prefabricated off-site, improving productivity and construction time. Timber products and other biomaterials like bamboo and hemp also presents the possibilities of carbon sequestration, absorbing carbon dioxide from the atmosphere.

6 Adopted from the Design for Manufacturing and Assembly Mass Engineered Timber v1.0, September 2018, BCA.

7 Moving forward, the National Environmental Agency is exploring to deploy district level off-site food waste treatment facilities in the near future, on top of the upcoming Tuas co-digestion facility that will be operational by 2024.

BIOGRAPHY

LEE Eng Hua is Director Building and Infrastructure. He leads the Programme Centre in the planning and development of defence infrastructure for MINDEF and the SAF. He graduated with a Master of Technology (Knowledge Engineering) and a Bachelor of Engineering (Electrical and Electronics Engineering) from the National University of Singapore (NUS) in 2004 and 1994 respectively.

TAN Tze Leng is Director (Infrastructure) in Building and Infrastructure. He started his career with the Lands & Estates Organisation, MINDEF. He played a key role in the master planning, design and development of camps and infrastructures. He was the Programme Manager responsible for developments such as the SAFTI Military Institute, Singapore Discovery Centre, DSO (Kent Ridge), Kranji Sanctuary Golf Course, Seating Gallery at Marina Bay, RSAF Training facilities in Pearce, Oakey & Cazaux and numerous army camp complex developments. Tze Leng graduated with a Master of Science (Civil Engineering) and a Bachelor of Engineering (Civil Engineering) from NUS in 1994 and 1989 respectively.

KUEK Choon Han is Head (Environmental Sustainability) in Building and Infrastructure. He is involved in driving environmental sustainability initiatives for MINDEF and the SAF. He graduated with a Master of Science (Environmental Design and Engineering) from University College London in 2017 on the DSTA Postgraduate Scholarship, a Master of Science (Building Performance and Sustainability) from NUS in 2014, and a Bachelor of Engineering (Mechanical) from Nanyang Technological University (NTU) in 2010.

CHUNG Yee Peng Jolene is a Senior Engineer (Building and Infrastructure). She is part of the team that drove the design and development of the first net positive energy building in the RSAF. Jolene graduated with a Master of Science (System Design and Management) from NUS in 2019, and a Bachelor of Engineering (Mechanical) from NTU in 2016.

TOWARDS A DATA-ENABLED ORGANISATION

KOH Lay Tin, CHONG Yonghui Benjamin, LIM Hui Yi Florence

ABSTRACT

The innovative use of data presents game-changing opportunities to deliver new defence capabilities. However, even with increasing data availability and technological advancements, many organisations are still unable to realise the full potential of data analytics (DA) and leverage insights discovered through DA to boost operational outcomes (Bean & Davenport, 2019). This is especially so for large organisations where the operating environment has become increasingly complex and fast paced, yet their operations and systems have not been digitalised and modernised to suit such an environment. Besides technology adoption, people and process issues are commonly cited obstacles to a data-enabled organisation.

DSTA understands the impetus to transform MINDEF and the SAF into data-enabled organisations and that a strategy is needed to advance their digital transformation journeys. This article provides an overview of DSTA's data-centric strategy to help MINDEF and the SAF achieve their data-enabled transformation, including the Fleet Management System initiative, which demonstrates the exploitation of instrumentation data and DA on military platforms to improve the readiness of platforms, streamline maintenance, and reduce operating costs.

Keywords: data-enabled, data-centric, data strategy, data science, fleet management system

INTRODUCTION

DSTA has put in place a set of data analytics (DA) enablers (Ho, Koh, Chong, & Ho, 2018), namely the (a) Enterprise Data Analytics Platform (EDAP); (b) Data Lake and Data Store Portal; and (c) Analytics, Collaboration and Experimentation (ACE) Lab. These enablers support the development of DA capabilities for MINDEF and the SAF in resource management, policy formulation, governance, and decision-making. Building on this foundation, the emergence of new technologies, increasing wealth of data, and the development of DA techniques have given rise to opportunities to seek new and innovative uses of data. A data-centric strategy is essential to enhance the understanding on roles that people, data assets, technology platforms, partners, and organisational processes play in advancing an organisation in its data-enabled transformation.

DATA-CENTRIC STRATEGY

The strategy considered five main aspects (see Figure 1): (a) Data; (b) DA and Artificial Intelligence (AI); (c) Ecosystem; (d) Insights, Recommendation and Automation; and (e) Enterprise Systems and Processes. This section discusses DSTA's strategy in strengthening the key enablers for DA and the alignment of operations and IT during a data-enabled transformation.

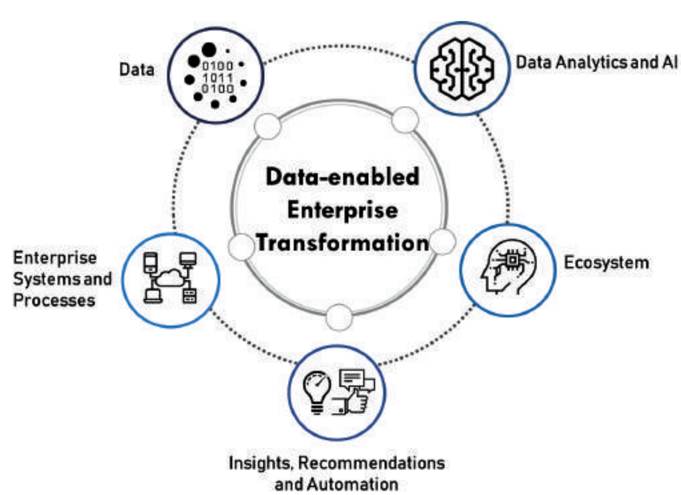

Figure 1. DSTA data-centric strategy

DATA

A data strategy is required to establish the foundation in managing data in EDAP's Data Lake. It anchors on the three principles of (a) Make Data Available; (b) Make Data Usable; and (c) Make Data Shareable and Secure.

Make Data Available

EDAP was designed to ingest, store and process different data types from a myriad of data sources (see Figure 2). System data refer to data in machine-readable form which reside in IT systems hosted in the network or as standalone systems. Besides duplicating or archiving data from existing systems, data are also generated by new IT systems and stored in EDAP. External data outside the organisation can be obtained through data acquisition clauses in contracts or established means of data interfaces such as Enterprise Data Hub and GeoSpace for Whole-of-Government (WOG) sharing. User data refer to any data that the user creates or owns. These data exist as there is no system process to capture and store them in a repository currently. Users can make use of the self-upload function in EDAP's Data Store Portal to share their data with the community. For uncollected data, digitisation and instrumentation are means to convert and collect them respectively.

Make Data Usable

Data are considered usable when cleaned, structured, in machine-readable format, fully documented, and ready for analysis and interpretation. Depending on the original format, data coming into EDAP go through different stages of conversion processes to be usable for analysis (see Figure 3). The conversion process includes a combination of operations – filtering, merging, sorting, aggregating, and joining of data. A data standardisation process is also in place to standardise the meaning of data, remove duplicate data, and reconcile conflicting data. This will ensure complete, accurate, and consistent data records for cross-line-of-business (LOB) analysis.

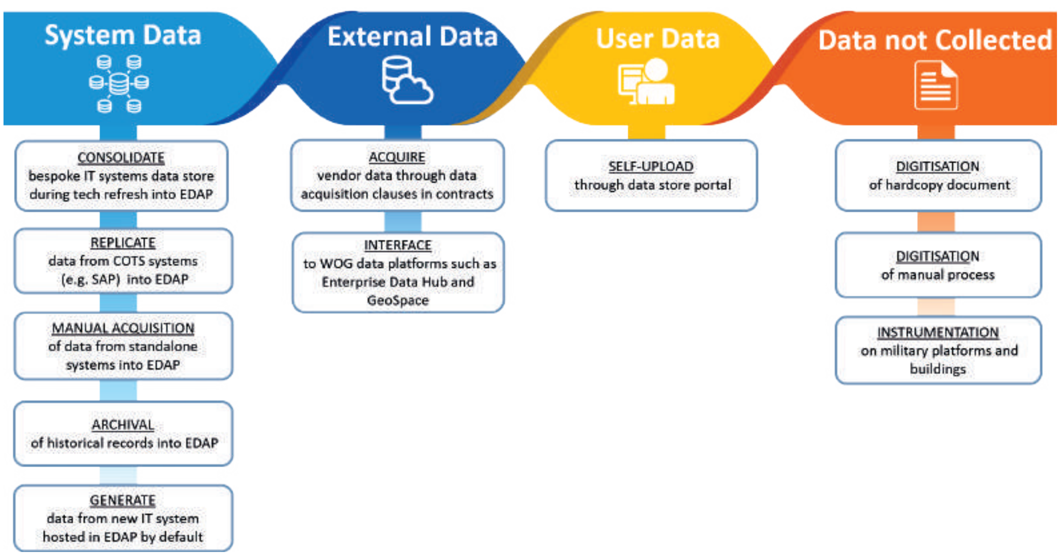

Figure 2. Strategies to make data available

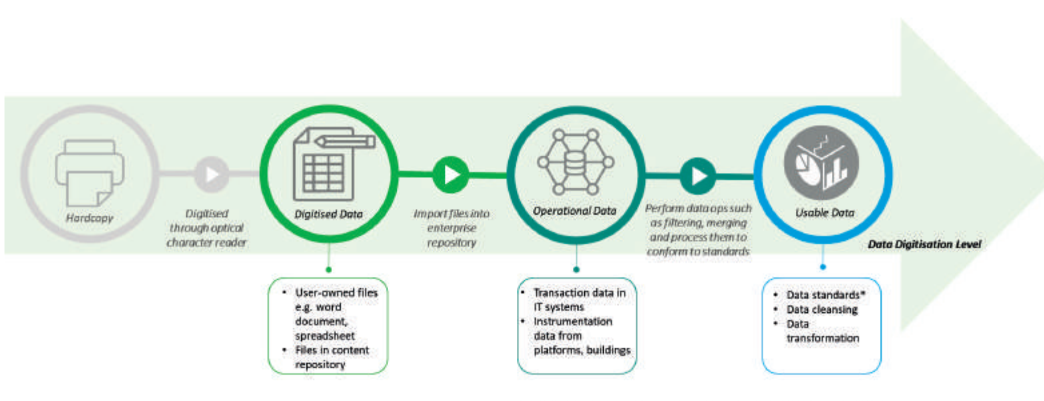

Figure 3. Conversion process of various types of data

Make Data Shareable and Secure

To promote sharing of data within MINDEF and the SAF, the EDAP's Data Store Portal (see Figure 4) was set up to unify the understanding of data for cross-LOB analysis. The data are catalogued with metadata information such as data owner, field descriptions, data type and refresh rate. The data shared on the portal are stored in the unified data platform and governed according to MINDEF's security requirements, unlike public data sharing portals where data are available in flat files for download. An integrated workflow (see Figure 5) was designed to link up the data requestor, supervisor and data owner for the data request and approval process as compared to the use of email correspondences to request for release of data in the past. Personal data are also automatically anonymised in the Data Lake to safeguard privacy and to lower the impact of data loss in the event of data leakage.

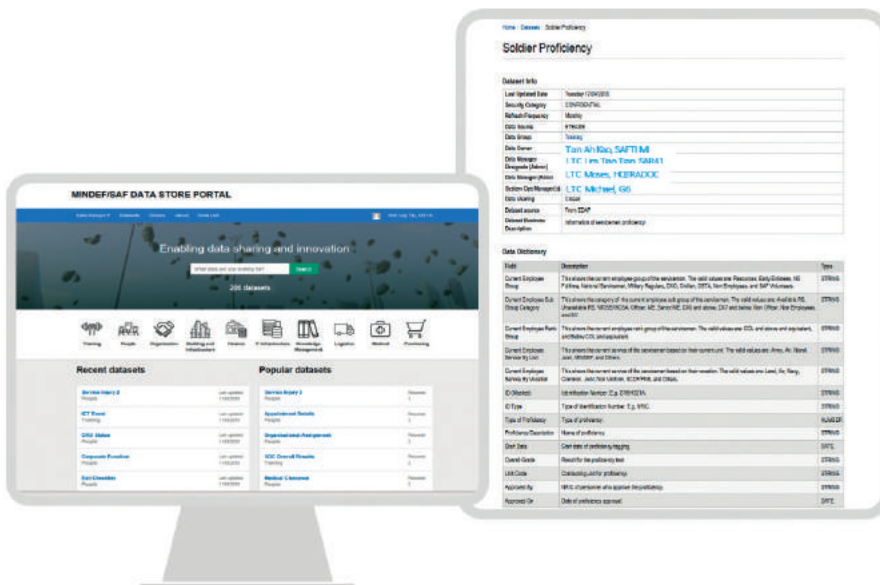

Figure 4. Data Store Portal and metadata of dataset

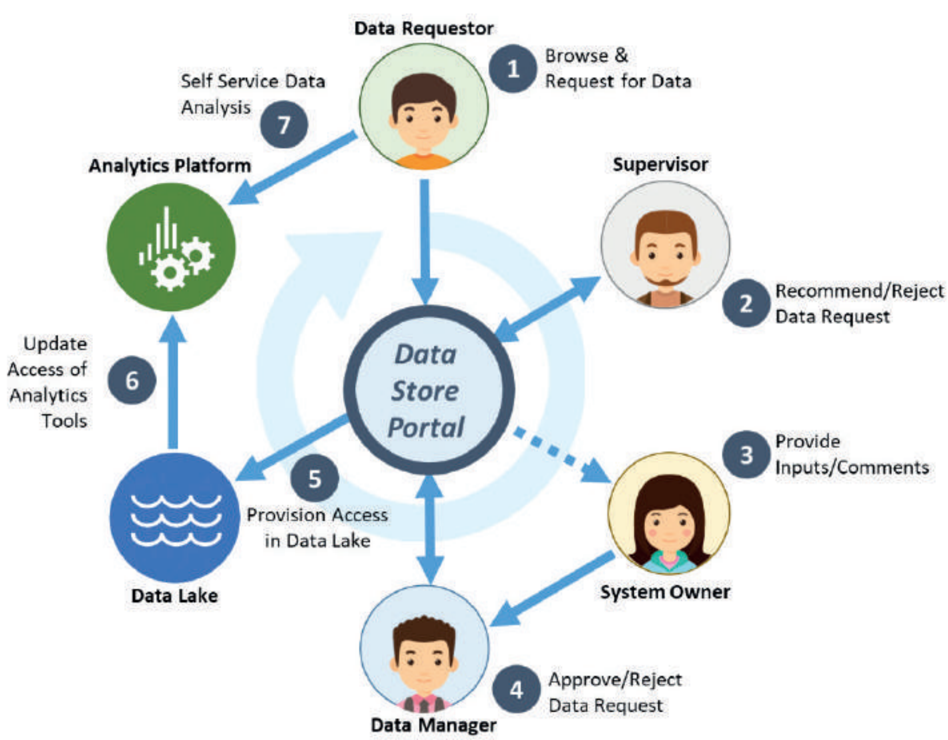

Figure 5. Data request workflow

DATA ANALYTICS AND ARTIFICIAL INTELLIGENCE

Building staff's competency in DA and AI is key to advance the use of the data, besides other relevant skill sets in data management, data processing, and data governance. In DSTA, a multi-pronged approach is used to train a pool of engineers and data scientists to support DA initiatives by:

(a) Customising a DA training programme for staff to acquire skills and knowledge (see Figure 6)

(b) Creating mini-projects and conducting hackathons for staff to gain practical experience

(c) Providing enablers with ready tools and live data for experimentation and creation of DA products (see Figure 7 and 8)

(d) Establishing industry collaborations through innovative and experimentation projects to acquire advanced DA/AI methods

Figure 6. DSTA DA training programme

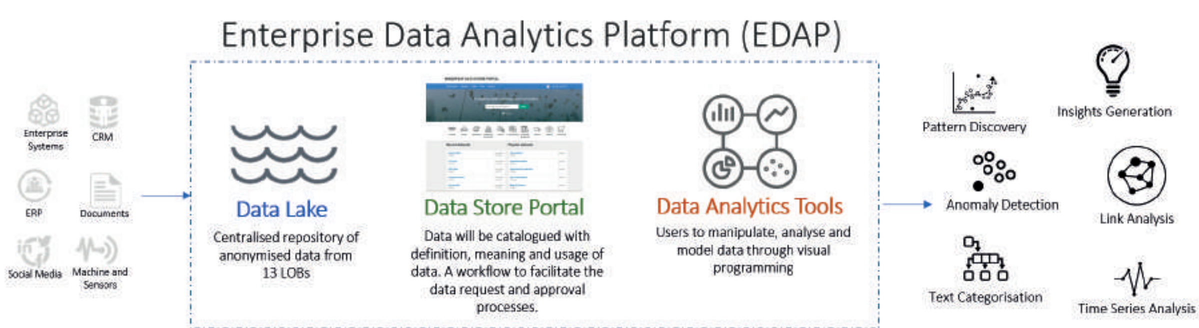

Figure 7. Digital enablers for DA (EDAP)

Figure 8. Digital enablers for DA (ACE Lab)

Figure 9. Ecosystem of the DA community

ECOSYSTEM OF DA COMMUNITY

A typical DA development life cycle comprises various stages starting from business understanding, data acquisition and processing, model development, to interpreting and presenting the analysis or deploying the models in a production environment depending on whether it is an analytical study or DA application development. To complete a DA life cycle, the skills and abilities required are vast and diverse ranging from statistics, machine learning, programming, and data engineering to domain knowledge and communication skills.

Data scientists cannot be experts in all areas and a team with diverse skill sets is required. DSTA recognised this early on and built a team of individuals with different skill sets to support the DA life cycle. For example, engineering and infrastructure requirements to develop enterprise DA applications involve a significant step-up in the data and software engineering knowledge required. Therefore, the DSTA team comprises a group of data engineers and software engineers to complement the data scientists in these areas.

It is also imperative to establish an ecosystem of strategic partners to enable wider data sharing, technology transfers and create opportunities for the co-development of advanced DA capabilities. Beyond the defence technology community, DSTA has established a network of partners from academia, the local AI/DA industry and Original Equipment Manufacterers (OEM) (see Figure 9).

INSIGHTS, RECOMMENDATIONS AND AUTOMATION

DA capabilities generate insights from data and make recommendations to help users in their decision-making process. To motivate users to embrace analytics, these capabilities need to be embedded within existing business process flows and applications, enabling users to access the capabilities in a seamless and efficient manner.

There is a variety of approaches to integrate analytics into systems ranging from adding hyperlinks with parameters, using HTML iframes with application programming interfaces or passing the output of the analytics model to an application module. To close the analytics adoption gap, the output from analytics model should be easy to understand and delivered in a user-centric manner through intuitive User Interface (UI)/User Experience (UX) design. Organisations must also evolve their process and structures to leverage data across their functions, such as setting up a citizen data scientist team to bridge the gap between business users and data scientists. These are usually existing staff with domain knowledge reskilled to take on the role of performing descriptive analytics such as data exploration and visualisation.

ENTERPRISE SYSTEMS AND PROCESSES

Transforming an organisation to change the way users operate and work requires a deep understanding of the existing business processes. In order to build the right analytical capabilities, stakeholders need to decide which domains and business processes require transformation. As the strategic partner of MINDEF and the SAF, DSTA has deep domain knowledge through acquiring, implementing, and supporting warfighting platforms, Control, Command and Communications (C3) as well as IT systems for the past 20 years. Combined with the build-up of strong in-house DA and AI competencies and an established network of partners, DSTA has embarked on tech-push initiatives with MINDEF and the SAF to develop transformative enterprise systems and reengineer business processes as part of their data-enabled digital transformation journeys. One flagship initiative is the Fleet Management System (FMS).

TRANSFORMING FLEET MANAGEMENT IN THE SAF

FMS is a DSTA tech-push initiative to tap the increased availability of system, environmental, logistics, engineering and administrative data to improve maintenance efficiency and operational readiness. The following is a case study on how DSTA's data-centric strategy helped the SAF achieve data-enabled digital transformation of their maintenance planning and logistics support functions, resulting in an enhancement of the readiness and fighting capability of the SAF's combat platforms.

IMPETUS

The SAF fleet is becoming increasingly complex and expensive to operate, further aggravated by a shrinking manpower projected to reduce by 30% in 2030 due to declining birthrates (MINDEF, 2015). To overcome these challenges, there is a need to harness 4th Industrial Revolution (IR) technologies to develop data-enabled capabilities that will help the SAF reduce manpower reliance and costs without compromising on operational readiness.

USING DATA TO TRANSFORM FLEET MANAGEMENT

The system for fleet management that the FMS team envisaged and designed uses a data-enabled approach to ensure high readiness of various platforms across the Air Force, Army and Navy (see Figure 10). At the edge, platform assets are instrumented with sensors to collect system health and utilisation data in real time. These data are fed to the respective services' fleet management operations centres for monitoring and analysis. The FMS analytical lab in DSTA comprising FMS data scientists would then augment system health data with supply and maintenance data made readily available in the EDAP data lake, and use EDAP DA tools to develop new analytical models. These models are deployed in the SAF platform assets to detect, predict and prevent system failures.

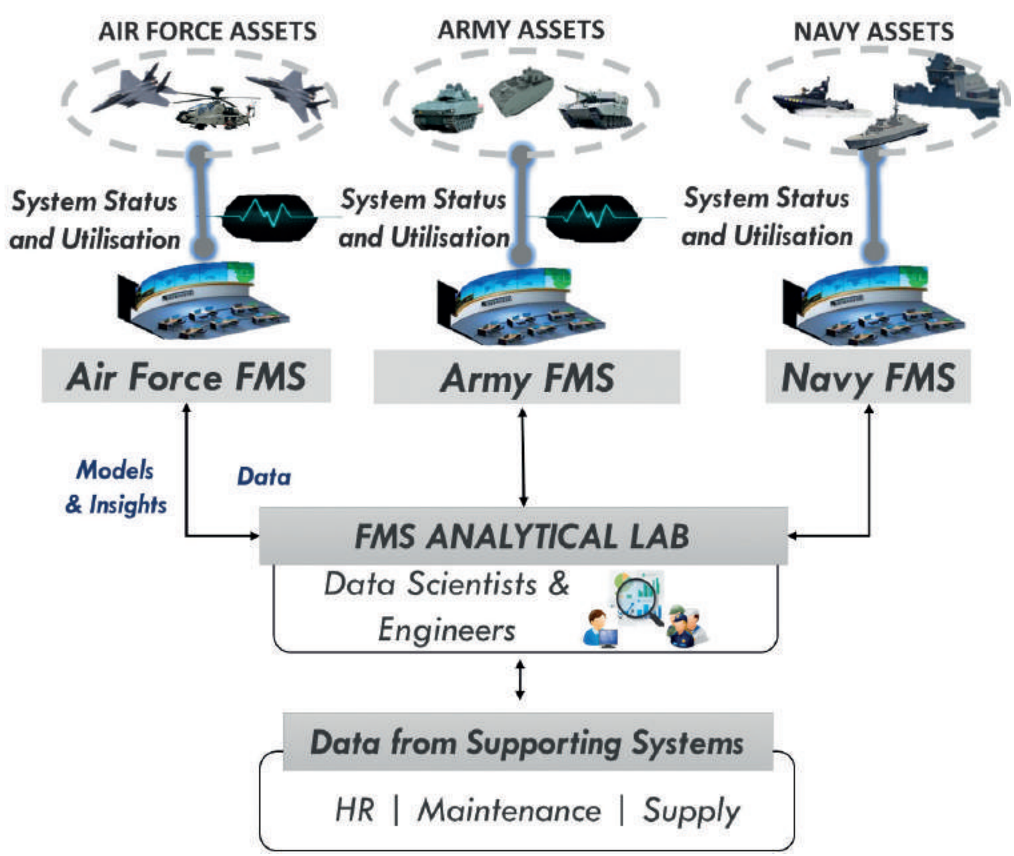

Figure 10. Data-enabled digital transformation of the SAF fleet management with FMS

THE FMS TRANSFORMATION ECOSYSTEM

The FMS team from the Enterprise IT Programme Centre (PC) understood that a strong ecosystem of partners is required to realise the data-enabled transformation of the SAF fleet management in a scalable and sustainable manner. Within DSTA, the FMS team adopts a whole-of-DSTA approach by working closely with the Air, Land, Naval, and Systems Architecting PCs in areas like capability delivery planning, data engineering governance, OEM collaborations, and systems integration.

Beyond these areas, the FMS team also looks at innovative ways to ensure that new platforms designed and acquired by the acquisition PCs are data-enabled for FMS capabilities. One ongoing initiative is an embedment programme where batches of system engineers from the Air, Land, and Naval PCs with an inclination for digital technologies will receive DA training and attend an immersive DA course as part of their Level 3 DA training. Following that, they are embedded with the FMS DA team for six months to co-develop predictive maintenance models as citizen data scientists.

The programme provides an avenue for system engineers to pick up DA skill sets through practice on real problem statements and data while FMS data scientists get to interact with the systems engineers and acquire domain knowledge about the platforms. In addition, with knowledge about DA techniques and development process, these engineers are better equipped to specify instrumentation design, data, and integration requirements when they manage the digitalisation aspects of platform acquisition projects in the future. Over time, it is expected that the relevancy, adequacy, and quality of the data streams made available from those platforms will improve. FMS data scientists can then develop a wider range of DA and AI capabilities while application developers can develop smart applications that incorporate these capabilities for the end-users (see Figure 11).

In collaborating with the SAF tri-services, the FMS team adopts a top-down and bottom-up buy-in engagement approach through activities like capability demonstrations, design workshops, clinic sessions, and minimum viable product try-outs. The FMS team also identifies user champions from each service to engage them for ideas and seek their assistance to link the team with other stakeholders. Through these partnerships, FMS data scientists are able to work and tap the respective service's engineering experts and ground engineers to acquire data, as well as to test and validate the predictive maintenance algorithms on the platforms. In addition, members from each service also take part in the embedment programme alongside the DSTA system engineers with the intention of nurturing future DA champions in the services, blurring the boundaries between operations and technology.

Extending the reach of partnerships and collaborations, the FMS team also establishes collaboration agreements with key platform/component OEMs like Boeing and ST Electronics to tap their deep engineering expertise, benchmark fleet performance against global averages and co-develop predictive models validated with global data. These collaborations are mutually beneficial as FMS data scientists can use these collaborations to circumvent data inadequacy issues due to fleet size constraints and resolve data accessiblity issues due to proprietary data formats while OEMs can take the opportunity to develop new data-enabled product suites catered for military platforms (see Figure 12).

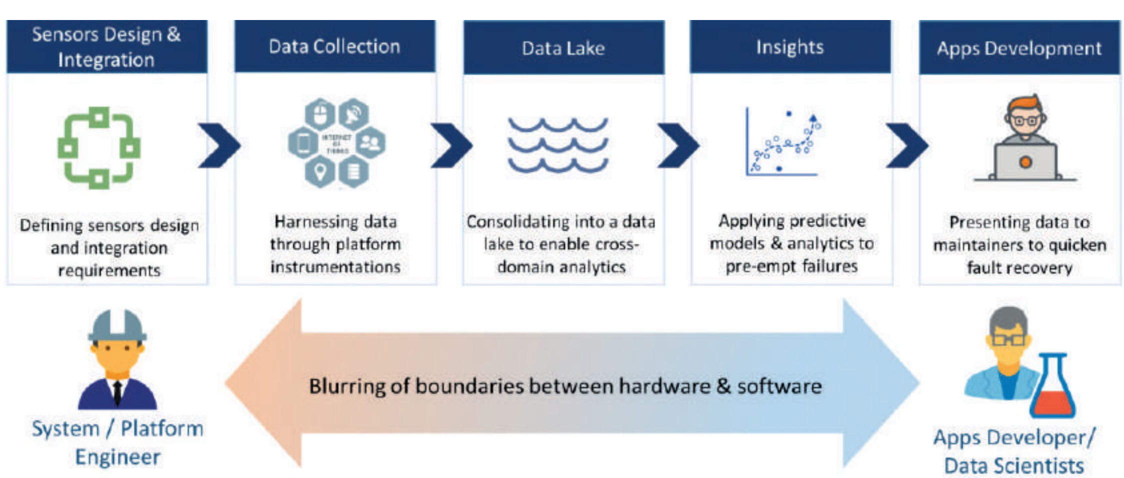

Figure 11. Systems engineering meets DA and software engineering

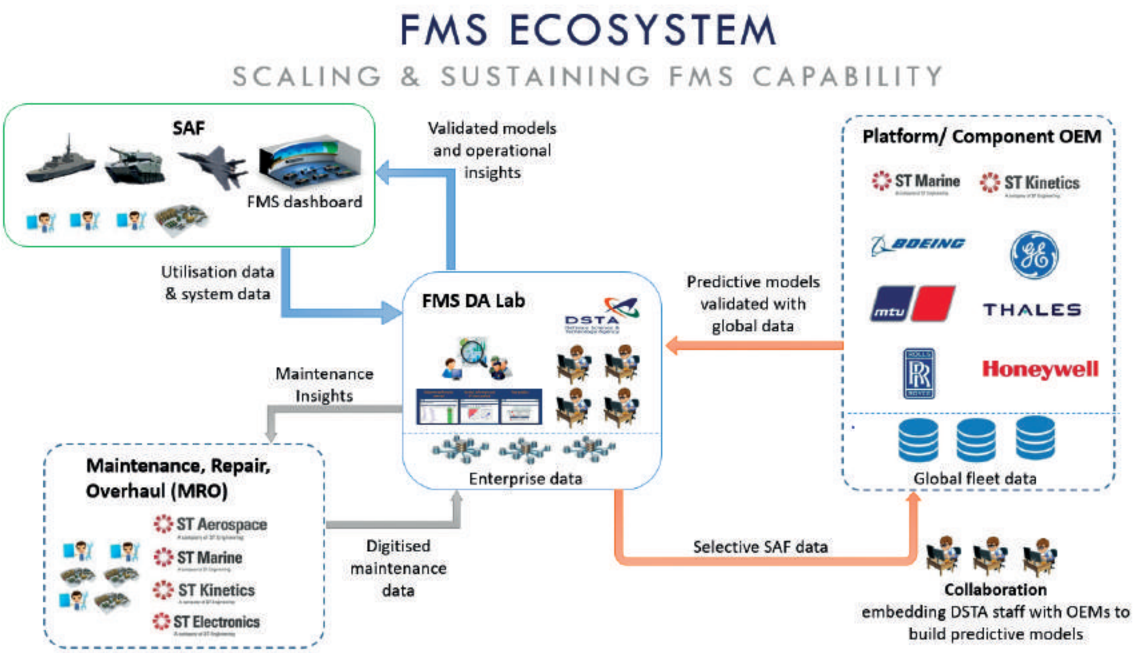

Figure 12. Scaling and sustaining FMS DA capabilities

FMS APPLICATIONS

An Example of Data-Enabled Approach to Early Detection of Failure

Singapore's naval vessels are equipped with state-of-the-art health monitoring capability from OEMs that provide greater visibility to the status of critical systems on-board. However, the alarms and alerts are usually designed based on stipulated rules and thresholds, and may not be adequate in detecting early signs of failures. Techniques in machine learning can be used to model the telemetry behaviour of different subsystems of the naval vessels and detect anomalies. A data-enabled approach to monitor telemetry data from ship machinery will be able to enhance existing system monitoring to be more pre-emptive of failures, so that the ship crew can take effective measures at the first sign of anomalies to minimise disruptions to operations. From one of the earlier models developed, the Navy achieved cost savings of S$0.5 million in 2018 by averting a failure for one of the systems on board their ship.

Scoring Machine Learning Models On the Edge

Ship machinery is complex with many components, making maintenance a huge challenge. Machine learning models for anomaly detection help alert users of any anomaly by learning the patterns and correlations between related sensors, and monitoring the health of the sensors across all operating states.

The models are integrated into the FMS application where incoming telemetry from machines would be continuously scored using the models. Users would be notified when an anomaly is picked up by the model. For recurring failures, the notification would alert the user on the specific impending failure such as a crack in a component. If not, a message consisting of the list of sensors exhibiting anomaly patterns and their respective anomaly score would be presented to the user (see Figure 13). These anomaly models would be effective in aiding shipboard engineers anticipate impending failures so that necessary measures can be put in place to reduce the probability of unexpected and catastrophic failures that would disrupt operations. The implementation of a system-health monitoring system as a key function of condition-based maintenance can potentially reduce the cost of component failures and minimise unscheduled maintenance downtime as well.

Figure 13. Anomaly detection notification on FMS application

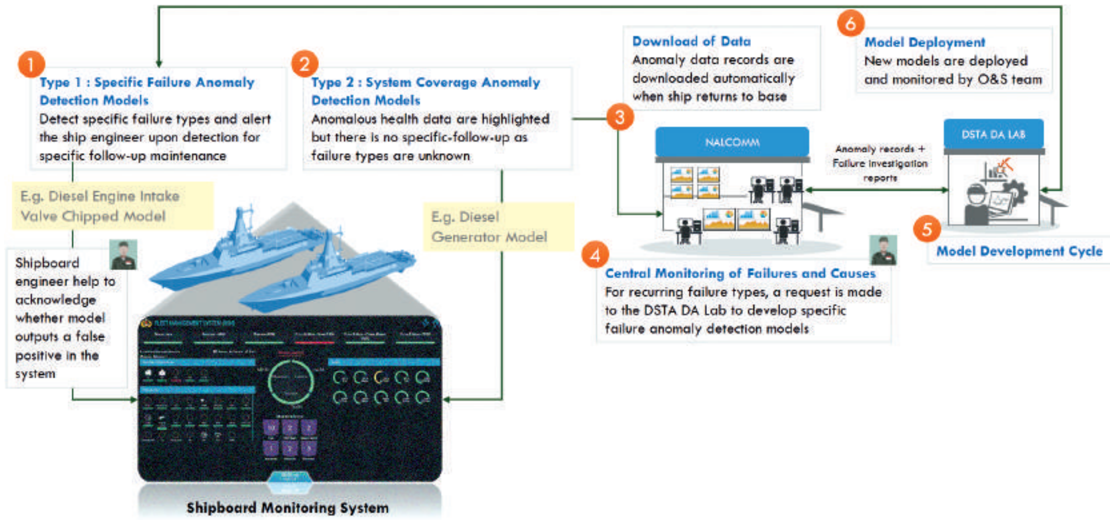

Figure 14. Continuous DA model development process

Continuous Development of Predictive Models

To proliferate this capability to the systems on ships, a development process to ensure continuous production of anomaly detection of machinery components has been conceptualised (see Figure 14). The process involves the extraction of data from returning vessels and centralising the monitoring of all deployed models to ensure the continuous cycle of identifying new and critical components for model development and validating against newly reported failures. This ensures sustainability and relevance of all the models that are currently deployed and for models in the process of deployment.

OTHER DATA-ENABLED TRANSFORMATION EFFORTS

Besides FMS, DSTA is also embarking on other data-enabled transformation efforts in the audit, procurement, and medical domains. In the audit domain, DA helps MINDEF to manage organisational risks by using data from past audit findings and procurement transactions to develop dynamic risk scoring models with adaptive thresholds, to monitor the compliance of cost centres on a continuous basis and identify possible systemic issues analytically.

In the medical domain, DSTA is working with the SAF to develop data-enabled capabilities to strengthen the soldiers' operational readiness, enhance medical operations and support, and build a positive healthcare experience. For example, medical records are analysed alongside other data sets to understand hidden risk factors and relationships associated with soldiers' health, medical history training and environment. These insights can be translated into targeted and early intervention measures, providing proactive care for soldiers with similar dispositions.

DATA-ENABLED TRANSFORMATION CHALLENGES

The journey towards a data-enabled organisation is not an easy one. Some of the challenges include (a) balancing the speed of digitalisation with the pace of operations; (b) grappling with data quality issues to provide meaningful insights; (c) understanding and managing the resistance to change; and (d) lack of business process reengineering efforts to embrace new operating models. A comprehensive and concerted data-centric strategy developed by DSTA (see Figure 1) is required to guide the data-enabled transformation.

CONCLUSION

The advancement of 4th IR technologies like DA and Internet of Things coupled with rapid digitalisation has given rise to new opportunities in the innovative use of data with technology. To be data-enabled, organisations need to roll out the right initiatives to evolve its culture and processes and make data at the core of all levels of decision-making. A data-enabled strategy is imperative to align the organisation and advance its data-enabled digital transformation. The FMS case study for fleet management is just one example of how DSTA, MINDEF and the SAF are applying this strategy. Currently, there are efforts in other domains and more of such efforts would follow.

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THE DEVELOPMENT OF A SYNTHETIC BATTLESPACE

TEO Chong Lai, SIM Kwang Lip Dave, SEET Yew Siang, LEE Mun Hong, HO Eng Kian

ABSTRACT

The Third Generation SAF operates as a networked fighting force with a diverse suite of advanced sensors, weapons, platforms and command and control systems integrated as one. Developing and validating such complex System-of-Systems (SoS) and Concept of Operations (CONOPS) is challenging.

DSTA leveraged modelling and simulation technology to create a digital twin of the battlespace to support SoS and new CONOPS development. This has enabled a coherent and expedient build-up of new capabilities for the SAF. This article shares the approach taken and the experience gained in developing a synthetic battlespace to support new capability development.

Keywords: system-of-systems, digital twin, modelling and simulation, verification and validation, concept of operations, M&S architecture

INTRODUCTION

The Third Generation SAF operates as a networked fighting force with a diverse suite of advanced sensors, weapons, platforms and command and control (C2) systems integrated as one. Developing and validating such new warfighting capabilities is a complex endeavour. With individual systems being networked as a larger System-of-Systems (SoS) (INCOSE, 2018), new emergent properties will surface and the ability to understand them upfront is critical. The Concept of Operations (CONOPS) and SoS architecture also need to be established early with high level of confidence in meeting the desired mission effectiveness. The complexity of integrating and testing constituent systems as an integrated SoS also increases significantly when each has its own development cycle.

DSTA leveraged heavily on modelling and simulation technologies to facilitate the build-up of new SoS capabilities. A synthetic environment that acts as a digital twin to the battlespace was used to support the entire SoS capability development cycle. The behaviours of the entities in the battlespace, such as sensors, platforms, weapons, communications effects, C2 systems, doctrine as well as techniques, tactics and procedure, were codified in the digital twin to allow studies, experimentations, testing and training to be conducted without involving the physical assets. The development of the new Littoral Mission Vessel (LMV) and Island Air Defence (IAD) capabilities are examples where such an approach was successfully applied.

To reduce the manpower required to operate the LMV for maritime security operations, a new design to co-locate the three separate control areas, namely the Bridge, Combat Information Centre and Machinery Control Room, into a single Integrated Command Centre was proposed. A realistic battlespace simulation coupled with an immersive mock-up of the Integration Command Centre was developed. This allowed operators to validate the new LMV's operating concepts first-hand before the system was built.

In the development of new IAD capability, instead of adopting the traditional air defence design where air defence weapons rely on their own organic sensors for target engagement, all weapons and sensors were networked together to provide flexibility in weapon-sensor pairing. This improved the overall SoS resiliency and overcame space constraints where only a limited number of sensors could be deployed due to electromagnetic interference. The synthetic battlespace was extensively used to evaluate the robustness of the new IAD SoS architecture as well as new operating concepts. It also supported the progressive integration of the consistent systems to mitigate technical and schedule risks typically associated with such complex systems integration.

The use of synthetic battlespace enabled a more expedient and coherent build-up of new SoS capabilities for the SAF. This article elaborates on the approach taken and the experience gained in developing a synthetic battlespace.

DEVELOPMENT APPROACH

A synthetic battlespace is used throughout the SoS capability development lifecycle as illustrated in Figure 1 using the Defence Capability Management Framework from MINDEF.

In the capability planning phase, the synthetic battlespace is used to support SoS architecture and CONOPS studies including man-in-the-loop experimentations to evaluate options and analyse complex issues. During the capability delivery phase, it provides a rigorous scenario-based SoS testing to uncover integration issues way before on-site integration that would then be more costly to fix. Once the capability is developed, the synthetic battlespace could also be easily turned into a trainer to facilitate training at the individual system level as well as SoS level.

A well-designed modelling and simulation architecture is critical to ensure the digital twin provide a good representation of the battlespace and reflect the SoS capabilities. Furthermore, the solutions need to support different levels of simulation (see Figure 2) ranging from effect-based simulation to detailed engineering models, as well as support integration with actual systems to enable a mix-and-match of real and virtual systems to build up the SoS capabilities progressively.

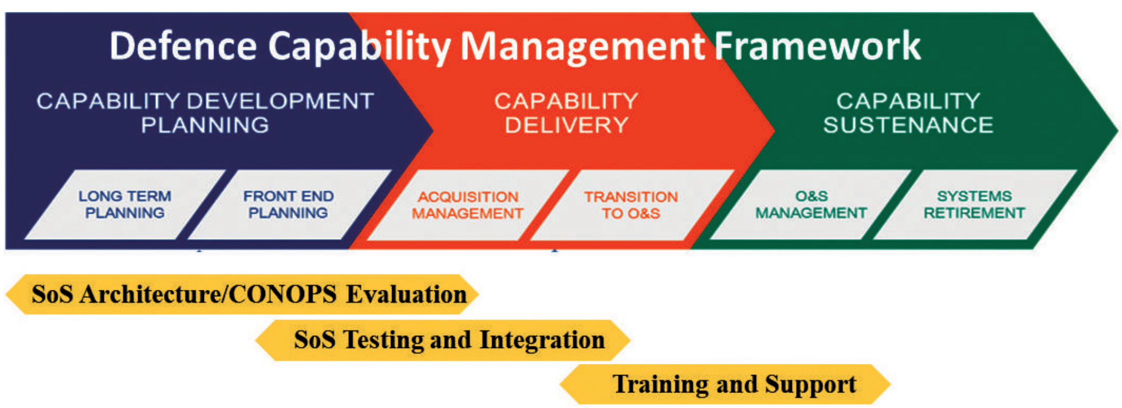

Figure 1. The application of synthetic battlespace in the capability development lifecycle

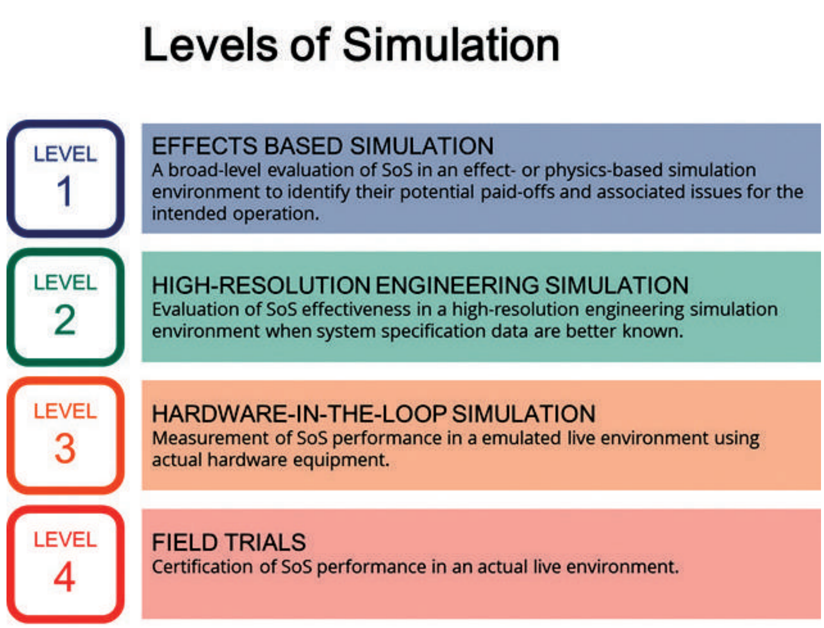

Figure 2. Levels of simulation

A wide range of models was developed to cover the SAF's assets such as Radio Detection and Ranging (RADAR), electro-optic sensors, weapons, platforms, and communications capability. The team leveraged the deep technical knowledge of subject matter experts (SME) in DSTA to ensure that the performances of the assets were correctly modelled and validated. Through constant iteration with the SAF users, the behaviours of the fighting force, doctrine and tactics were also modelled to enable computer-generated forces (CGF) to interact autonomously in the virtual battlespace with minimum human intervention.

People and processes influence the outcome of a battle as much as the capability of warfighting assets. The team incorporated process simulation concepts commonly used in the business/IT world and integrated them with the battlespace simulation such that C2 processes, human cognitive tasks and loading can be modelled. This enabled the team to study and evaluate the effects of force structure and C2 processes together with the SoS capability.

DESIGN CONSIDERATIONS

For the digital twin of the battlespace to keep pace with the SAF's capability development, it needs to be scalable, extensible, reusable and interoperable.

The simulation system has to be designed with scalability in mind as future battle scenarios will grow in complexity and consume more computing resources to simulate. It has to be extensible to allow new entity types to be simulated when required. It is also imperative that models developed across projects are interoperable and contribute to a coherent build-up of a comprehensive battlespace digital twin.

ARCHITECTURE

Overview

Based on the design considerations above, a synthetic battlespace simulation system was developed by DSTA to provide a digital twin where various battlespace scenarios can be simulated. The synthetic battlespace simulation system was designed in a loosely coupled and highly cohesive manner to increase reusability and maintainability. The architecture of the solution is shown in Figure 3.

Simulation Engine Design

The simulation engine is the heart of the battlespace simulation. To ensure a realistic simulation, all the entities in the battlespace need to be refreshed at least at 10Hz to 30Hz, or once in every 33ms to 100ms. An increase in number of entities will result in an exponential increase in processing due to the need to compute the interaction between entities.

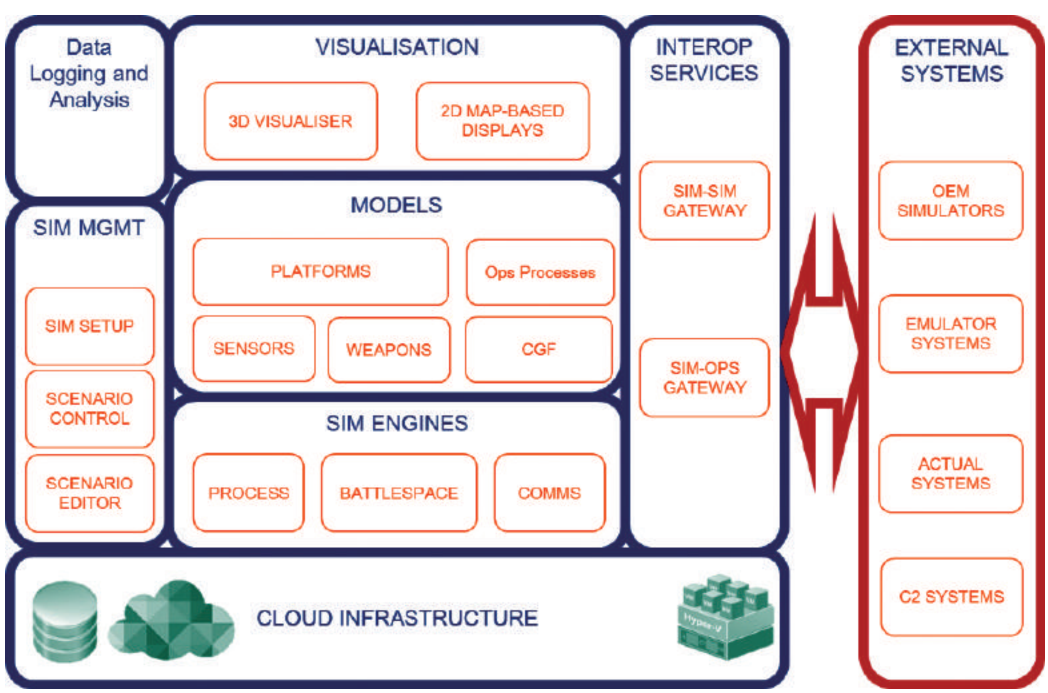

Figure 3. Architecture of the synthetic battlespace

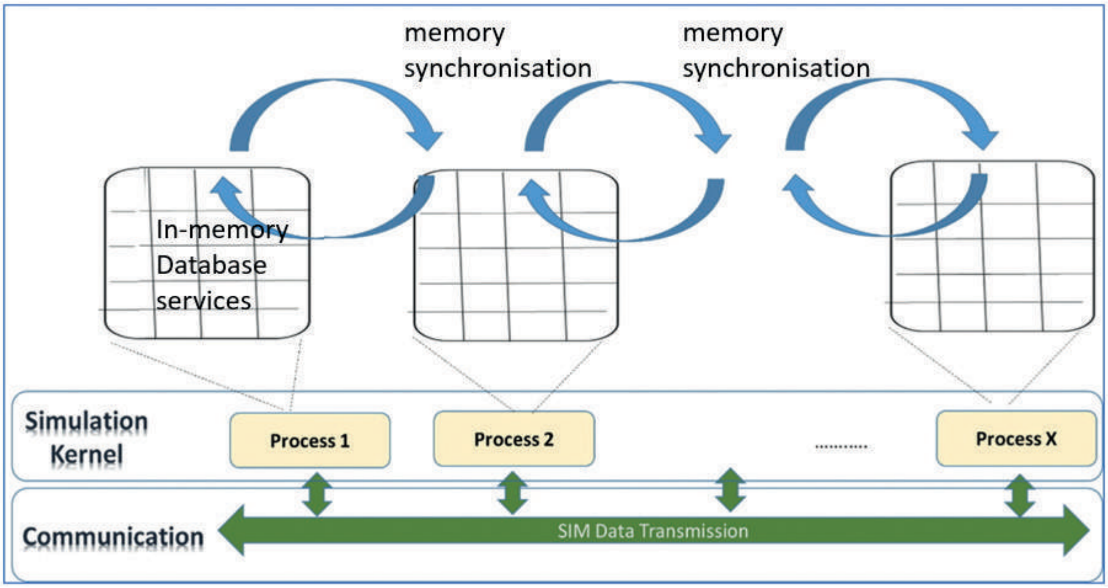

Figure 4. DSE architecture

The simulation engine was designed to be a time-driven Distributed Simulation Engine (DSE) to allow it to scale up as required when the complexity of the battlespace scenarios increases. The DSE consists of three key modules, namely simulation kernel, in-memory database services and communication (see Figure 4). The simulation kernel, at the heart of simulation engine, manages the real-time execution of simulation activities within the required time frame. Each kernel is responsible for performing state computation on a set of entities and models, and update the new state into its own memory databases. The content in the databases will be replicated to other kernels' memory database through a high performance, multi-threaded inter-process communication module to ensure simulation states are synchronised across the entire simulation application.

To ensure timely and synchronised management of simulation data across processes, the DSE was designed to execute in three stages within a single time frame – pre-tick, do-tick and post-tick. Under the pre-tick condition, DSE will unpack the simulation data received from other processes in its message queue buffers and update them into its own in-memory databases for simulation state synchronisation. During the do-tick condition, the DSE will execute its models to calculate simulation results and update its computation into own in-memory databases. Under the post-tick condition, the DSE will pack the computed data from memory databases into its message queue buffers for the communication module to serve out to other processes.

The DSE was designed with the concept of entity, model, and event objects to simplify simulation engine development. The inheritance in Object Oriented (OO) design pattern was adopted to allow for base properties and implementation retention. Some examples are F-16 entity's inheritance from aircraft entity properties, F-16 physic model's inheritance from fixed-wing aircraft physic model, and missile detonation event's inheritance from time event. A communications engine was implemented as an additional plug-in to the DSE to generate the communication effects. A façade layer with well-defined open application programming interfaces (API) was implemented to facilitate simulation control and access to the battlespace without affecting real-time performance of the DSE. The process engine that is mostly event-driven rather than time-driven was interfaced with the DSE via the APIs.

The DSE was designed to run in the cloud virtualisation environment, which provides dynamic on demand computing resource allocation with respect to intended scenario size for resource optimisation.

Simulation Models and Entities

The real world's systems or objects with their physical characteristics and attributes are represented by entities in the in-memory replicated database, while behaviour, logic and algorithms are represented by the simulation models.

Each entity is composed of one or more models encapsulated as standalone modules loaded by the simulation engine during runtime. Models are generic concepts used to simulate the different behaviour, logic and algorithm of the entity. Although the models are standalone libraries, they are not completely independent. When there is a need for the model to communicate with each other, the model does so by sending simulation events to each other or through shared entity data.

When new types of entities are introduced to the battlespace, new models can be easily developed and added to the synthetic battlespace. As the models are independent of one another, the newly developed models, and thus new type of entity, have minimal impact on the existing models.

In addition, the design allowed the team to extend the simulation via model reuse which reduced developmental efforts. As the models communicate with one another via simulation events and entity data, by careful design of the events and data, the team was able to replace one model with another to represent different type of entities. For example, the same aircraft type from different forces can be represented by composing the entity with the same physical models but different behaviour models.

The team was able to reduce the computing resources required by choosing models of different fidelity to run during runtime. They developed high fidelity motion models and medium fidelity motion models for the aircraft. While high fidelity motion models represent motions of the aircraft better than medium fidelity models, it is higher in computation load. The team balanced the resource required and realism of the simulation by dynamically choosing which motion model to run during runtime based on the mission of the aircraft. For example, medium fidelity models are sufficient to simulate aircraft movement along a simple flight path. However, during engagement, high fidelity motion models will kick in to provide a more realistic simulation and accurate engagement outcomes.

Integration Design

The integration with external simulators and C2 system is carried out by the Interop Services module. It was designed to be based on open simulation standards for better interoperability, and it also implemented the actual C2 interfaces to support system-in-the-loop testing in the synthetic battlespace.

Often, the Original Equipment Manufacturer (OEM) provides a high-fidelity simulator with the logic, algorithms and performance of the actual system. By integrating with them, the team was able to save on developmental effort and benefit from a high-fidelity simulator for the external system. The High Level Architecture (HLA) standard was adopted for integration with external simulation systems. It is an internationally recognised open simulation standard with a comprehensive simulation data structure and interactions to suit most simulation needs.

The team also developed gateways to support system-in-the-loop testing in the synthetic battlespace. The gateways were implemented based on the interface control document (ICD) of the C2 system. By testing early with the C2 emulator, the team was able to identify potential gaps and resolve them early in the development cycle. The C2 emulator can then be easily replaced by the actual C2 system when it is available for a final integration test.

In addition to integrating with other simulations via HLA and C2 systems via C2 interfaces, the team designed and exposed the API in the form of an open API to allow any other external system to integrate with the simulation system.

In the SoS set-up, there are numerous C2 processes and human cognitive tasks between the various systems. It will be too manpower intensive to study and evaluate the effects of different force structures and the C2 processes together with SoS capability manually with man-in-the-loop. The team managed to reduce the manpower required significantly by modelling the C2 processes and human cognitive tasks in a process simulation engine, replacing the man-in-the-loop with process simulation and integrating it with the simulation system via the open API.

Data Analysis

The Data Logging and Analysis module captures the synthetic battlespace data, C2 data and operators' actions to support analysis for SoS testing and studies.

In the SoS environment, the team leveraged commercial off-the-shelf (COTS) HLA recording and playback tools to record HLA synthetic battlespace data. The proprietary HLA data can be exported into readable file formats such as CSV and Excel for data analysis purposes. For after action review, the HLA data can support scenario playback using a HLA compliant 3D visualiser.

In addition to HLA data, the Data Logging module can log external data such as C2 battlespace information, operator actions and decisions made via C2 decision support system recommendations. It can also capture other critical battlespace information not defined in the HLA Federation Object Model (FOM) required for more comprehensive data analysis.

The Data Logging module can be seamlessly integrated with COTS data visualisation and analysis tools for real time validation of sensor and weapon systems' performance or discovering system abnormalities. For CONOPS development involving SoS, real time analysis of both simulation and C2 data generated during multiple scenario runs can be performed to gather immediate insights.

Simulation Management and Visualisation

To manage the simulation, the Simulation Management module performs scenario planning, simulation controls and enables injects to be introduced dynamically during runtime while the Visualisation module provides the functionally to monitor the synthetic battlespace simulation.

CHALLENGES AND EXPERIENCE GAINED

Credible Models and Simulation

In the development of the synthetic battlespace, the team had to deal with systems that were not yet acquired or delivered, and very often relevant system data were also not readily available. It would be too late if they waited for all inputs to be available before starting the model development and study activities. It was a challenge to ensure models and simulations were credible. This is important because results from unreliable models are likely to be erroneous and would result in costly wrong decisions being made.

A simulation and its results have credibility only if stakeholders and other key personnel accept them as correct. The following four-step process was adopted to ensure that models and simulation are credible.

In the Requirements & Data Collection phase, the appropriate levels of model detail, fidelity and performance based on the simulation intent will be carefully considered. SMEs should be consulted early in the process for them to gain a good understanding of the system to be modelled, data and algorithms to be applied, and operating concepts – wrong assumptions or invalid data are the main culprits for inaccurate models. Where data are not available, the SMEs' advice on appropriate assumptions would be sought.

In the Design Review phase, the SMEs and stakeholders will provide inputs on the model design, data to be applied, behaviour, assumptions, and be briefed on limitations of the model before development starts. When reusing a previously validated model, it is important to ensure that it is under the same valid context, and that stakeholders are briefed to build up confidence.

Model development starts with a finalised design. Verification is a process to ensure developers 'build the thing right'. Comprehensive simulation tests with different scenarios are conducted and results will be documented to verify that model is built according to design.

In the Validation phase, SMEs and stakeholders ensure that the 'right thing' has been built according to the intent. Performance charts, simulation results, test scenarios, errors and demonstrations will be shown for acceptance before use.

When there is live testing with the actual system, it is a good opportunity to collect live data so that appropriate calibration can be carried out to further improve the model or simulation.

System-of-Systems Integration

The synthetic battlespace development involved integration with various emulators provided by external contractors. The challenge here was to establish a common method for interoperability and also taking into consideration that future systems acquired should not affect previously integrated systems. To realise this, the HLA was adopted, as it is an internationally recognised open simulation standard and has a comprehensive simulation data structure and interactions to suit most simulation needs. In addition, to synchronise interpretations and implementation of HLA (e.g. enumerations, FOM and interactions) for better plug and play among different simulators, DSTA developed the 'HLA Interoperability Guide for SAF Simulators' to define a common set of rules and practices

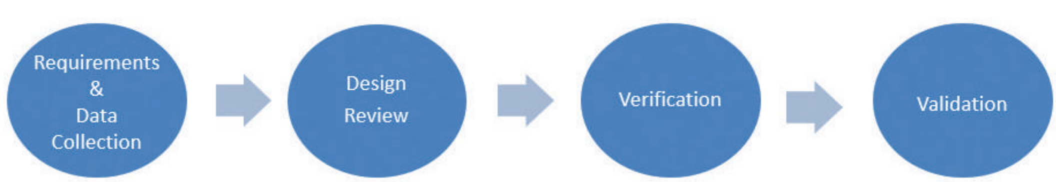

Figure 5. Model development process

on the usage of the HLA and implementation. The HLA guide was promulgated to all M&S practitioners and projects to ensure the adoption of a common integration strategy for simulators across the entire SAF to enhance interoperability.

In addition, practising the exchange of the Message Emulator between two parties before the start of integration was found to be useful in minimising integration risk. This helps to surface interface issues early and allows a smoother integration.

MOVING AHEAD

Future Battlespace

With the emergence of new technologies, the nature of warfare will be more complex in the future. Advances in areas such as autonomous systems and robotics are likely to redefine future warfare. In addition, the ability to engage in warfare is no longer limited to the kinetic domain. Non-kinetic warfare, such as information, electromagnetic and cyber, will play a more critical role in future military operations. The synthetic battlespace will need to be expanded to cover new domains to remain relevant. The technical solutions for non-kinetic warfare can be very different, and the architecture will need to incorporate new modelling and simulation technologies. Exploratory projects have been initiated to evolve the solution to support future battlespace.

Cloud-Native Architecture

The existing synthetic battlespace environment has employed various cloud technologies such as virtualisation (Infra-as-a-Service) and web technologies. The plan is to move the software towards cloud-native architecture, leveraging container technology to provide better composibility and ease in software reuse. Efforts are ongoing to decompose exisiting solutions into microservices to evolve the solutions towards cloud-native architecture.

Artificial Intelligence Technology for Model Development

The current implementation of CGF is rule-based. Rule-based CGF requires modellers to understand the complex warfighting domain in order to translate the thoughts of the warfighters into rules to codify them. This is a painstaking process, both time-consuming and often incomplete. With the advancement of deep machine learning and reinforcement learning, smarter CGF can be developed. For example, data-based behaviour modelling can reduce the time taken to develop the CGF by using deep machine learning to learn from existing data and generate behaviours based on the data. Through the use of deep reinforcement learning, more reactive CGF can be developed.

SUMMARY

This article has shared the approach taken and the experience gained in developing a synthetic battlespace that has contributed to a more coherent and expedient build-up of new SoS capabilities for the SAF. For the synthetic battlespace to remain relevant to future warfare, the solutions will need to evolve continuously to support new domains and technologies.

ACKNOWLEDGEMENTS

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HYBRID APPROACH FOR COST-EFFECTIVE DEVELOPMENT OF EXPLOSIVE STOREHOUSES

KANG Kok Wei, SEAH Chong Chiang, KOH Yong Hong

ABSTRACT

In the field of explosive safety, it is common practice to conduct large-scale explosive field tests of the actual systems to ascertain the associated hazards. While this approach does generate sufficiently good data for safety assessment and certification, the cost to conduct such tests is very high. Compounded with a limited number of test ranges which are capable of supporting such requirements, reliance on large-scale field tests limits innovations to mitigate explosive hazards. However, there is now an opportunity to leverage advancements in scientific know-how and engineering technologies to conduct safety assessments and develop innovative solutions cost effectively, instead of relying on expensive large-scale explosive field tests. The Building and Infrastructure Programme Centre has embarked on a systematic effort, which synergises know-how in using a combination of small-scale explosive testing and numerical modelling of large-scale structures to develop new explosive containment facilities that have the capability to mitigate fragment and debris hazards. This eliminates the need to conduct large-scale explosive field tests, with a corresponding reduction of cost by 20 times. It is to be noted that the systematic approach is not applicable for the development for all types of explosive storage facilities but only to those that store smaller amount of explosive which would not rupture the storehouse.

Keywords: protective engineering, explosive storehouse, large and small-scale explosive field tests, safety, experiment, numerical modelling

INTRODUCTION

In order to protect personnel and assets in modern society, it is universally accepted that sufficient safety restrictions be imposed on proximity to ammunition storage facilities. The most common restriction takes the form of safety distances from Potential Explosion Sites (PES), in which guidance can be found in prescriptive codes such as the Allied Ammunition Storage Transportation Publication, AASTP-1 (NATO, 2015). This approach requires something Singapore is short of – space. With a land area of about approximately 700km^2 and almost 6 million inhabitants, Singapore has one of the highest population density in the world, which results in a highly competitive environment for land usage. Due to such land scarcity, there is a strong impetus to innovate to overcome the land constraints, with technologies that can reduce hazards arising from the unlikely event of an accidental explosions in ammunition storage facilities (MINDEF, 2001; Kang, Toh, Lai & Koh, 2018).

In developing innovative solutions to enhance explosive safety, it is common practice to conduct explosive tests to validate and certify the performance of the proposed technologies. From 1971 to 1985, the US Department of Defense Explosive Safety Board (DDESB) conducted a testing programme called Explosive Safety Knowledge Improvement Operation (ESKIMO) to determine accurately the minimum safe separation distance between Earth Covered Magazines (ECM) storing high explosives (Weals, 1973; Weals and Finder, 1979; Murtha and Beyer, 1986). The large-scale explosive tests (see Figure 1) conducted involved detonating explosives weighing between 24,000lbs (10,886 kg) and 200,000lbs (90,718 kg) (Conway, Amini & Fryman, 2018). In Australia, a series of large-scale trials was conducted by the Australian Department of Defence to determine the ability of a commercial construction system called Spantech to provide satisfactory protection for their contents and prevent propagation to adjacent storehouses, in the event of an accidental explosion occurring within the NATO intermagazine safety distances (Lucas and Roberts, 1994). Three of the four tests involved detonating 75,000kg of explosives within the donor structure while the fourth involved burning 6,000 105mm shells. Recently, the DDESB conducted the International Standardization Organization (ISO) test programme, which consisted of seven tests to assess the explosive hazards in storing ammunitions in standard commercial ISO containers commonly used in field storage and forward operating bases (Conway, Amini & Fryman, 2018). This test series, which spanned from 2006 to 2010, tested explosive weights ranging approximately from 2,000lbs (907kg) to 8,000lbs (3628kg).

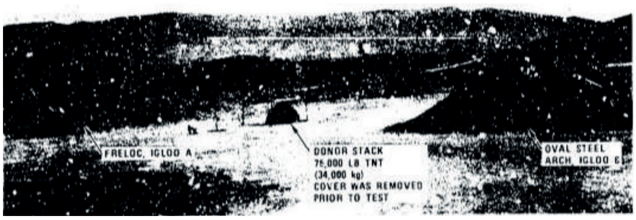


Figure 1. Test overview from ESKIMO V (Weals and Finder, 1979)

However, there were also attempts to leverage small-scale tests in research and development in this field. Notably, the Swiss conducted a considerable number of scaled tests in view of constraints such as land scarcity to conduct large-scale tests (Kummer, 2007). In 1975, they conducted 1:10 model tests with shallow buried reinforced concrete ammunition storage magazines to study the air blast and debris hazard propagation. In 1977, they conducted another series of tests on earth covered steel arch magazines used to store one tonne of explosive within the actual magazine. As the scale used was 1:20, only air blast propagation was studied. Next, in 1990, they developed earth covered magazines, built using fibre reinforced plastic and they used a scale of 1:2.5 to ascertain the air blast propagation, debris hazard propagation as well as the effects on adjacent magazines (see Figure 2).

In addition, the Explosive Storage and Transport Committee (ESTC) from the Ministry of Defence (MoD) of the United Kingdom (UK) conducted a series of 32 tests of various scales to evaluate the degree of damage to earth-covered and non-earth covered reinforced concrete magazine (Kummer, 2002). Equation 1 and Equation 2 were developed to evaluate the structural damage, which is defined as damage category (DC), of non-earth covered and earth covered reinforced concrete structures respectively. DC ranges from 1 (least damage) to 6 (pulverisation), and can be calculated based on the scaled venting area and the loading density.

(a)

(b)

Figure 2. (a) Pre- and (b) post-blast views of test structure (Kummer, 1990)

$$DC = \frac{\ln LD - \ln SVA + 2.85}{0.68} \tag{1}$$

$$DC = \frac{\ln LD - \ln SVA + 2.15}{0.68} \tag{2}$$

where, DC = Damage category
LD = Loading density (kg/m^3)
SVA = Scaled venting area (m^2/(m^3)$^{2/3}$) = $A/V^{2/3}$
A = Venting area (m^2)
V = Internal volume (m^3)

The description of the damage category is tabulated in Table 1, with images showing the extent of these DCs as follows (see Figure 3):

Damage Category	Damage Description
0	- no visible damage - only temporary elastic deformations
1	- very small deflections / distortions - hairline cracks - structure can be re-used without repair work
2	- larger cracks in the centre of the slabs and along the edges - visible, but relatively small deflections in the centre-lines of slabs - plastic deformations - no spalling - structure may be re-used after repair work - no debris throw
3	- large deformations - structure ripe for demolition - few spalled areas - no holes in slabs - limited debris throw, short distances, small pieces of debris
4	- structure destroyed, very large deformations - but different parts of the structure still hold together - few to many reinforcement bars broken - heavy spalling over large areas - holes in slabs - limited debris throw, longer distances, small pieces of debris
5	- structure disintegrated into a smaller number of larger parts - reinforcement bars broken or torn out of the concrete along edges - substantial debris throw to the surrounding area - however, parts of the structure remain at the PES
6	- structure more or less “pulverized” - all structural material is thrown up to large distances - large amounts of small debris pieces - crater may be formed

Table 1. Description of the damage categories (Kummer, 2002)

(a)

(b)

(c)

(d)

Figure 3. Examples of structures in DC of (a) 1 with no visible damage; (b) 3 with large deformation; (c) 4 with structure destroyed; and (d) 5 with structure disintegrated into small numbers of large parts (Kummer, 2002)

DOES SIZE REALLY MATTER?

Using scaled models to study complex phenomena is a common practice in the engineering field. More so, for civil engineering works where prototypes of actual structures and components may be too large to construct in a laboratory or controlled environment. Examples include the studies of the response of high rise structures to wind and earthquake loads, the design of coastal breakwaters to wave actions and the response of bridges to various transient loads. In these experiments, small-scale models are used to predict the behaviour of large-scale prototypes through the Laws of Similitude which states two systems are dynamically similar when their dimensionless ratios are equal. For illustration purposes, in the design of a reinforced structure which is subjected to dynamic loads, the main variables are acceleration (a), material stresses (σ), density (ρ) and length (L). The ratio $\rho aL/\sigma$ is one of the dimensionless parameters. Hence, for similitude to exist between the model and prototype, their respective dimensionless parameters must be equal i.e. $(\rho aL/\sigma)_{model} = (\rho aL/\sigma)_{prototype}$. In view that there are other dimensionless parameters that can be formed, it is rarely possible to achieve similitude in all of them (Nalluri and Featherstone, 2001).

Replica scaling is the most popular method for constructing scaled models. In replica scaling, the model is fabricated by scaling down the prototype in three fundamental dimensions: length (L), mass (m), and time (t). The scaling factors of length, mass and time can be defined by $\beta_L = L_{model}/L_{prototype}$, $\beta_m = m_{model}/m_{prototype}$ and $\beta_t = t_{model}/t_{prototype}$ respectively, on which the scaling of other parameters are then based. For example, the scaling factor of force, F can be derived forming the following dimensionless parameter $\Pi = F/Lmt^{-2}$. The Law of Similitude require ∏ to be equal in the model and the prototype system. As such, by resolving, $(F/Lmt^{-2})_{model} = (F/Lmt^{-2})_{prototype}$, the scaling factor for force β_F can be defined as $\beta_L\ \beta_m\ \beta_t^{-2}$. By using the same approach with other dimensionless parameters, it can be derived that stresses σ and density ρ are the same in replica scaling. The same theory will also show that the scale factors for mass and time can be defined by scaling factor of length as $\beta_t = \beta_L$ and $\beta_m = \beta_L^3$ applies in replica scaling. Thus, the scaling factors of principle parameters can be defined as a function of the scale factor of length, among which some are tabulated in Table 2.

In the ESTC test by UK MoD, a comparison was made to study the scaling effects on reinforced concrete structures subjected to internal detonation. The structure with an internal volume of 1.46m^3 (1.22x1.22x0.95m) was compared with a model which was approximately half-scale, with an internal volume 0.18m^3 (0.61x0.61x0.49m) (Kummer, 2002). Although the net explosive

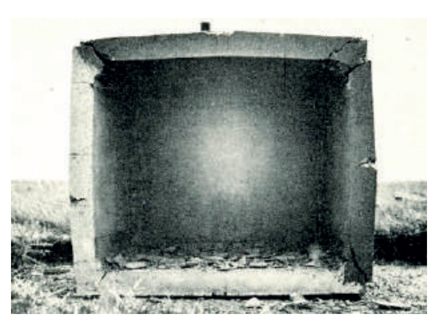
Quantities	Scaling factor
Stress	1
Strain	1
Velocity	1
Acceleration	$1/\beta_L$
Energy	β_L^3
Pressure	1
Force	β_L^2
Deflection	β_L

Table 2. Scaling factors for principle parameters in structural dynamic systems

quantities (NEQ) which were detonated within the structures were different due to the need to scale mass of the explosive material in replica scaling, the loading density was kept constant at 0.73kg/m^3. This was also due to the Law of Similitude. The comparison of the two tests is shown pictorially in Figure 4 and both structures exhibited similar levels of damage, with cracks at the connections between the walls and roof and at the midspan of the walls. This test validated the replica scaling approach as a scaled reinforced concrete model by a factor of two was able to provide sufficient indication of the response of a large-scale structure.

However, there are scenarios in which replica scaling cannot be achieved. This can be illustrated in two series of earth covered magazine (ECM) tests and similar to the test described in the preceding pargraph, one of them is geometrically constructed to be half of the other (Kang et al., 2015). The larger structure

(a)



(b)

Figure 4. Comparison between a (a) full and (b) half-scale reinforced concrete structure subjected to internal detonation (Kummer, 2002)

(a) (b)

(c) (d)

Figure 5. Comparison between the (a) large and (b) half-scale earth covered magazine before the test, and the on-site observation of the (c) large and (d) half-scale structure after detonation (left wall intact)

had an internal volume of 6.4m^3 (2x2x1.6m) and an earth cover thickness of 0.48m above the structural roof. In comparison, the half-scaled structure had an internal volume of 0.8m^3 (1x1x0.8m) and an earth cover thickness of 0.24m. The loading density of both tests was maintained at 20kg/m^3. It was observed that the structural responses for both tests was largely similar, in which the front walls fragmented, and the roof and wall sheared off at their joints and landed close to the structure (see Figure 5). In addition, the launch velocity of the roof as well as the peak overpressure from the external blast propagation recorded from the two tests were of similar magnitude, which followed the Law of Similitude (Kang et al., 2015).

However, it was analysed that the Inhabited Building Distance (IBD)[1] to guard against debris hazards, which is defined as minimum prescribed separation distance between a hazardous explosive source and inhabited area, showed significant differences between the two tests. Comparing the debris densities along the front, side and rear axes from the two tests in Figure 6, the debris density along the side and rear was not well replicated. In fact, the side and rear IBD, derived from the half-scale test were farther than those derived from large-scale test. This can be primarily attributed to gravity. In order to exercise replica scaling, gravity, which is a form of acceleration, must be scaled by a factor of $1/\beta_L$. This means that the gravity imposed on the half-scale test must be doubled in order to adopt replica scaling fully. Since gravity cannot be altered in the tests, the suppression effects of earth overburden to mitigate debris from the side and rear in the half-scale test cannot be replicated. In addition, the non-scalability of gravity could have led to a longer debris throw distance in the half-scale test. Thus, in order to obtain the actual debris throw distance for an actual ammunition storehouse, a full-scale (larger scale) test would be required as gravity effects cannot be scaled effectively.

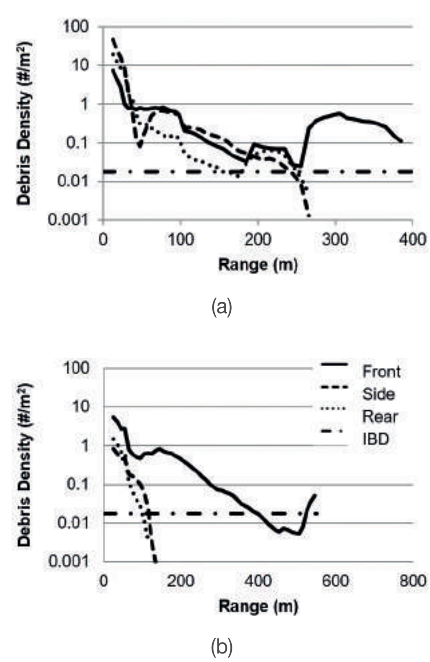


Figure 6. Comparison of the debris densities along the front, side and rear axes from the (a) half and (b) large-scale ECM tests

Other then gravity, there are two other non-scalable parameters which may be of concern when adopting replica scaling in explosive safety tests. They are the strain rate effects on the material and material fracture energy. Following the Law of Similitude, the scaling factor for strain rate is $1/\beta_L$, which means that a smaller scale model should experience higher strain rate than the large-scale prototype. As common construction materials exhibit higher strength when subjected to high strain rates, the smaller scale model will possess higher strength than the large-scale prototype, which may result in overestimation of the structural resistance of the prototype if the results from the small-scale models are used.

The Crack Band Theory can illustrate the non-scalability of concrete (Bazant, 1976; Bazant and Oh, 1983). In the crack band model, when a quasi-brittle material is subjected to tension, fracture is assumed to occur in a localised region called crack band, illustrated in Figure 7. A typical constitutive (stress versus strain behaviour) relationship for quasi-brittle materials, which have a linear elastic range followed by softening, is shown in Figure 8. The highlighted area in Figure 8 represents the energy per unit volume consumed during fracture, which is denoted by γ_F. When fracture happens, only the crack band region goes beyond the peak strength into the softening range. The rest of the specimen volume will unload along the elastic curve.

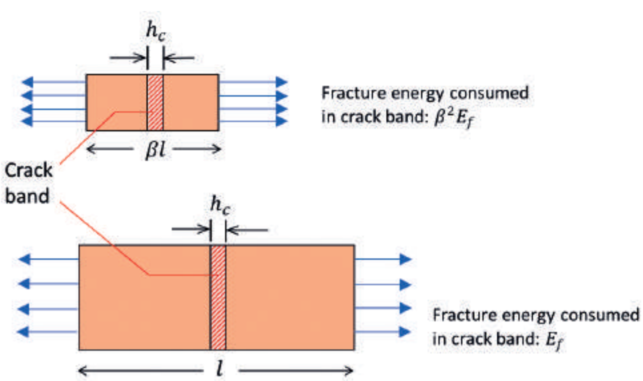


Figure 7. Schematic diagram showing the crack band of geometrically similar concrete specimen (top is scale model and bottom is full-scale model)

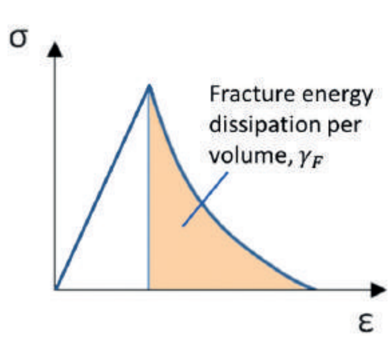


Figure 8. Typical constitutive relationship of concrete when subjected to tension

As the width of the crack width h_c is independent of specimen size, the fracture energy E_F, which is obtained by multiplying γ_F by the cross sectional area and h_c, is proportional to the cross-sectional area of the specimen. In order to adopt replica scaling, the E_F must be scaled by β_L^2. Therefore, a smaller specimen will consume more than proportionate energy and appear to be stronger as compared to a large specimen in resisting fracture.

Due to the three abovementioned parameters (gravity, strain rate and crack energy) that do not scale, it may not be that straightforward to conduct a small-scale test and apply replica scaling to the physical observations to derive recommendations and guidelines. However, the extent of influence of these parameters to differentiate the response from the model to the prototype structures will depend on the test configuration and requirements. For example, in situations when the rate of load is slow enough, the non-scalability of strain rate effect would not be significant. Therefore, it is important to assess the appropriateness of conducting a scaled test, and numerical modelling could be an important tool before launching into an experimental campaign.

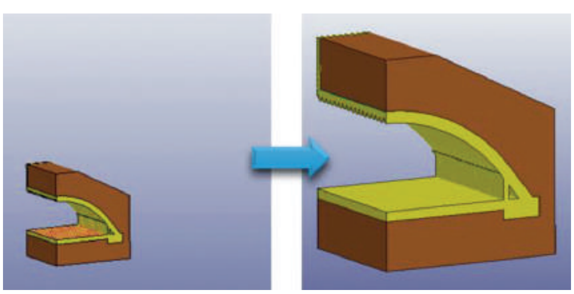
NUMERICAL MODELLING – THE BRIDGE

Numerical models are powerful and effective tools in protective engineering as they have the capability to simulate of the effects of explosions in a virtual environment, without the need to subject actual buildings and infrastructure to real explosions. By solving fundamental physics equations from first principles, these models are able to predict the outcome from complex structural configurations which are subjected to highly dynamic loadings, some of which can happen in less than a millisecond. Despite the long computational time required to calculate the output, the resource required is a fraction of the time and manpower required to execute the scenario physically. In addition, it also eliminates the hazards associated with handling of explosives and highly dynamic systems.

Similar to conducting experiments, numerical modelling is a niche domain that requires both engineering know-how and experience. As such, it is normally limited to a small number of expert users. Another similarity is the fact that these models may be subjected to errors and uncertainties. Although these can be minimised through working with experienced personnel and well-developed codes and software, verification and validation (V&V) using physical models is important to benchmark the models and forms a crucial step in the design process. However, in the event that there are no experiments to conduct V&V, numerical models can still contribute to the design process by being the platform which can quantitatively assess the influence of certain changes to the inputs, such as non-scaling parameters (i.e. parameters that do not scale by just reducing the specimens size accordingly).

In order to illustrate the influence of gravity and strain rate effects on replica scaling, a study to determine if a buried reinforced concrete arch structure is capable of sustaining an accidental detonation of explosive stored within will be used. An example of such a test structure model is shown in Figure 9(a) and the scaling study will be conducted using numerical models as shown in Figure 9(b). In optimising the calculation efficiency, a quarter symmetry is assumed since the charge is placed at the centre of the arch compartment. In addition, the small-scale model is three times (3x) smaller than the large-scale prototype.

(a)



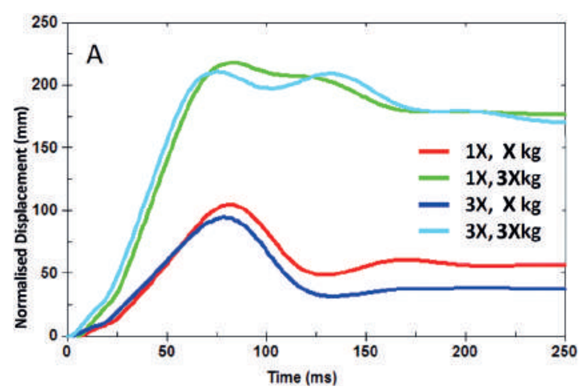
(b)

Figure 9. (a) Experimental set-up and (b) numerical model showing quarter symmetry adopted in the numerical model

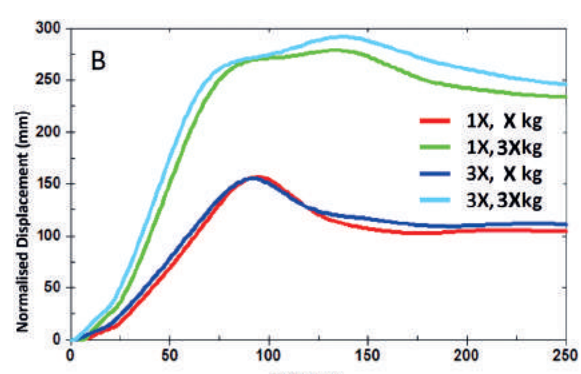
It is essential to bound the problem, which in this case would be to investigate the influence of the non-scaling parameters between two explosive quantities: Xkg and Ykg (in model scale), where $X < Y$. Figure 10 plots the normalised displacement histories at the crown of the arch models in various scale and charge weights. While Figure 10(a) plots the normalised displacement histories assuming that the non-scaling parameters are activated, Figure 10(b) plots are based on the models where non-scaling parameters are switched off (i.e. the model does not include gravitational forces and strain rate effects). It can be deduced that the influence of non-scaling parameters such as gravity and strain rate effects are not significant to the structural response based on the following observations:

(a) Considering gravity was not scaled up and strain rate effects were scaled down in the model, it can be seen in Figure 10(a) that the differences in the normalised displacement histories between the model (1x) and prototype (3x) were not significant for both charge weights.

(b) In Figure 10(b), where the displacement histories of the model (1x) and prototype (3x) without the non-scaling parameters of gravity and strain rate were plotted, a closer correlation between the model and prototype response was observed as compared to the corresponding cases in Figure 10(b). The response in Figure 10(b) was more extensive than those observed in Figure 10(a) as there was no downward mitigating effects from the earth overburden and no strength enhancements from high strain rates. These slight differences between the model and prototype was due to the non-scalability of fracture energy and potential other numerical approximations in the calculations.



(a)



(b)

Figure 10. Scaled arch crown displacement history of the model and prototype models (a) with and (b) without the influence of the non-scaling parameters

As such, in the above scenario, it is appropriate to conduct scaled experiments to:

- Draw conclusions from the structural response observed in the experimental small-scale models for application in the actual large-scale structure.

- Conduct V&V of the small-scale numerical mode to enhance the predictability of the numerical modelling technique for the large-scale response.

PROPOSED APPROACH WITH EXAMPLES

Drawing upon the capability of small-scale explosive field model tests and numerical modelling, an approach to assess the explosive hazards effects from the accidential explosion of ammunition storehouses is proposed by utilising a combination of these two methods (see Figure 11). As mentioned in the preceding paragraph, the small-scale tests would be used to conduct V&V of the numerical models. Subsequently, the same models which are scalable, could then be 'upscaled' to predict the response and hazards of actual ammunitions storehouses. This approach will negate the need to conduct expensive large-scale explosive field tests which may also be impracticable and impossible to conduct locally.

Two examples of the proposed approach have been successfully adopted by DSTA to illustrate the viability and practically of this approach. They are the arch type structure and the box type structure as shown in Figure 12.

For the arch type structure, the test structure was a scaled down (1:5) version of the actual structure of interest. The arch structures were subjected to internal detonation of loading densities ranging between 1kg/m^3 and 2kg/m^3. Various instruments such as pressure gauges and high speed camera were installed to obtain the required data, such as external blast pressure, door and debris throw angles and velocities and structural response (see Figure 13).

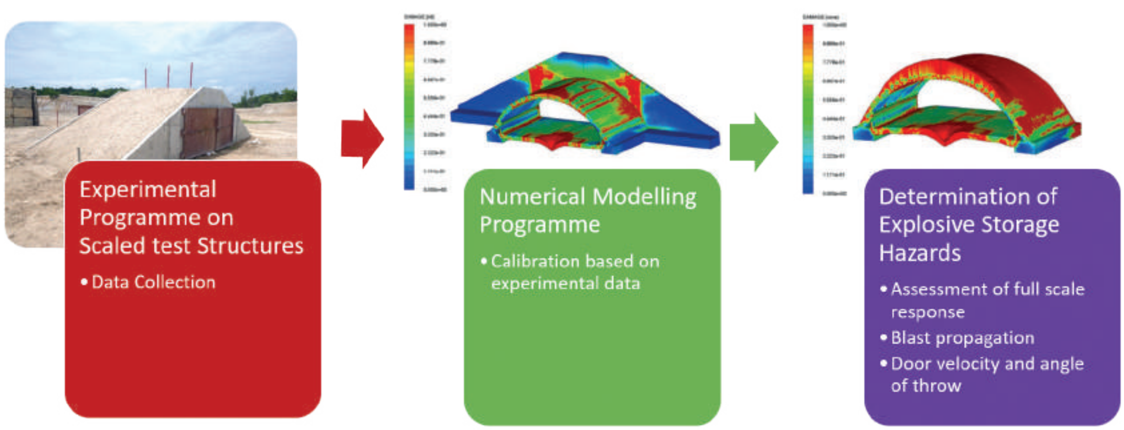


Figure 11. Schematic diagram of the proposed approach – utilisation of small-scale explosive test and calibrated numerical model to predict responses of actual scale structures

(a)

(b)

Figure 12. Photographs of small-scale text structures: (a) arch type and (b) box type

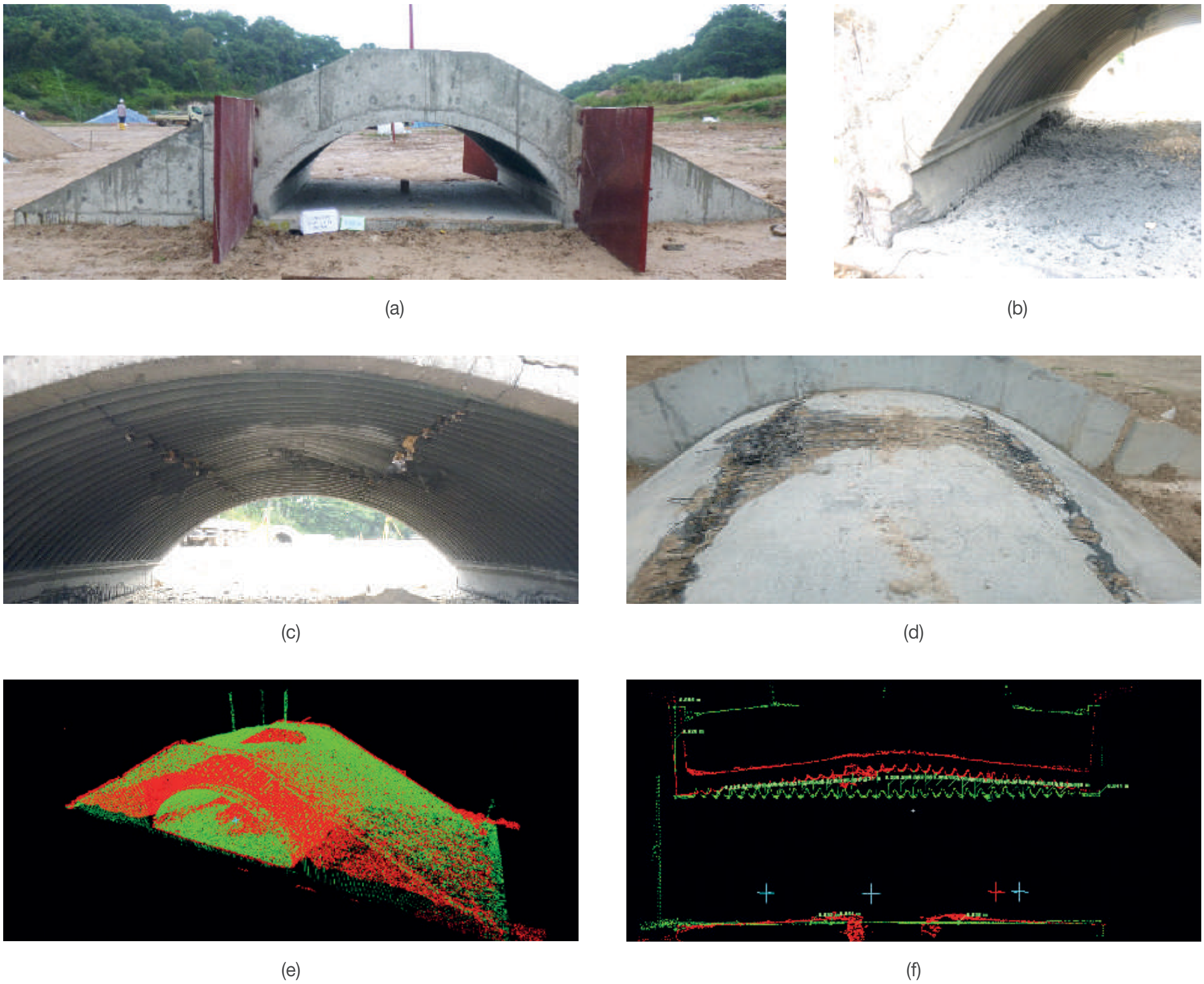


Figure 13. Illustrations of the arch test: (a) elevation view; (b) internal damage of the side wall; (c) internal damage of the roof; (d) external damage of the roof; (e) Light Detection and Ranging (LIDAR) scan overview; and (f) LIDAR scan sectional view (red signify deformed shape after test)

The collected data were compared with the numerical models developed with the Ernst Mach Institut of Germany. From the comparison, reasonable fit was established between the test and simulated results (Figure 14) thus enhancing confidence of its usage. Using the calibrated model, the full-scale structure of the interest was then simulated and the explosive hazards such as blast pressure, door throw velocity and angles were obtained.

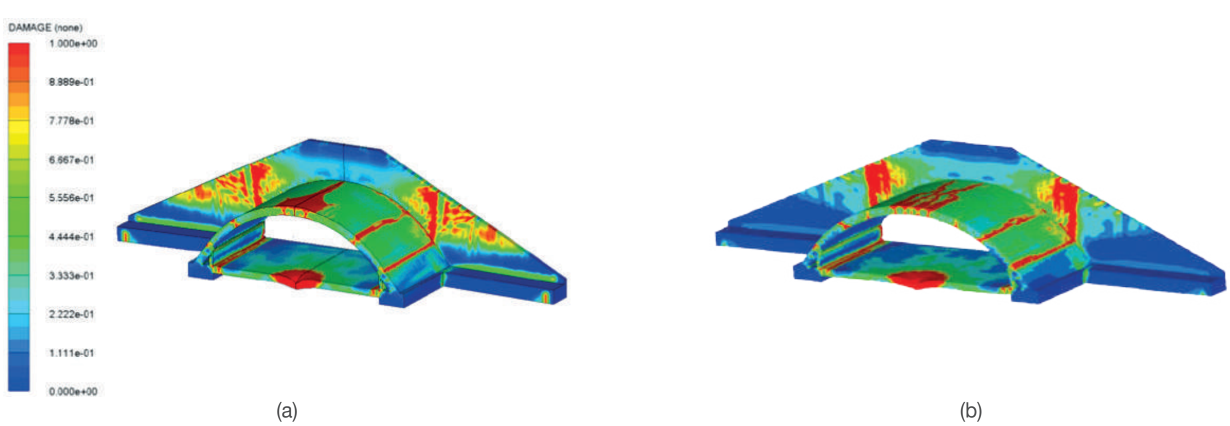
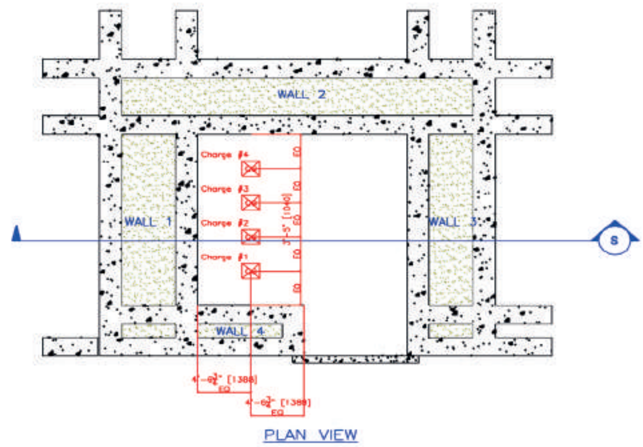


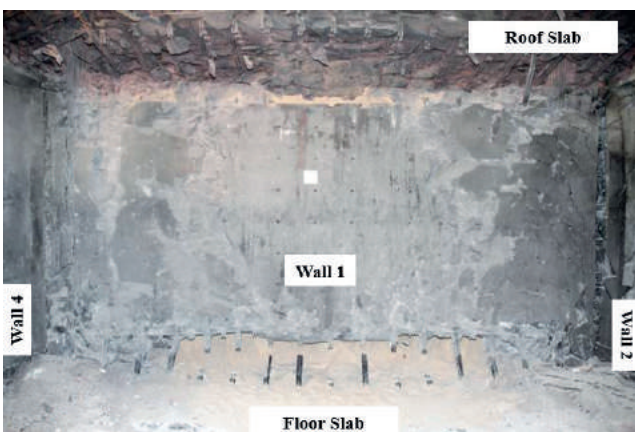
Figure 14. Illustrations of the simulation results: (a) small-scale test simulations; and (b) large-scale test simulations

For the box type structure, the test structure was a scaled down (1:2) version of the actual structure of interest. The box structure with four composite walls (reinforced concrete wall infilled with sand) was subjected to internal detonation of loading density of approximately 10kg/m^3. Various instrumentation such as pressure gauges and high speed camera were installed to obtain the required data, such as internal and external blast pressure, debris throw angles and velocities and structural response, as shown in Figure 15.

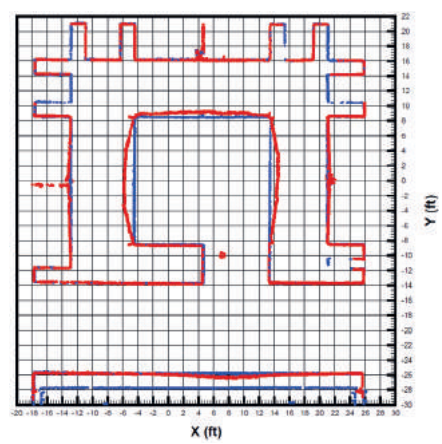
(a)



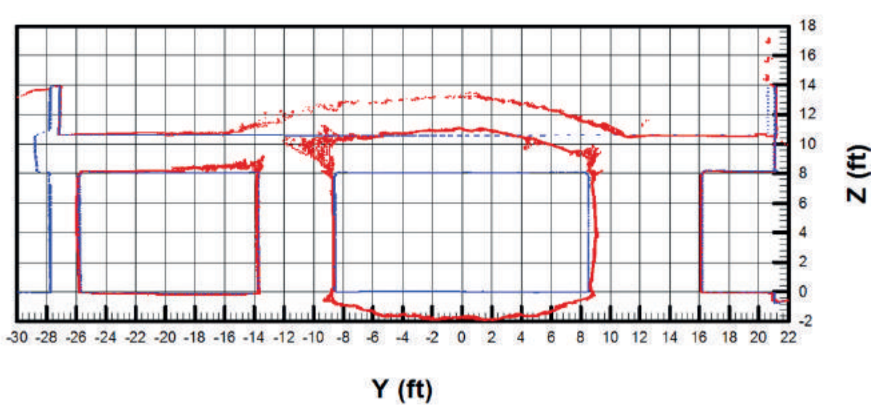
(b)



(c)



(d)



(e)

Figure 15. Illustrations of the box test: (a) isometric view; (b) plan view of the test structure; (c) internal damage of the test structure; (d) LIDAR scan plan view; and (e) LIDAR scan of the elevation view (red colour shows the deformed shape after test)

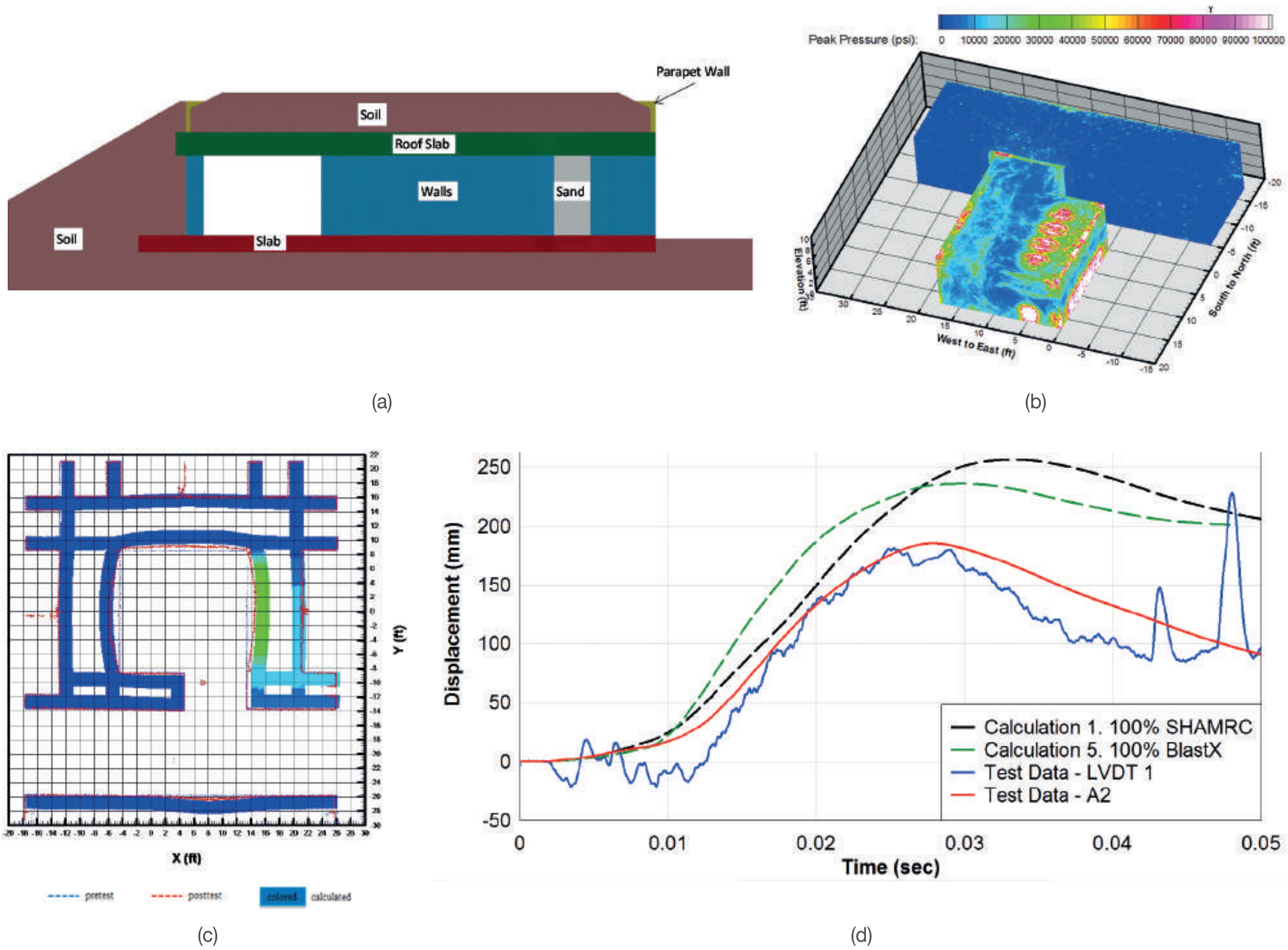


Figure 16. Illustrations of the simulation results: (a) numerical models section view; (b) internal blast pressure simulations; (c) plan view of simulation results; and (d) comparison of displacement results between tests and simulations

Similarly, the collected data were compared with the numerical models developed (see Figure 16). From the comparison, reasonable fit was established between the test and simulated results thus enhancing confidence of it usage.

INTERNATIONAL COLLABORATION AND PEER REVIEW

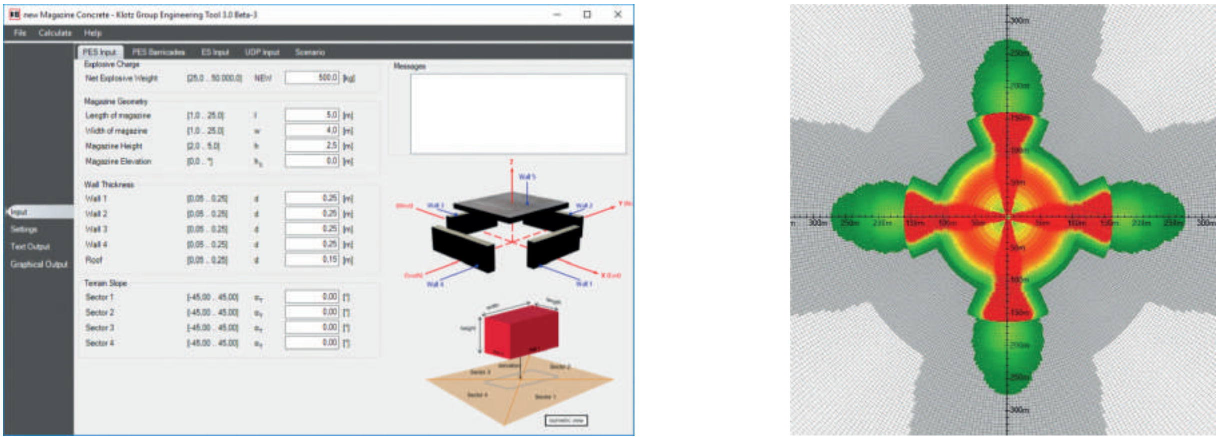
In addition to small-scale experiments coupled with numerical simulation, it is important to seek critical review of the approach and work with expert panels, to tap into a wider knowledge bank and ensure the assumptions made are relevant and correct. In the area of explosive safety, DSTA represents Singapore in several of these panels and groups. One of these working groups is Klotz Group, which consists of experts from eight nations[2] who collaborate with these objectives:

(a) To improve the knowledge base on ammunition and explosive effects with the storage, processing and transport of ammunition and explosives.

(b) To develop engineering databases to quantify the explosion effects that enable safety focused consequence assessments and risk analyses.

One of the main products from this collaboration is the Klotz Group-Engineering Tool (KGET), which is a fast running software to predict the hazardous secondary fragments or debris from internal detonations. Figure 17 shows screenshots from the KGET.

DSTA also participates in the Conference of National Armaments Directors (CNAD) Ammunition Safety Group codenamed AC/326 in NATO. AC/326 is responsible for ammunition life



(a) (b)

Figure 17. Screenshots of the (a) input fields and (b) one of the graphical outputs showing the debris density map of KGET

cycle safety in support of NATO priorities. This group is also charged with standardisation in explosive safety. As such, it is not just a forum for Singapore to seek critical review but also a means to be updated on the latest developments and guidelines in this field.

LIMITATIONS AND RANGE OF VALIDITY

It is critical to understand the limitations of the proposed approach. This approach is only applicable for explosive storehouses that do not rupture under internal explosion as the debris hazard range generated is not scalable due to gravity effects. The range of validity of the approach is summarised in Table 3.

S/N	Parameters	Valid For	Remarks
1	Type of Structure	Box and Arch	
2	Loading Density	1-10kg/m^3	
3	Scale of test structure	1:2 to 1:5	1:1 depict full-scale test
4	Structural Response	Non- rupture	
5	Hazards	Blast, door throw velocity and angles	No structural debris are generated

Table 3. Summary of the validity range of this approach

CONCLUSION

There is a strong need for innovative explosive safety solutions in Singapore due to land scarcity. However, for the same reason, it is a challenge to adopt the conventional approach of large-scale tests to develop new types of explosive storehouses to reduce the sterilised land. In this chicken-and-egg situation, DSTA is adopting a hybrid approach to combine small-scale explosive field tests and numerical modelling to overcome this constraint. Not only does this technique negates the need for extensive resources to conduct full-scale tests, the two components complement each other by covering individual shortfalls. However, there are limitations to such an approach and they should be considered before adoption.

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ENDNOTES

1 Inhabited Building Distance is defined as the distance where the allowable blast pressure from an accidential explosion from a Potential Explosion Site is less than 5kPa and that the lethal (debris with kinetic energy > 79J) debris density is less than 1/56 m^2.

2 The participating nations of Klotz Group includes Germany, Norway, Singapore, Switzerland, Sweden, the Netherlands, United Kingdom and the United States of America.

BIOGRAPHY

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OPERATING AND SUPPORTING THREE GENERATIONS OF WEAPON LOCATING RADARS

TAN Jit Yong, LEE Chee Hoong, CHUA Wah Seng

ABSTRACT

The SAF started deploying Weapon Locating Radars (WLR) in the 1980s. In the early 2000s, a highly mobile weapon locating system was acquired to supplement the first generation fleet of WLRs. Recently, the Army inducted the third generation of WLRs. Technological evolution in antenna, microwave and computer processors has significantly influenced radar applications and capabilities. These advances and their outcomes are evident across the three generations of WLRs. For example, the performance envelope, reliability, and supportability of the third generation WLRs based on an active electronically scanned array are unlike the first generation WLRs utilising a passive electronically scanned array. Consequently, operational and maintenance support concepts and practices have evolved. However, these advances and enhancements have their own pain points and trade-offs. This article will share the evolution across different generations of WLRs, with a focus on the operations and support aspects.

Keywords: radar, antenna architecture, processor, operations & support, built-in test, mean-time-between-failure, human-machine-interface

ROLES AND BASIC PRINCIPLES OF WEAPON LOCATING RADARS

Indirect fire weapons[1] like rockets, artillery guns, and mortars (collectively termed RAM) are typically deployed behind and fired over undulating terrain at objectives not in the line of sight of the RAM launchers. A Weapon Locating Radar (WLR), as the name suggests, is deployed to detect and locate adversary RAM units when they fire so that a swift response can be directed to take out the 'shoot-and-scoot' launchers. Commonly known as a Hostile Weapon Locating (HWL) mission, the process involves several steps (see Figure 1 and 2):

(a) Establish a search fence by electronically scanning the horizon several times per second (aka revisit time)

(b) Intercept an incoming projectile in its ascending trajectory

(c) Verify the initial detection in order to handle any false alarm

(d) Track the projectile along its ascending trajectory

(e) Simultaneously extrapolate back along the trajectory to predict and report the launch point (LP) and forward along the trajectory to predict and report the projectile impact point (IP)

Depending on the antenna elevation coverage and projectile trajectory, tracking the projectile can take several seconds, to collate sufficient track measurement points to predict the LP and IP. Thus, the entire process from initial projectile interception to LP and IP reporting can take tens of seconds. A few key indicators define a WLR capability, namely the probability of locating the launchers, LP and IP reporting accuracies, and confidence in target classification (whether it is a rocket, artillery gun, or mortar).

A secondary role of a WLR is to support friendly fire elements. When operating in a Friendly Fire Registration (FFR) mission, as illustrated in Figure 3, the WLR sets up a 'window' through which its own RAM projectile will pass through. Unlike the HWL's search fence, this 'window' is established a priori based on own fire orders. This allows the WLR to track the projectile in its descending trajectory and extrapolate forward along the trajectory to predict its impact point. This information is used to compute fire correction data for its own RAM launcher to improve firing accuracy.

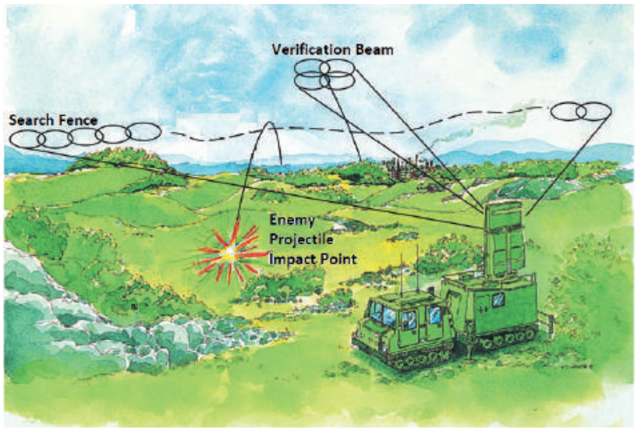

Figure 1. WLR's HWL mission

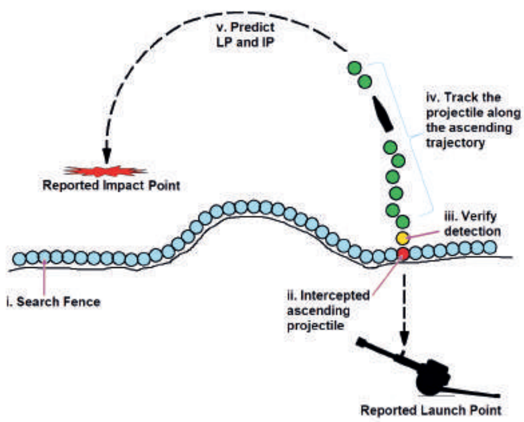

Figure 2. Search, detection, verification, and tracking process of a HWL mission

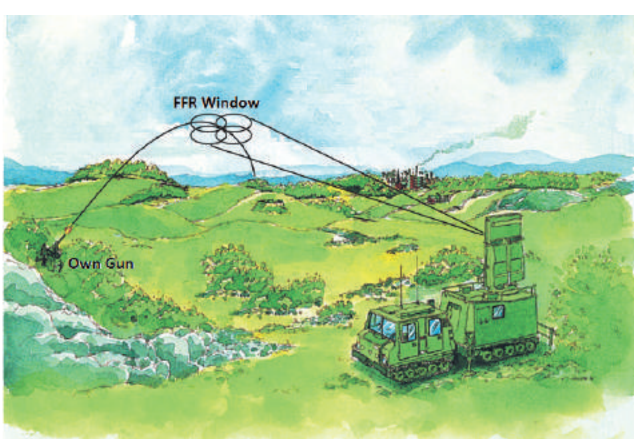

Figure 3. WLR's FFR mission

THE SAF'S FIRST GENERATION WLRs – TPQ36 & TPQ37

The TPQ36 and TPQ37, presented in Figure 4, were developed in the 1970s. The SAF acquired and fielded them in the mid-1980s and early 1990s, respectively. Back then, they were considered state-of-the-art systems because they were among the first systems to introduce two-dimensional electronically steering array (ESA) for beam flexibility. The two-dimensional ESA has an antenna beam electronically steered in both the azimuth and elevation planes, to carry out dedicated search and track of extremely small radar cross section (RCS[2]) projectiles. For example, an artillery shell has an RCS of $0.001m^2$. In comparison, an air surveillance radar typically employed a one-dimensional ESA. The one-dimensional ESA has an antenna beam electronically steered in elevation while mechanically steered in azimuth, to perform track-while-search[3] of aerial targets that were more than 1,000 times larger than a RAM projectile. Those were the days before the advent of stealth aircraft and small drones.

TPQ36 and TPQ37 played complementary roles in the battlefield, with the TPQ36 covering the short-range and the TPQ37 covering the long-range. Both have a similar configuration, comprising the (a) Antenna Transceiver Group (ATG), which comprises a passive ESA (PESA) antenna and travelling wave tube (TWT)-based transmitter; (b) Operations Control Group (OCG), essentially where all the processing and controls are carried out; and (c) Diesel Generator Unit (DGU).

The key distinction between the TPQ36 and TPQ37 lies in the ATG due to the following:

(a) **Frequency band** – TPQ36 operates in X-band, whereas TPQ37 operates in S-band.

(b) **Effective Radiated Power[4] (ERP)** – TPQ37 has a larger antenna and more powerful transmitter necessary to achieve a higher ERP to fulfil its long-range role.

(c) **Transmitter** – TPQ37's more powerful TWT-based transmitter operates at a higher transmission duty cycle[5] that requires liquid-cooling. TPQ36's TWT-based transmitter operates at a lower duty cycle with air-cooling and thus has simpler configuration.

(d) **Antenna Architecture** – While both antennas are PESA technology, they differ in their electronic scanning mechanisms. The TPQ36 does phase scanning in azimuth and frequency scanning in elevation. Electronically controlled phase shifters are used to steer the beam along the horizontal plane, while a sequence of contiguous transmissions at different frequencies is used to steer the beam in the vertical plane. The TPQ37 does phase scanning in both azimuth and elevation planes, and there are phase shifters in both planes.

Figure 4. TPQ36 (top) and TPQ37 (bottom)

TPQ36 and TPQ37 use similar back-end hardware in their OCG. The first generation signal processor (SP) comprises 128 single-layer Circuit Card Assemblies (CCA). The radar computer has a 128KB RAM and software programmes residing in a 2MB magnetic tape. The human-machine-interface (HMI) comprises a rotatable map drum, a Cathode Ray Tube (CRT) monitor called the B-scope, an alphanumeric keypad and trackball. Some of these hardware are highlighted in Figure 5.

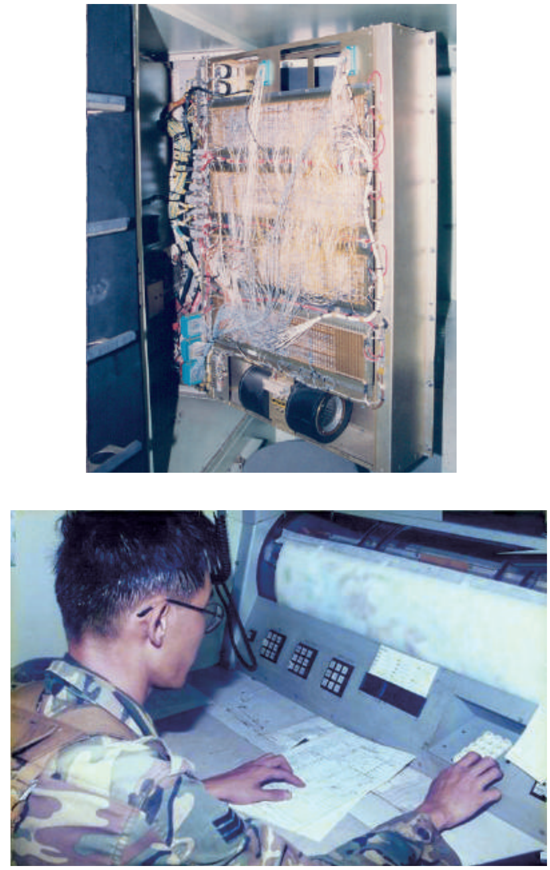

Figure 5. Inside the OCG: SP back plane (left) and HMI (right)

Operating and supporting the TPQ36 and TPQ37 was labour-intensive and time-consuming, as outlined:

(a) Each system was manned by a crew of eight men and set-up took 30 minutes. Interconnecting the ATG, OCG and DGU units required five men to lay out three cables physically, with each cable up to 50m in length and 150kg in weight. Levelling the ATG required the four legs to be manually cranked. When the transmitter was switched on, it took a few minutes to warm up, similar to the cathode ray tube television of the old days.

(b) Routine processes and controls relied heavily on hardware like magnetic tapes, LEDs, switches and map drums. Booting up or rebooting the computer required winding and unwinding the magnetic tape to load software programmes. To report the LP and IP, a computer-controlled servomotor would physically roll the map drum to the proper northing coordinates and a small light spot projected onto the map from inside the drum indicated the easting coordinates.

Figure 6. Signal tracing using circuit diagrams

(c) Troubleshooting was laborious and hazardous. Handling the bulky transmitter and its peripherals required at least two men and it was a hazardous undertaking as it involved high voltage power supply. Troubleshooting the SP back plane, where each CCA had 100 pins mated to the SP back plane pin plate and the 128 CCAs were connected via more than 10,000 wire-wrapping, could take more than an hour as it involved signal tracing over several pages of circuit diagrams (see Figure 6).

(d) The basic ops-loading list (BOLL, aka field level spares and consumables) comprised more than 500 line item types. Field test equipment included the bulky oscilloscope and spectrum analyser.

SECOND GENERATION WLR – ARTHUR

ARTHUR (see Figure 7), an acronym for '**ART**illery **HU**nting **R**adar', is a C-band radar introduced into service in the early 2000s to complement the fleet of TPQ36 and TPQ37. Unlike the TPQ's separate OCG, ATG and DGU units, ARTHUR's hardware is contained in a 10ft rear cabin of the track articulated all-terrain carrier Bandvagn 206 to meet its mobility role. Size, weight, power, and cooling (SWaP-C) were thus critical considerations in the conception, design, and equipment layout of ARTHUR.

(a) Its antenna is stowed and deployed on the roof of the rear cabin. To keep the antenna architecture simple and lightweight, it features PESA technology that carries out phase scanning in azimuth and frequency scanning in elevation to steer the beam, similar to TPQ36.

(b) Hardware count is significantly reduced as ARTHUR leverages powerful processors, multi-processing computers and software. Radar processing can be carried out with less than 10 CCAs. Software programmes and Digital Terrain Elevation Data (DTED) maps are installed in a 2GB hard disk. Its HMI comprises a LCD monitor, keyboard and mouse, which presents a pleasant user experience.

(c) An on-board generator relies on the vehicle engine and resides in the front cabin. This requires the vehicle engine to run as long as the radar was in operation.

(d) It is manned by a crew of four and is set up in less than 10 minutes.

(e) BOLL comprises less than 200 line item types.

Figure 7. ARTHUR

Though ARTHUR is significantly smaller in SWaP-C compared to TPQ37, it has a similar performance envelop by exploiting the latest technology in radar radio frequency (RF) generation and computer hardware. Advances in RF generation achieved the desired RF spectral purity and signal stability over a wide instantaneous bandwidth, which is necessary to carry out coherent Doppler processing in order to handle non-stationary and non-homogenous clutter conditions. A RF receiver complemented this with improved sensitivity and lower noise figure. Finally, it was also important that field programmable gated array processors were introduced to run complex radar signal and data processing algorithms (e.g. Doppler filtering, adaptive false alarm rate processing, fine resolution clutter maps and fuzzy logics). This will enable good sub-clutter visibility[6] in order to enhance the target signal-to-returns (clutter and noise), thus improving target detectability.

There was also ingenuity in exploiting inherent design features, which might at first be deemed a limitation. ARTHUR's frequency scanning in elevation deprives it from the performance and operational benefits of exploiting frequency change or diversity. For a given search beam position, the transmission frequency would remain the same on successive scans. Thus, if a RAM projectile happens to present a weak RCS in that position, successive scans may not improve the projectile's detectability. To overcome this limitation, an innovative feature was introduced to transmit a different frequency at the same beam position. A slight change in frequency can drastically alter the RCS, essentially changing the RCS profile. This improved the projectile's detectability and tracking accuracy.

Generally, compared with the TPQs, troubleshooting and recovery from an ARTHUR defect is quicker and less laborious, as it is largely driven by enhanced built-in-tests (BIT) powered by computers and software. With BIT, technicians and even operator-maintainers can easily identify a faulty module and replace it. There is no longer a need to carry bulky and generic test equipment for troubleshooting as most signals are monitored and reported by the radar computer.

THIRD GENERATION WLR – SAFARI

The SAFARI WLR (see Figure 8) was introduced into service in the mid-2010s to modernise the physically aging and technologically obsolete WLR fleet. It is a highly compact radar configured on a locally built track articulated BRONCO platform.

Figure 8. SAFARI

On the exterior, SAFARI looks similar to ARTHUR, but there are distinct differences in their antenna technologies that are key to the SAFARI's superior performance and availability. The first WLR to introduce active ESA (AESA) technology, its AESA antenna enjoys several advantages over the first and second generation WLRs:

(a) The SAFARI antenna is populated with hundreds of solid-state transmit and receive modules (TRM), which allows it to enjoy a high availability and graceful degradation. It can continue to operate when there are the occasional TRM failures. Primarily for this reason, mean-time-between-critical failures (MTBCF) was adopted instead of the commonly used mean-time-between-failures (MTBF) associated with a single point of failure.

(b) Its beam steering network allows it to steer the beam electronically wider in azimuth and higher in elevation to increase its spatial coverage.

(c) It employs dual-axis multi-beamforming consisting of multiple simultaneous receive beams in azimuth and elevation to increase the radar dwell time aka 'time-on-target' to detect further.

Drawing a lesson learnt from ARTHUR's reliance on its vehicle engine to draw power and to keep within the SWaP-C constraint of the BRONCO vehicle, a novel Integrated Power and Cooling System (IPCS) independent of the vehicle engine and peripherals was introduced. The IPCS supplies power to the radar and provides cooling to the cabin interiors for operator comfort and equipment well-being. Thus, any vehicle engine issues will not affect radar operations.

EVOLUTION ACROSS THE THREE GENERATIONS OF WEAPON LOCATING RADARS

A comparison between the three generations of WLRs is summarised in Table 1. It provides an outline of how technologies in antenna, microwave, and computer processors have advanced, and their positive influences on radar performance, operations and support.

The shift from PESA to AESA has been a significant game changer for radar applications. Generally in a PESA radar, the focus is on short pulse widths due to the high peak power and low duty cycle offering of microwave tube-based transmitters. It was about 'power-on-target'. Power is the defining factor in specifying and realising a radar capability. The advent of AESA, with their high duty cycle TRMs and the ability to accomplish multi-beamforming shifted the radar focus to 'time-on-target' (or 'energy-on-target'). Another advantage of AESA over PESA is eliminating the need for external RF waveguides. Depending on the length (rigid or flexible) and type of waveguides (choice of material like aluminium or copper), the RF loss between the transmitter and antenna radiating elements is significant. For

	Generation 1		Generation 2	Generation 3
	TPQ36	**TPQ37**	**ARTHUR**	**SAFARI**
Development Era	1970s		1990s	2010s
Antenna	PESA (phase scanning in azimuth; frequency scanning in elevation)	PESA (phase scanning in both azimuth and elevation)	PESA (phase scanning in azimuth; frequency scanning in elevation)	AESA (phase scanning in both azimuth and elevation)
Transmitter	Air-cooled TWT	Liquid-cooled TWT	Air-cooled TWT	Few hundreds TRM
Signal Processor	128 CCAs		< 10 CCAs	< 10 CCAs
Computer	128KB RAM; magnetic tape		2GB hard disk	64GB solid-state drive
Human-Machine-Interface	B-scope; map drum; indicator lights; trackball		LCD monitor; keyboard; mouse	LCD monitor; keyboard; mouse
Power & Cooling	Two generator sets; one air-con		One generator (relied on vehicle engine); one air-con	Integrated power and cooling system
Performance Envelope	1x	2x	2x	> 4x
Crew Size	8		4	4
Emplacement Time	30mins		< 10mins	< 10mins
MTBF	100hrs	90hrs	550hrs	810hrs[7]
MTTR	2hrs		60mins	< 45mins

Table 1. Summary of comparison between three generations of WLRs

example, the two-way RF loss of the ARTHUR waveguide is about 1dB. It also saves on the need to service the waveguides.

A complementary and critical aspect of AESA is the increasing levels of digitalisation within the antenna. High performance digital circuits (e.g. analogue-to-digital and digital-to-analogue converters as well as networks) enable ease and speed of conversion of analogue radar signals to digital signals. Once converted to digital signals, powerful digital signal processors and commercial off-the-shelf microprocessors enable complex radar signal and data processing algorithms to be executed in real time, to enhance small target detection and target classification.

On the other hand, the AESA antenna brings a high degree of sophistication that requires a corresponding level of service attention compared to the simplicity of PESA. As the antenna is 'active' with numerous transmitters and electronic circuits, electrical power and thermal management is critical to ensure a healthy and stable environment within the antenna. Given its importance and complexity, more maintenance time and resources are allocated to SAFARI's AESA compared to the TPQs, where attention was mainly on the transmitter and signal processor rack.

The advancement and proliferation of computers and software also benefitted WLR operations and support. It enhanced user experience in setting up and operating the WLR. This is evident when comparing the HMI of TPQs, ARTHUR and SAFARI. In the TPQ, the operator is required to recall and enter the right function codes (there are about 50 function codes) to set up the radar. In SAFARI, the corresponding actions require a few intuitive mouse clicks.

It has also improved BIT to aid in the troubleshooting of equipment defects and ultimately enhance system availability. Paradoxically, with increasingly enhanced BIT coverage and system availability, technicians have fewer opportunities to hone their troubleshooting skills and maintain currency. It is also increasingly challenging for BIT to catch up with the industry trend of developing critical embedded systems assembled from off-the-shelf hardware and software components. The increasing levels of hardware and software dependencies have resulted in increasing ambiguities in troubleshooting and identifying where the defect lies, which then require the intervention of technicians. Therefore, there are two challenges. The first lies in providing sufficient hands-on exposure and maintaining currency. The second is the need to develop software and IT competencies in addition to the traditional electrical and mechanical expertise of the technicians.

Mobility and smaller platforms will continue to put pressure on SWaP-C. While increasing levels of hardware miniaturisation and hardware-software integration have mitigated SWaP-C constraints, an overemphasis to deliver a compact system comes with operations and support trade-offs. There may be insufficient room to incorporate redundancy of critical subsystems, thus compromising mission availability. Confined space may restrict operator movements and technician workspace. For example, the highly compact and integrated IPCS of SAFARI has limited the field maintenance scope.

FUTURE OF WLRs

Just as in the beginning with the introduction of TPQs, stringent WLR missions will continue to demand state-of-the-art technology and applications. With its inherent demands to detect and track extremely small RCS projectiles, there is potential to go beyond the classical WLR role to include supporting counter-RAM mission and detecting drones. Supporting a counter-RAM mission to intercept the incoming threat requires the WLR to increase its elevation coverage, in order to track the projectile along the entire trajectory. Detecting drones requires increased 'time-on-target' to detect and classify low-flying, slow-moving and small drones while contending with distractions like birds, road and pedestrian traffic.

To improve radar availability and optimise operator workload, there are initiatives to introduce condition-based maintenance (CbM). Radars typically rely on classical practices for its upkeep. This includes a preventive maintenance regime to carry out calendar-based activities, and a corrective maintenance regime based on BIT to recover the radar after a fault has occurred. CbM based on health monitoring and alerting will allow for early detection and identification of developing faults so that timely actions can be taken. Such initiatives can also apply to WLRs.

CONCLUSION

This article discussed how radar technologies, capabilities, as well as operations and support practices have evolved over three generations of WLRs. Compared to the first generation WLR, the third generation WLR is manned by half the crew size, more than two times capable, significantly quicker and easier to deploy and handle, and more reliable[7]. A powerful BIT makes it easier to troubleshoot and recover from equipment defects, thus enhancing system availability. However, defects are increasingly sophisticated and ambiguous due to the increasing hardware and software dependencies associated with new technologies. This requires the technicians' skill sets to expand beyond the traditional electrical and mechanical expertise to include software and IT competencies.

ACKNOWLEDGEMENTS

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REFERENCE

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ENDNOTES

1 NATO defines indirect fire as "fire delivered at a target which cannot be seen by the aimer". The target may be beyond the horizon or at a far distance away behind a terrain and thus beyond the fire's line-of-sight.

2 A target is ascribed an effective area called the radar cross section (RCS), which is a measure of the proportion of incident energy reflected back to the radar. RCS varies with a multitude of parameters such as transmitted frequency, target geometry, orientation and reflectivity.

3 As all the radar time-energy resource were dedicated to search, target tracking was carried out passively, thus the expression track-while-scan (or track-while-search). A target track would be updated when there was a detection during the search process; if there was no detection, the target track position would be predicted for reporting to allow for track continuity.

4 Effective Radiated Power is the product of antenna gain and average transmission power.

5 Duty cycle is the fraction of time that the radar is in active transmission. It is the product of pulse width and pulse repetition frequency.

6 Often target signals are masked in clutter returns that can be 1000 times or more strong. This requires good sub-clutter visibility, which is a measure of a radar's ability to "see through" clutter in order to detect weak target signals.

7 Mean-Time-Between-Critical-Failure is used to better depict the system reliability as there is a high level of redundancy of transmit and receive modules in the active electronically steering array that allows for graceful performance degradation.

BIOGRAPHY

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DESIGN AND INTEGRATION OF THE LITTORAL MISSION VESSELS' LAUNCH AND RECOVERY SYSTEM FOR FAST RESPONSE CRAFT

WONG Bingxiong David, TAN Yi Ming Justin, CHEW Boon How, KOH Leong Nigel, GAN Su-Shan Tessa

ABSTRACT

The deployment of fast response craft at sea is essential for a range of navy missions including maritime security and search-and-rescue. Traditional launch and recovery of fast response craft like rigid-hull boats and unmanned surface vessels employ side davits and cranes. In light of evolving technology, multi-role navy vessels like the Republic of Singapore Navy's (RSN) *Independence*-class Littoral Mission Vessel have incorporated stern ramp Launch and Recovery Systems (LARS) to overcome the slower deployment times associated with cranes and davits. Twin stern ramp LARS are suitable for the requirements of multi-craft operability, while achieving faster craft launch and recovery with fewer deck crew required. This article compares LARS designs and outlines the integration process for stern ramp LARS applicable for multi-role naval vessels.

Keywords: launch and recovery systems, littoral mission vessel, unmanned surface vessels

INTRODUCTION

The deployment of fast response craft such as Rigid Hull Boats (RHB) and Unmanned Surface Vessels (USV) from navy and coast guard ships is essential to the success of seagoing missions. Collectively termed fast craft, these assets are typically reconfigurable and offer cost-effective alternatives in conducting missions ranging from maritime enforcement, salvage, drug and migrant interdiction, and rescue insertion/extraction.

During high tempo operations, the deployment and recovery of fast craft make for shorter mission turnaround duration. Traditional over-the-side launch and recovery systems (LARS) typically require 15 minutes to deploy or recover a fast craft. Deck crews from the mothership are required to handle painter lines attached to fast craft to prevent uncontrolled movement throughout the launch and recovery process. At higher sea-states, the mothership has to create a lagoon of flat waters by performing an inward turning-circle manoeuvre, to aid the launching. For time-sensitive operations such as drug interdiction, 15 minutes makes all the difference between a successful interdiction and futile pursuit. Navy and Coast Guard vessels seeking shorter fast craft deployment time or multi-craft operability are turning to stern ramp LARS to meet their operational requirements. The advantages of stern ramp LARS are shorter deployment times, and lower manpower costs associated with launch and recovery.

This article summarises the team's assessment of LARS designs, and outlines the design evaluation and integration process for the Littoral Mission Vessel's (LMV) stern ramp LARS. The processes outlined are applicable for evaluation and integration of LARS on other naval vessels.

LAUNCH AND RECOVERY SYSTEMS

Several LARS designs were evaluated against the LMV's requirements for the efficient launch and recovery of multiple craft types from the mothership. It was also desired for minimal deck crew to perform launch and recovery operations. There are two broad classes of LARS for naval vessels – davit systems and stern ramp systems.

Davit Launch and Recovery Systems

Davit systems employ hydraulically powered cranes or rigid frames to manoeuvre the fast craft over the sides of the mothership, as shown in Figure 1. This is followed by lowering or raising the fast craft with a series of motorised winches. More complex systems on the market feature additional sensors and winch tensioners to support launch and recovery of fast craft in higher sea-states. An open literature survey concluded that davit systems typically require a crew of four and 15 minutes for launch or recovery. The typical deck crew requirements are one supervisor, two deck hands on the painter lines, and one winch operator.

While the davit system makes it less dependent on the skills of the fast craft coxswain during recovery operations, it may impose operational envelope limitations on the mothership in performing recovery operations in higher sea-states. For example, some motherships create a lagoon of flat waters by performing an inward turning-circle manoeuvre to minimise the risk to crew when they fix up the lines during the recovery operation. Some motherships remain stationary to avoid generating side wakes, which makes the recovery operation more tedious. The disadvantages of davit LARS are the relatively longer deployment times and larger crew numbers required to man the guide ropes to minimise sway during hoisting and lowering operations. A design comparison will be shown later in this article.

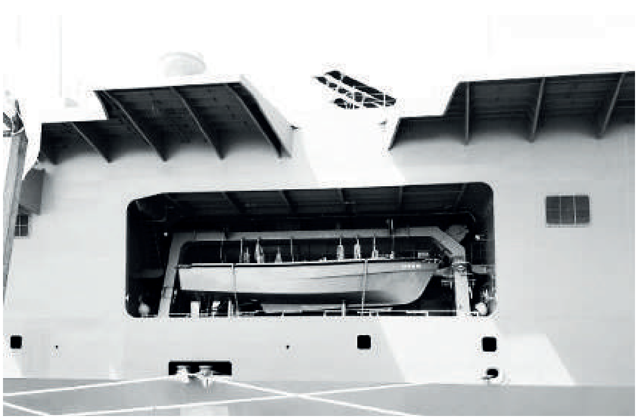

Figure 1. A boat davit on the *Izumo*-class helicopter carrier

Variants of davit LARS were studied:

Crescent Davits. A two-armed davit that is moved outboard of the ship by a hand crank or an air-powered motor, as shown in Figure 2. Once outboard, the fast craft is lowered by lifting the brake handle and allowing the weight of the boat to lower itself.

Figure 2. Crescent davit
(© Bill Walendzinski / File:SS Stevens boat deck view 05 port side life boats.jpg / Wikimedia Commons / CC-BY-SA-3.0)

Pivoted Gravity Davit. A two-armed gravity davit that works in two distinct stages. After the fast craft are readied for lowering, the brake is released and the winch pays out. The davit's arms pivot into the outboard position and come to rest against mechanical stops. The RHB is lowered onto the water during the second stage, as shown in Figure 3.

Figure 3. Pivoted gravity davit
(© Jon Dasbach / File:US Navy 070414-N-6854D-002 Deck department Sailors and surface rescue swimmers perform emergency boat operations during a man overboard drill aboard Nimitz-class aircraft carrier USS Dwight D. Eisenhower (CVN 69).jpg / Wikimedia Commons / ID 070414-N-6854D-002 / Public Domain)

Trackway Gravity Davit. A two-armed gravity davit that works similarly to the pivoted davit except that the arms slide down on an inclined trackway on rollers, as depicted in Figure 4.

Figure 4. Trackway gravity davit
(© Hunini / File:Boat davit(right) of JS Sendai (DE-232) at JMSDF Maizuru Naval Base July 29, 2017.jpg / Wikimedia Commons / CC-BY-SA-4.0)

Single-Arm Trackway Gravity Davit. A one-armed version of the trackway gravity davit, as shown in Figure 5. The single arm is mounted in the centre of the davit area and designed for a motor whaleboat equipped with a bail that bolts into the lifting pad-eyes in the bilge. The use of the bail and quick-trip hook allows for faster, safer launch and recovery operations at higher sea-states than other davits.

Figure 5. Single-arm trackway gravity davit
(© Clipper / File:Bossoir a gravité.jpg / Wikipedia / CC BY-SA 3.0)

Slewing Arm Davit. A slewing arm is rotated around a turning centreline and comes with lowering functionality customised to individual demands. A cradle fitted onto the davit aids in recovery, as shown in Figure 6.

Figure 6. Slewing arm davit
(© Flominator / File:Strbd boat davit.jpg / Wikimedia Commons / Public Domain)

Stern Ramp Launch and Recovery Systems

Launching a fast craft using a stern ramp involves opening the stern gate and releasing the craft. The fast craft either slides down the ramp under its own weight or via hydraulic /pneumatic rollers to control its launch speed. Once clear of the mothership, the craft drives away under its own power. During recovery, the craft is either driven or winched aboard the mothership's ramp and quickly secured.

The team assessed that stern ramp launch systems are inherently safer, taking into account associated deck crew hazards, seamanship, and stability of the fast craft throughout launch and recovery. On robustness, the stern ramp LARS can perform a one-off fast craft launch without stored power in the event of a blackout, through gravity-assisted descent. Launch and recovery operations for stern LARS require fewer deck crew than other designs. Stern ramp LARS variants were considered:

Tilt frame with sliding bed. A frame is tilted up by hydraulic arms before extending the sliding bed into the water. A recovery line is attached to the fast craft once it is driven into the sliding bed.

Capture hook. A line is released from the mothership and attached onto the fast craft. With this connection, a rigid capture head can be attached to the fast craft for winch in operation. Alternatively, the fast craft is captured by a fixed hook on a traverse system to pull the RHB up the ramp.

Extended ramp. An extended ramp helps to increase sill depth during launch and recovery operations, which improved fast craft capture by LARS infrastructure. Rollers on ramps are hydraulically operated to move the craft up or down the ramp with no need for recovery lines.

LARS elements to optimise include the size and angle of ramps and doors, door design, fenders, water management, and interface between the mothership and the fast craft. Dallinga & Harmsen (2008) concluded that scale model tests were useful for validation of LARS system safety, water management and optimal heading. Carette (2014) conducted time domain simulations in addition to model tests to investigate optimal launch and recovery design. McTaggart (2014) used simulation models to investigate the effects of hydrodynamic interactions between a small boat and mothership. Schmittner & Carette (2010) discussed the merits of model tank tests in modelling the mission-representative hydrodynamic environment for launch and recovery operations.

Several proposals have been put forth to improve craft recovery. Cosmo (2008) proposed a brightly coloured towline to improve visibility and design of a compliant member to reduce loads and risk of latch damage. Petersen (2008) explored a probe-receiver device for towing. Galway (2008) outlined design considerations and design loads of a towline capture latch systems. Kilbourne (2008) reviewed multiple latch designs to snag a towline trailing from the mothership. These could also be extended to applications for fully autonomous unmanned surface vehicle (USV) and unmanned underwater vehicle (UUV) recovery, with the aid of computer vision and interface devices.

Design Criteria and Selection

The two main classes of LARS were evaluated. Stern ramp launch systems are preferred based on the considerations in Table 1. Most naval vessels achieve multi-craft launch ability via cranes and well docks. The team pursued an alternative approach to simplify multi-craft launch and recovery without the long deployment time associated with cranes. A series of technical assessments, cognitive walkthroughs, and crew interviews identified the twin stern ramp solution as the most suitable system for the LMV's operating requirements.

Attributes	Davit	Stern Ramp
Launching and recovery sea-state	Up to sea-state 3	Up to sea-state 4/5
Launching and recovery duration	Average 15 mins Control of fast craft requires coxswain skill to stay alongside the mothership for hook-up; this is challenging in higher sea-states.	Shorter time required – about to 90s, depending on whether launch speed is controlled Control of fast craft requires coxswain skill; fastest recovery time recorded averaged 40s
Safety of fast craft crew	Fast craft suspended in mid-air and may sway during launch and recovery; risk of crew injury and equipment damage at higher sea states	Fast craft movement is constrained to ramp or cradle, no risk of sway; lower risk of injury and equipment damage
Safety of deck crew	Deck crew required to be near LARS during operations to guide painter lines / ropes to minimise craft sway	Deck crew not required to be near LARS during launch & recovery ops.
Space	More deck space required	Less deck space required
Stability of mothership	Higher centre-of-gravity; imposes higher stability requirements on mothership	Lower centre-of-gravity; minimal or no extra stability requirements imposed on mothership
Maintainability	More complex hydro-pneumatic machinery, requires more maintenance	Less complex machinery, simpler maintenance
Reliability in event of blackout	Non-operable without emergency power supply in event of blackout	Launch operations can be performed without stored power
Multi-craft operability	Requires multiple davits or additional craft transfer system within mothership between storage and davit location	Requires multiple ramps or additional craft transfer system within mothership between storage and stern ramp location
Space flexibility	Deck space committed to davit unable to be repurposed	Deck space over stern ramp may be used to store containerised payloads

Table 1. Comparison between davit and stern ramp LARS
(advantages highlighted in green, disadvantages highlighted in orange)

INTEGRATION AND OPERATIONALISATION PROCESS

The integration and operationalisation of stern ramp LARS involved a series of quantitative and qualitative tests to validate the selected design, as well as measures of performance and effectiveness. The process is described in Figure 7.

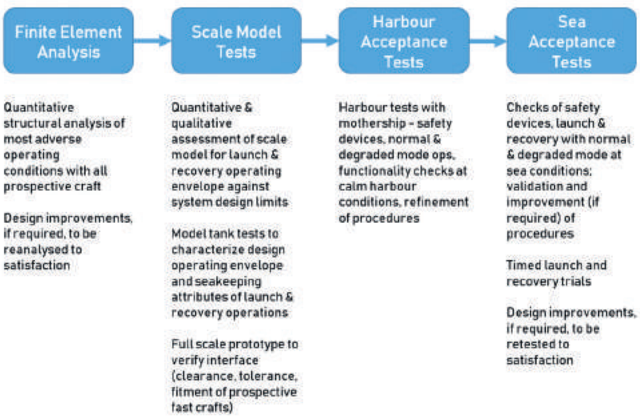

Figure 7. Integration and operationalisation process for naval LARS

Finite Element Analysis

A series of Finite Element Analysis (FEA) studies was conducted on the shipboard LARS structures against the forces anticipated at the extremes of the mothership and fast craft operating envelopes. Structures were modified for strengthening, and re-analysed to satisfaction prior to the conduct of scale model tests.

Scale Model Tests

The objectives of the model tests were to verify the indicative operational envelope and limitations of the mothership, fast craft and LARS in the envisaged operating conditions. The numerical evaluation of stern ramp LARS required a different set of measurements, namely the forces induced on the stern ramp hydraulics, and relative x-, y- and z-axis motions of the fast craft and the mothership. Qualitative observations were also recorded in unsafe launch and recovery scenarios, for example the occurrence of stern ramp emergence, which would pose a collision hazard for the fast craft during recovery operations.

The test campaigns for the LMV stern ramp LARS involved more than 100 runs of launch and recovery operations under simulated wave within a towing tank[1]. Video recordings and photographs were also used to supplement quantitative data.

The mothership and fast craft models used were manufactured with a geometric scale ratio of about 1:12. All tests were performed with the same expected loading conditions of the mothership and fast craft.

The LMV scale model was also employed for free-running seakeeping assessments and powering tests. The remote-control model featured a twin shaft design with two stock propellers. A pair of steerable rudders and long bilge keels were incorporated on the model. The model LARS comprised a stern ramp and stern door as shown in Figure 8. For all tests, the stern door was kept open by two hinges and a fixed pipe mounted on the side of the stern ramp. A force transducer on the fixed pipe measured forces borne by the hydraulic system for comparison against design limits. Two pairs of pods and four pairs of wheels were installed on the outer stern ramp door section to guide the model fast craft, while eight pairs of wheels were installed on the stern ramp.

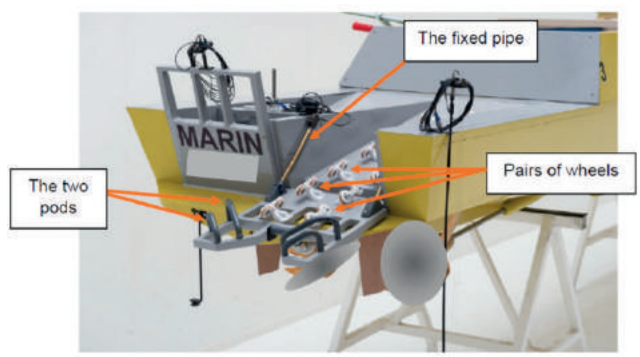

Figure 8. LMV scale model with stern ramp LARS – stern quarter view

The fast craft model was prototyped based on the envisaged craft dimensions as shown in Figure 9. The remote-controlled fast craft model was equipped with one water jet, which allowed the helmsman to vary its direction and speed for the launch and recovery tests. Both models were self-propelled and remote-controlled during all launch and recovery tests as shown in Figure 10. Connections between the mothership and towing carriage comprised free-hanging electric wires for relay of measurement signals and power supply. The mothership model was manoeuvred via autopilot reacting on course deviation, rate of turn and lateral displacement. The fast craft was completely wireless, and steered by a helmsman who was positioned aft of the mothership on the towing carriage. The measured quantities comprised basic six degrees of freedom motions of the mothership and fast craft, wave elevation at the mothership's stern, mothership speed, and force borne by the hydraulic piston keeping the stern ramp door open.

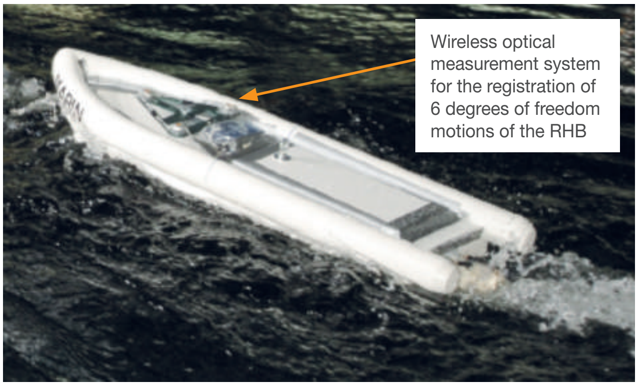

Figure 9. Fast craft scale model (RHB shown)

Figure 10. Launch and recovery model tank tests

Test Arrangement

The sea-state definition and significant wave heights of the sea-states applied for this project were based on NATO STANAG 4194, which is consistent with model testing best practices of other navy vessels. A Pierson-Moskowitz spectrum was used to generate irregular wave conditions for mission-representative wave conditions up to sea-state 4.

Each test campaign was designed with sea-states varying from 2 to 4, in 6 different headings (0, 90, 135, 180, 270 and 315), and different mothership speeds to replicate real operations.

The model scale of 1:12.173 translated to a timescale of 3.49x faster than reality. The time for the human helmsman to react was therefore significantly shorter. This effect was compensated by positioning the helmsman aft of the RHB and mothership with a bird's eye view. In consequence, the model operational behaviour is assumed to be realistic. The quality of fast craft control is dependent on the helmsman's experience and skill. In reality, the success of fast craft launch and recovery operations is contingent on the crew's competency in parallel to the dynamic environment, operational conditions and safe system design. Test runs (with variation in relative wave speed and direction) were conducted randomly in terms of the sea-states, wave height and directions, and ship speed. This was to ensure that helmsmen did not become overly accustomed to the wave conditions which could skew the results.

The relative motions of the fast craft compared to the mothership were important in understanding the operating envelope and outcome of hydrodynamic interactions during launch and recovery operations. Relative x-, y-, z-axis motions and acceleration between the mothership and fast craft were derived from measured signals. Plotting relative x-motions against relative y-motions indicated the difficulty of aligning the fast craft with the mothership. Plotting the relative z-motions against relative x-motions gave insight into the effect of hydrodynamic interactions at the stern of the mothership as illustrated in Figure 11.

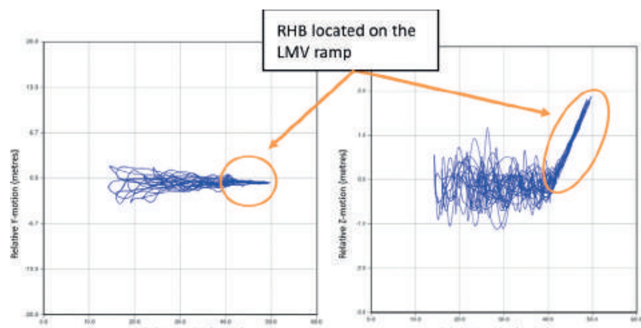

Figure 11. A sample relative motion plot to investigate effects of alignment difficulty (left) and effects of hydrodynamic interaction at stern of mothership (right)

The safety of RHB launch and recovery was scored on a three-grade Likert[2] scale by members of the test team comprising representatives from DSTA, RSN, SAAB Kockums (then ThyssenKrupp Marine Systems AB), ST Engineering Marine Limited (STEML), and Marin.

Full Scale Verification with Prototype Ramp and Ship

The first of these validation tests began with the construction of a full-scale prototype LARS comprising hydraulic roller pairs installed on a ramp simulating one of the LMV stern ramps, as shown in Figure 12. These hydraulic rollers were configured to launch and recover various small craft from the LARS prototype, including a 9m USV and a 6m RHB. These tests were done to ascertain the viability of the launch and recovery of RHBs in the full-scale design before implementation on the LMV. This step also helped navy crews to refine their operating procedures prior to full scale tests on the actual ship.

Figure 12. Prototype LARS set up for different fast craft

Harbour Acceptance Tests

The next phase of the LARS qualification process entailed full-scale tests of the design under calm harbour conditions with the actual fast craft to validate the model tank test results in calm seas. The focus of the Harbour Acceptance Test (HAT) phase was assessing construction quality of the LARS assembly, potential in-theatre operating issues, and qualification of safety devices.

Upon completion of the first LMV, full-scale verification encompassed installation checks, pressure tests of hydraulic systems, verification of safety interlocks and system functions under normal and degraded modes. HATs were conducted for all eight ships of the class to ascertain multi-craft launch and recovery capability for each ship. Figure 13 depicts launch tests under calm harbour conditions. A summary of HAT requirements is shown in Table 2.

Figure 13. Fast craft launch tests from the LMV

LARS Subsystem	Test Description	Applicable Standard (or equivalent)
Construction Tolerance	a. Launch way angle b. Centreline c. Spacing between rollers d. Centre between port starboard rails e. Bolt tightening f. Non-Destructive Testing (NDT)	a. ISO 2768-m b. IACS-47 Guide for Shipbuilding & Repair Quality Standard for Hull Structures during Construction c. EN ISO 5817 d. DNVGL Note 7 on Non-Destructive Testing
Hydraulic System	a. Hydraulic hoses, piping and relief valves b. Safety devices and interlocks	System lines pressure tested to 1.5x working pressure; system flushing to meet ISO 4406 or NAS 1638 class 8 or better.
Winches	a. Winch pull test b. Safety devices and interlocks c. NDT on winch foundation after load test	Conducted to at least 1.1x Safe Working Load (SOLAS Ch. III)
Stern ramp door equipment and installation	a. Alignment, tolerances, torque values b. Functionality of locking mechanism	a. ISO 2768-m b. ISO 13920 Class A c. IACs47 d. JSQS
Launch and Recovery System	a. Normal and degraded mode operations b. Local control panel and remote operations c. Winch-only launch and recovery d. Hydraulic crossover operations	Test matrix designed to cover all possible modes of normal and contingency operations.

Table 2. Summary of HAT Requirements

Sea Acceptance Tests

The Sea Acceptance Test (SAT) phase follows the HAT phase, and validates system performance under mission representative conditions, as shown in Figure 14. The SAT entailed measurement of operating parameters and the duration of craft launch and recovery for each operating mode. In addition, qualitative comments from the fast craft coxswains on the approach and ease of alignment with the mothership, especially at higher sea-states, were recorded.

Secondary test data collected during SAT included noise level measurements to ensure that the LARS machinery noise did not adversely affect crew communications during the launch and recovery operations.

Figure 14. LMV acceptance test at sea

SUMMARY OF KEY TAKEAWAYS

Model Tank Tests

The model tank tests successfully established the indicative operational envelope for fast craft launch and recovery operations on the LMV stern ramp, as well as load and acceleration limits for further optimisation of the LMV stern ramp design. The influence of the tested wave peak period on fast craft launch and recovery operations was assessed to be not significant. Notable observations include the slightly easier fast craft recovery operations for test runs with higher mothership speeds. This was attributed to better fast craft handling characteristics at higher speed. At higher sea-states, fast craft launch and recovery operations were challenging, with the test team cancelling approaches with possible danger.

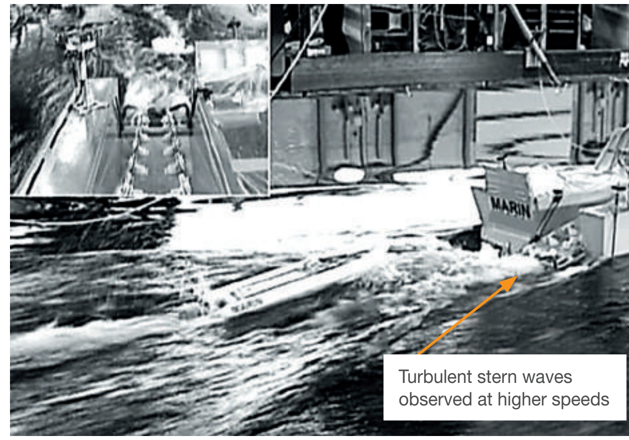

Figure 15. Turbulent stern waves observed at higher speeds

Pitching of the mothership in head seas (with waves arriving at the bow of the mothership at 0 degrees) at higher sea-states proved to be challenging for safe fast craft recovery, as shown in Figure 15. On a few occasions at higher sea-states, ramp emergence was observed to be almost as high as the fast craft bow. This increased the risk of impact between the fast craft and ramp and defined the optimal envelope for launch and recovery operations.

Consistent with the other fast craft launch and recovery tests, the stern and bow quartering conditions (with waves arriving at the bow of the mothership at 45 and 135 degrees) were the least favorable headings. In higher sea-state conditions, the success of safe stern boat operations was contingent on the helmsman's experience.

The opened ramp door damped transom stern waves below certain mothership speeds, which aided in fast craft recovery. However, in higher sea-state conditions, the vertical motions of the ramp generated by the mothership's wake made it challenging for fast craft operations aft of the mothership. Lastly, test data indicated that hydraulic forces for the stern ramp door were relatively independent of the mothership speed and wave conditions. The completion of model tank tests concluded the first phase of LARS design qualification process. The team concurred with Schmittner & Carette (2010) that model tests validated the selected twin stern ramp design's functionality and limits early in the design phase. This helped to avoid costly modifications to the as-built design. The primary limitation of model tank tests was the lack of accurate modelling of the impact of fast craft hull fouling and LARS hydraulic roller degradation on launch and recovery operations.

On Prototyping and Integration

Prototyping of the twin stern ramp LARS was an important step that enabled the engineering team to refine its design in the following areas:

Hydraulic Roller Configuration. The multi-role vessel LARS hydraulic roller pairs were configured to conform to hull forms of the expected range of embarked crafts, thus allowing the LMV to interoperate with various fast-response craft to support various mission profiles in a short turnaround time.

Fast Craft Hull Material. Through the recovery of the various types of small craft, it was noted that craft with smoother hull materials required more time (in the order of tens of seconds) to gain sufficient traction with the hydraulic rollers which were made of marine-grade rubber. No slipping was observed during the subsequent launching of the small craft with hulls with higher coefficients of friction.

Human Factors. Noise and vibration levels within the craft were within acceptable ranges. This was important to ensure operator safety during fast craft launch and recovery operations. The operators acknowledged the importance of the prototyping and HAT phases to refine procedures prior to the SAT and subsequent system operationalisation.

On Harbour Acceptance Test

Normal Launch and Recovery Modes. Normal modes of operation include powered wheeled launching, powered wheeled recovery, and winch-assisted recovery for both the port and starboard stern ramps. For these modes of operations, launching the fast craft from the multi-role vessel took less than 30 seconds. Recovery required less than 60 seconds – well within the designed range. This validated the LMV's ability to rapidly launch and recover fast crafts, thus providing the LMV with a rapid-response asset for its mission spectrum. No slipping or retardation of the fast craft on either stern ramp were observed during all launch and recovery tests.

Secondary Launch and Recovery Modes. Secondary modes of operation tested include (a) launching and recovering with hydraulic power unit crossovers from the port to starboard stern ramp and vice versa; (b) launching and recovering with one hydraulic line disabled; (c) launching and recovering with hand pumps to actuate the hydraulic rollers; and (d) emergency launching using the fast craft's own weight and free-wheeling rollers to slide down the stern ramps. Secondary launch and recovery modes required longer durations to complete than the normal modes, with the exception of the emergency launch mode which took less than 15 seconds. No slipping or retardation of the fast craft on the stern ramps were observed during all the launches and recoveries of the fast craft.

Fast Craft Alignment before Recovery. Under calm harbour conditions, the fast craft helmsman found it easy to align the fast craft to the centre of the stern ramp for recovery onto the LMV. Line-up lights were installed in the centre of each stern ramp following the prototyping phase to improve guidance under low-visibility conditions.

On Sea Acceptance Test

Normal Launch and Recovery. The modes tested in open sea were the same as those tested in harbour-powered wheeled launching, powered wheeled recovery, and winch-assisted recovery for both the port and starboard stern ramps. The SAT results for launch and recovery duration were very similar to the HAT results. No slipping or retardation of the fast craft on the stern ramps were observed during all launch and recovery tests, despite the roll and pitch of the LMV.

Secondary Launch Modes. The emergency launch was tested in open sea for both the port and starboard stern ramps, which yielded similar results to the HAT. No slipping or retardation of the fast craft on the stern ramps were observed during launch and recovery of the fast craft, despite the roll and pitch of the mothership.

Alignment before Recovery. The alignment of the fast craft to the centre of the LMV stern ramp in open sea required a considerable amount of time due to the resultant wake of the lowered stern door, and in part due to operator familiarity with the fast craft. Multiple line-up attempts were needed for each successful recovery. By analysing video footage and interviewing skilled coxswains, the team iterated with improved designs for the stern door fenders and guide poles to test at subsequent sea trials. Experimentation converged on a final design that resulted in shorter alignment and recovery durations. The final fender designs successfully channelled the fast craft to the centre of the stern ramp even for less ideal approach angles, hence increasing the RHB recovery envelope.

Human Factors. Operators on board the RHB found that forces and acceleration during launch and recovery were well within safe limits for all operating modes, despite the roll and pitch of the mothership. For operators on the mothership quarterdeck, voice commands to and from the RHB personnel could be effectively heard over the ambient noise. During the winch-assisted recovery, operators experienced little difficulty retrieving the floating winch line and securing it to the RHB despite the wake caused by the multi-role vessel. Operating the LARS for both RHB and mothership crews proved to be much easier, faster, and safer as compared to davit crane operations, thus validating the effectiveness of the twin stern ramp LARS for the LMV, where fast turnaround time and minimal impact to other operations were highly desired. A helmet mounted-camera at sea was used to further analyse operator gaze during recovery operations, in addition to crew interviews amidst the trials. Frame analysis indicated that experienced RHB coxswains used the centre of the stern ramp as visual reference for craft alignment prior to recovery. In contrast, less experienced RHB coxswains used the guide poles on either side of the stern ramp, which was found to result in higher incidences of RHB misalignment to the LMV stern ramp, as shown in Figure 16. Additionally, less experienced RHB coxswains were observed to have a higher chance of distraction if a senior commander – for example, the ship commanding officer or the squadron commander – stood in the vicinity of the ramp.

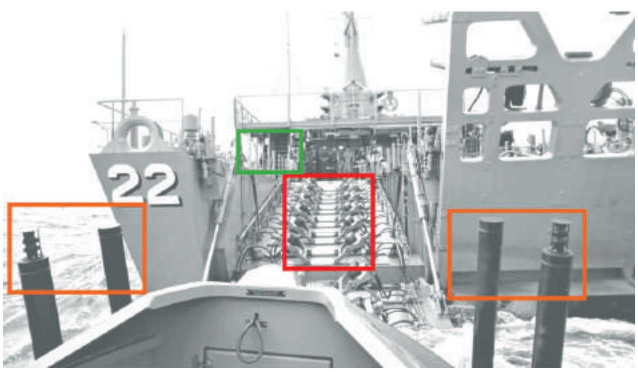

Figure 16. Visual reference cues used by coxswains are the centre of ramp cue (highlighted in red), guide poles (highlighted in orange), and typical senior commander observation position (highlighted in green)

FUTURE DIRECTIONS

The many advantages of LARS for multi-role vessels motivate continual design improvements and incorporation of emerging technology to enhance safety and operability. The twin stern ramp LARS on board the LMV continues to serve as an effective testbed to assimilate digital technologies and new sensors for future multi-role vessels for the RSN. Prospective future directions include:

LARS Simulator Training. Augmented reality wearables can be used for training coxswains for faster and safer LARS operations, with real time information such as waypoints, steering, and water currents being piped from ship sensors to a heads-up display.

Supporting Autonomous Launch and Recovery. The proliferation of unmanned assets in maritime security and search-and-rescue operations drive the impetus for future LARS to integrate sensors and communication links between the mothership and USVs for fully autonomous launch and recovery – completely eliminating human operators from the loop. Proximity sensors at the front of the USV could augment computer vision recognition of recovery patterns and real time propulsion corrections by a shipboard stability computer. This would assist in the alignment of the USV to the mothership's stern ramp for recovery.

CONCLUSION

The twin stern ramp LARS provides a versatile means for multi-role ships to interoperate with a wide range of embarked rapid-response vessels such as RHBs and USVs. Key benefits identified are multi-craft operability, faster turnaround time, manpower savings, and reduced safety risks as compared to traditional crane and davit launch and recovery operations. The operationalisation and integration process in which the twin stern ramp LARS has undergone enables the integration of other classes of fast craft in the future.

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ENDNOTES

[1] In a model tank, waves and currents are artificially generated and remotely-piloted scale model of ships are subjected to these conditions. Data can be easily collected on the performance of the scale model that would otherwise be much more expensive and time-intensive on actual ships.

[2] A rating scale in which the test panel indicated their assessed safety and ease for the launch and recovery operations

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REVIEW OF UNDERWATER BLAST SAFETY CRITERIA

SIM Gim Young, YUEN Ming Fatt, YAP Kah Leng, NEO Yinghao Anders

ABSTRACT

Health and safety considerations are paramount to the protection of human bodies underwater, especially in the vicinity of underwater explosions. Experiments involving animals and humans have been conducted in several countries to support the development of underwater blast safety data. However, this field remains less extensively studied compared to air blast safety. While studies are still ongoing, it is critical to stay up to date with international researchers and developments to enhance the understanding of underwater blast effects on divers and the associated underwater blast safety criteria. This article aims to examine past developments and compare the associated experimental results with safety standards from various sources.

Keywords: underwater, explosion, blast, overpressure, impulse

INTRODUCTION

Interest in underwater blast injury escalated during World War II when there were more instances of underwater presence during underwater explosions. It was reported that mortality from such injuries might approach 80% (Wolf, 1970) and that the effects of blasts underwater are more far-reaching and damaging than in air, presumably due to the lower loss of shock wave energy during propagation and more efficient transmission into human body in water (Cudahy & Parvin, 2001). Since then, studies have been conducted with animals and humans to better understand the explosion parameters for the purposes of safety and tolerability.

However, human injury due to underwater explosions remains less extensively studied compared to similar aspects in air blast. Besides, the criteria associated with blast parameters are different among researchers. This review examines several key studies on underwater blast, and compares past experimental results against published safety standards from various sources to promote a better understanding of the rationale behind the published safety standards. With this, it aims to enhance the understanding of underwater blast effects on divers.

KEY UNDERWATER BLAST EFFECTS

During an explosion event, a shock wave propagates spherically away from the charge at high velocities. Upon the arrival of shock front, there will be a steep increase in pressure, followed by exponential decay with time as illustrated in Figure 1.

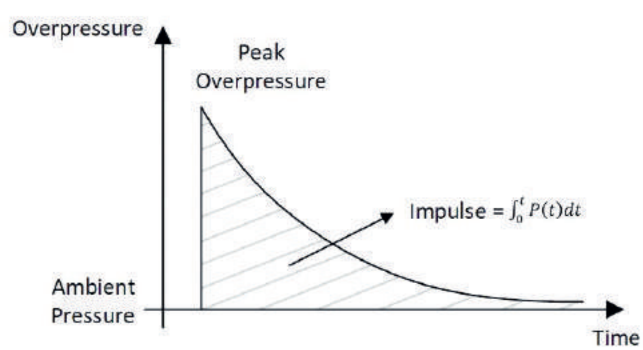

Figure 1. Shock wave characteristics

The shock wave lasts only milliseconds and the associated peak overpressure can be estimated with Equation 1. For example, the peak overpressure experienced by a diver at 500 ft from a 10 lb TNT explosion would be 46 psi. The impulse can be estimated with modelling and simulation in view of the need to consider shock wave reflection effects that are specific to the area of interest.

$$\text{Peak Overpressure (in psi)} = 21{,}600\left(\frac{\sqrt[3]{W}}{D}\right)^{1.13} \quad (1)$$

where W = Net Explosives Weight (TNT) in pounds
D = Distance between diver and explosion in ft.

Shock wave reflects when it encounters an interface of two different acoustic impedances. Upon encountering a less acoustic impedance, such as water-air interface, it reflects and becomes a tensile wave that immediately reduces pressure at a point. This phenomenon is known as surface cut-off. In contrast, reflection off a larger acoustic impedance such as the ocean bottom produces a compressive wave that immediately increases the pressure at a point (see Figure 2).

Behind the shock wave propagation, the released gaseous products expand rapidly due to the high temperature and pressure. This continues to the point when the pressure outside the bubble exceeds the pressure within the bubble, resulting in a change from the expansion phase to contraction phase. The contraction continues until the bubble cannot contract any more due to the compressibility of the gases within. This is followed by a reversal to the expansion phase, resulting in the first bubble pulse. This alternating expansion-contraction phenomenon continues until the bubble is released through the water surface, generating several bubble pulses along the way up. These secondary pressure waves generated are of reduced amplitude compared to the initial shock wave but of longer duration, lasting up to a few seconds. This phenomenon is illustrated in Figure 3.

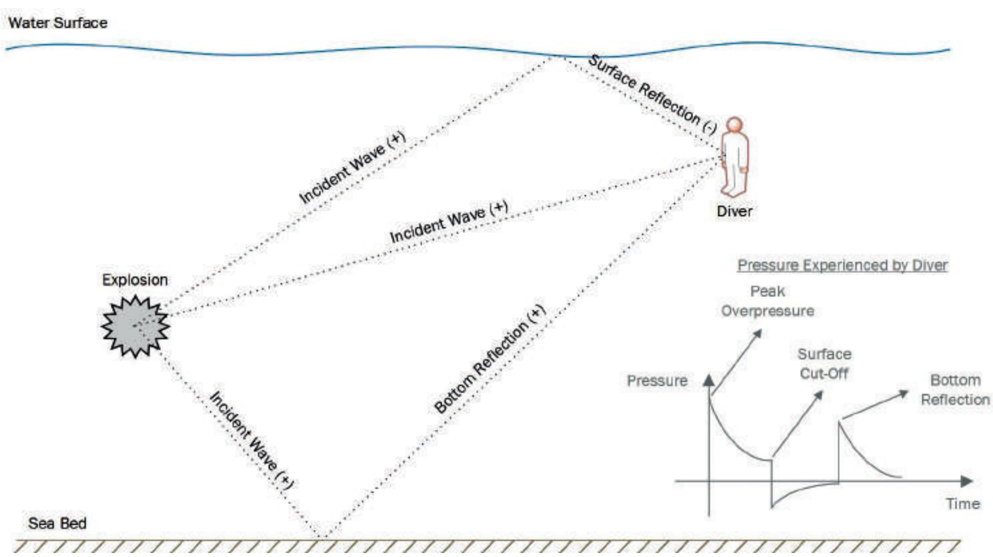

Figure 2. Reflected pressure waves

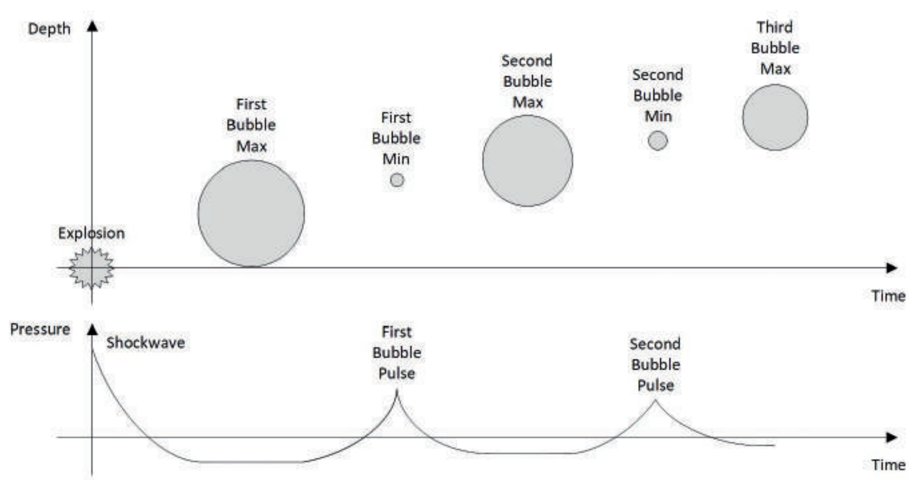

Figure 3. Bubble pulsation effects

It was observed that published safety criteria and studies focused on investigating the hazardous effects associated with the shock wave parameters on humans, namely peak overpressure and impulse.

PUBLISHED SAFETY CRITERIA

The differences in safety criteria recommended for divers are summarised in Table 1.

Reference Literature	Peak Overpressure (psi)	Impulse (psi.msec)
US Navy Diving Manual Revision 7 (Naval Sea Systems Command [NSSC], 2016)	< 50 psi	Not Mentioned
Swimmer Safe Standoffs from Underwater Explosions (Christian & Gaspin, 1974)	≤ 50 psi	≤ 2 psi.msec
Far-field Underwater Blast Injuries Produced by Small Charges (Richmond, Yelverton & Fletcher, 1973)	≤ 100 psi	≤ 3 psi.msec
O'Keeffe and Young (Lewis, 1996)	≤ 100 psi	≤ 2 psi.msec
US Navy EODB 60A-1-1-37 (US Navy, n.d.)	≤ 100 psi	≤ 2 psi.msec

Table 1. Non-injury limits for peak overpressure and impulse values

PAST UNDERWATER EXPLOSION STUDIES

A review of past studies was done to better understand the impact of these parameters on divers. Of particular interest was the research by Lovelace Foundation for Medical Education & Research (Yelverton, Richmond, Fletcher & Jones, 1973). A series of trials with several animals (comprising sheep, dogs and monkeys) was conducted with the intent of establishing safe ranges for swimmers. During which, an underwater blast criterion for aquatic mammals, with 5 psi.msec considered as the safe level was developed as well (see Table 2). Pressure-time measurements were taken to determine the exposure they were subjected to during the explosion experiments. In particular, there was no eardrum rupture at an impulse of 12.4 psi.msec (9.1% of eardrums ruptured for test subjects tested at 19.0 psi.msec to 19.2 psi.msec while 36.4% of eardrums ruptured for test subjects at 20.4 psi.msec to 23.5 psi.msec). This would mean that there is a good margin of safety for the 5 psi.msec blast criteria for aquatic mammals.

Impulse (psi.msec)	Effect
40	No Mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should be able to recover on their own.
20	High incidence of slight blast injuries including eardrum rupture. Animals should be able to recover on their own.
10	Low incidence of trivial blast injuries. No eardrum rupture.
5	Safe level. No injuries.

Table 2. Underwater blast criteria for underwater mammals

In order to provide additional data on the impact of impulse on divers, a series of trials with a swimmer in water was conducted (Richmond, 1977; Richmond, n.d.). During the test facility trial, it was reported that impulse levels of 1.9 to 3.0 psi.msec were tolerable and did not produce any discomfort. At impulse levels above 3 psi.msec, a transient stinging sensation over the front surface of the body was evident but tolerable. During the open water tests, it was reported that the swimmer, when exposed to impulse levels of approximately 2 psi.msec, experienced slight sensations at the lower abdomen or pelvic region but not discomfort. It was also observed that at peak overpressure ranges above 112 psi and at impulse levels 0.9 to 2 psi.msec, the swimmer began to experience slight thump in the lower abdomen or pelvic region. Lastly, the acceptability of sound levels from an underwater blast near an impulse level of 2 psi.msec was also investigated. It was reported that no ringing in the ears or discomfort was experienced by the swimmer who wore the upper half of a wet suit at an impulse exposure of 2.1 psi.msec with a corresponding peak overpressure of 71 psi.

A series of trials involving divers was conducted in the UK, off the coast at Spithead, Portsmouth (Cudahy & Parvin, 2001). At peak overpressure of 12.1 psi and impulse of 7.3 psi.msec, the divers reported hearing a bang, as well as feeling jolts and vibrations through the body. As the exposure increased to 30.3 psi and 14.9 psi.msec, the divers heard a loud bang and shuddered all over. As the exposure increased further to 45.1 psi and 19.4 psi.msec, the divers reported hearing a very loud rumbling bang, their whole bodies shook and were squeezed all over. They also felt a blow on the front of the chest and head as well as pressure in the ears.

The most comprehensive series of trials involving humans was conducted by the Royal Naval Physiological Laboratory to investigate the impact of underwater blast on humans (Christian & Gaspin, 1974). The divers wore hoods to prevent direct blast exposure to the ears and were exposed to relatively high levels of peak overpressure and impulse levels, which should not be considered acceptable for general applications. At an estimated exposure of 85 psi and 29 psi.msec, the diver experienced a loud bang and slight pressure on the torso but no discomfort. At an estimated exposure of 120-150 psi to 35-45 psi.msec, the diver felt a bang on the head but no discomfort to the ears or torso. Notably, it was observed that at an estimated exposure of 300 psi and 76 psi.msec, the diver experienced a severe blow to the head and torso, and his body was violently shaken but there was no substernal pain.

With reference to several published studies (Cudahy & Parvin, 2001; Christian & Gaspin, 1974; Yelverton, Richmond, Fletcher & Jones, 1973; Richmond, 1977; Richmond, n.d.; Parvin, Nedwell & Harland, 2007), the results of both human and animal trials are compiled and summarised in Figure 4.

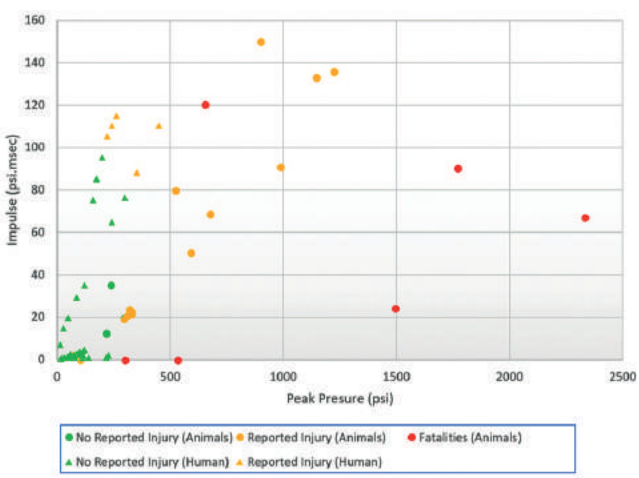

Figure 4. Summary of key past trials

There were no reported injuries to humans at the range of 100 psi and 3 psi.msec in the published studies. Hence, limiting the exposure to less than 50 psi and 2 psi.msec appear to be adequately safe, though it is to be noted that the studies did not cover the effects of repeated exposures or long-term effects.

REFERENCES ON DEFINING INJURIES

Apart from safety limits, several references aimed to define the injury criteria. The US Navy Diving Manual Revision 7 (NSSC, 2016) states that a peak overpressure wave of 500 psi is sufficient to cause serious injury to the lungs and intestinal tract (and even fatal injury under certain circumstances) while one greater than 2000 psi will result in death. A quantitative model was developed by Goertner (Cavanagh, 2000) to estimate injury to marine animals. This has been used in assessments and could serve as a reference for risk estimates for underwater explosions. The baseline thresholds of the Goertner model, where M is the mass of subject animal in kilograms, are as follows:

Onset of slight lung haemorrhage $I = 19.0\,(M/42)^{1/3}$ psi.msec (2)

Onset of extensive lung haemorrhage (1% mortality) $I_{1\%} = 42.0\,(M/34)^{1/3}$ psi.msec (3)

Extensive lung haemorrhage (50% mortality) $I_{50\%} = 83.4\,(M/43)^{1/3}$ psi.msec (4)

These equations relate impulse tolerance to animal weight – a marine animal of higher body weight will be able to tolerate impulse more as compared to one of lower body weight. An example can be found in Table 3.

Extent of Injury	60 kg Body Mass	80 kg Body Mass
Onset of slight lung haemorrhage	21.4 psi.msec	23.6 psi.msec
Onset of extensive lung haemorrhage (1% mortality)	50.8 psi.msec	55.9 psi.msec
Extensive lung haemorrhage (50% mortality)	93.2 psi.msec	102.6 psi.msec

Table 3. Comparison of injuries from impulse perspective

CONCLUSION

While there are variances in the safety criteria recommended by different researchers, 50 psi for peak overpressure and 2 psi.msec for impulse appear to be the most suitable for the purpose of safety. Nevertheless, there were no reported injuries in some of the aforementioned studies at higher exposures. It was also observed that the studies did not address the effects of repeated exposures or long-term effects. Thus, a safety factor could have been applied to cater for potential unknowns associated with underwater explosions. With a better understanding on the safety considerations and potential injuries associated with underwater blasts, more appropriate safety precautionary measures for training and operations can be established.

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BIOGRAPHY

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NOTES

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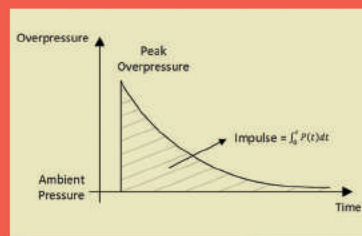

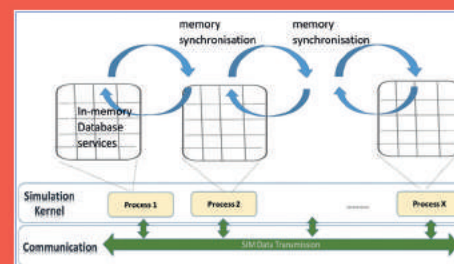

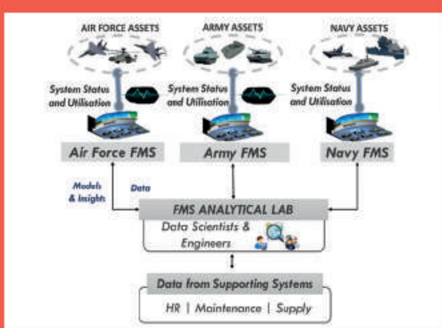

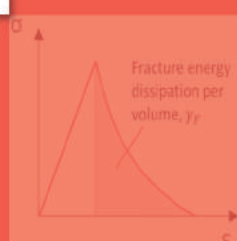

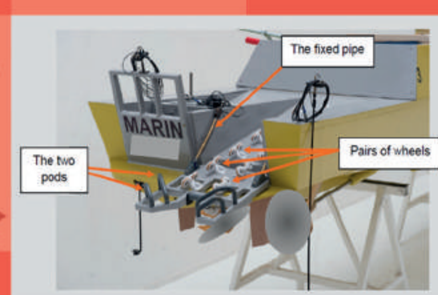

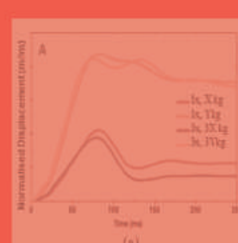

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