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.

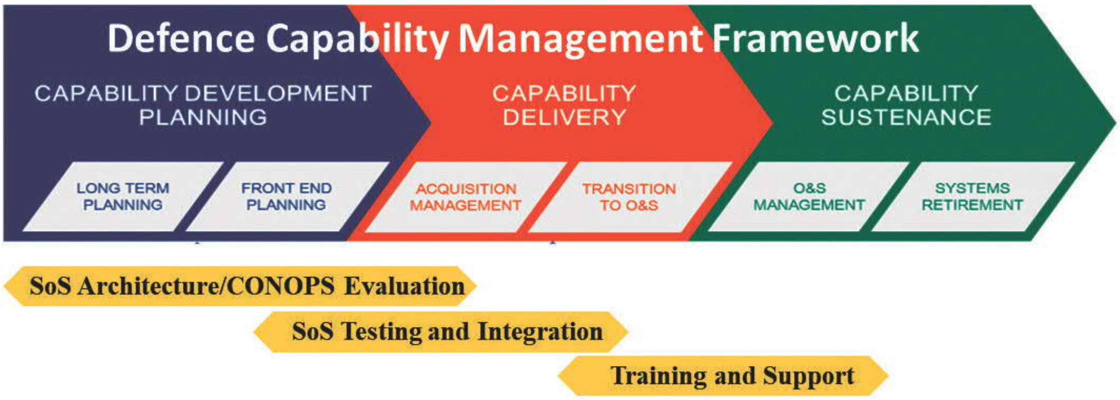
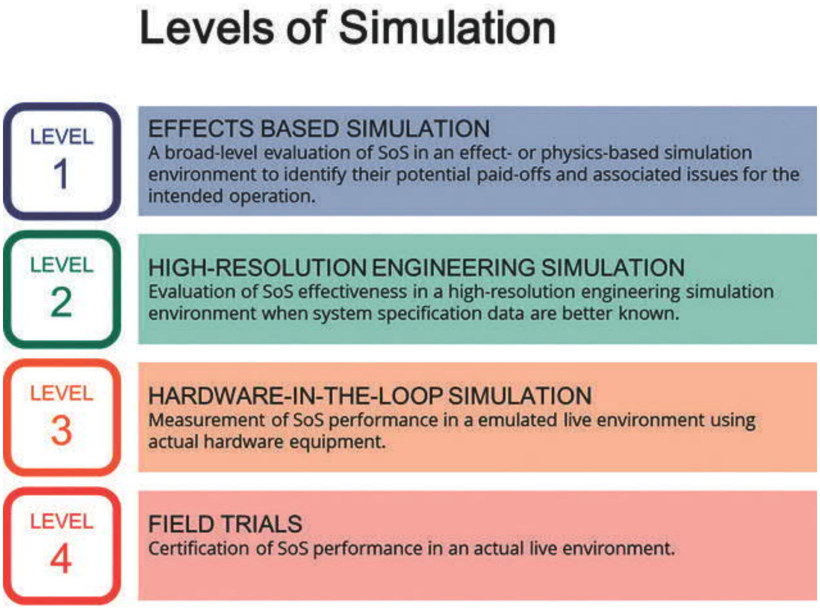


Figure 1. The application of synthetic battlespace in the capability development lifecycle



EFFECTS BASED SIMULATION
A broad-level evaluation of SoS in an effect- or physics-based simulation environment to identify their potential paid-offs and associated issues for the intended operation.

HIGH-RESOLUTION ENGINEERING SIMULATION
Evaluation of SoS effectiveness in a high-resolution engineering simulation environment when system specification data are better known.

HARDWARE-IN-THE-LOOP SIMULATION
Measurement of SoS performance in a emulated live environment using actual hardware equipment.

FIELD TRIALS
Certification of SoS performance in an actual live environment.

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.

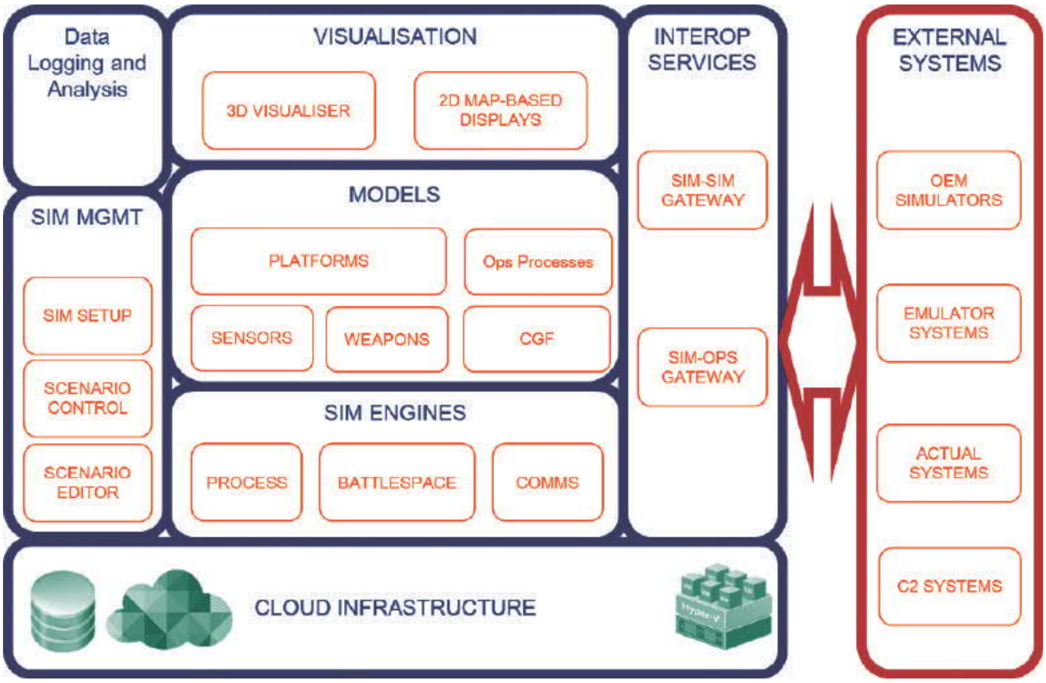


Figure 3. Architecture of the synthetic battlespace

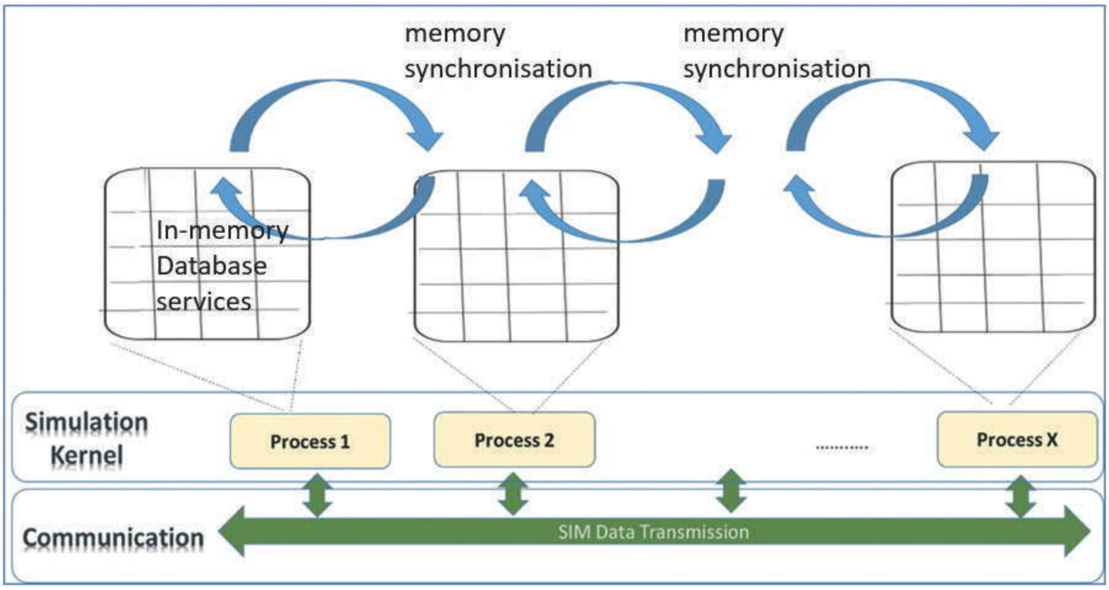


Figure 4. DSE architecture

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

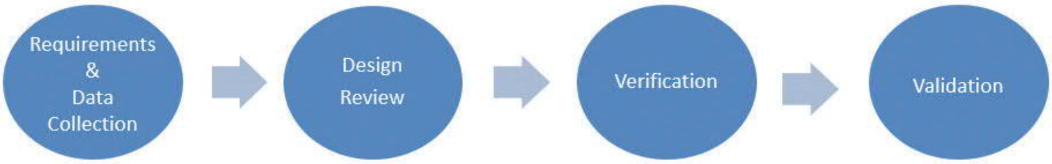


Figure 5. Model development process

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.

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BIOGRAPHY

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