Emulator-Based Command and Control Development:

A Systems Engineering Approach to Developing Command and Control Systems

ABSTRACT

Traditional Command and Control (C2) development involves system specification on paper designs and screen prototypes, which are usually tested after system implementation. Given the complexities of modern warfare, operational requirements are increasingly harder to define especially when the desired capability is a first-of-its-kind. Hence, the use of the traditional C2 approach may result in costly post-implementation changes. Emulator-based C2 Development is a systems engineering approach that focuses on defining and testing C2 functionality early in the development cycle. With the use of 3D modelling and an assembly of emulators and C2 modules, the approach allows commanders to operate a system before it is even designed and built. It offers an innovative and interactive way for engineers and operators to visualise, explore and develop systems. This paper describes the Emulator-based C2 Development process and highlights the insights gained from applying it to address challenging issues in a naval C2 project.

Dr Yeoh Lean Weng
Chung Wai Kong
Cai Jialing

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INTRODUCTION

Given the complexities of modern warfare, many defence applications are made up of systems of systems. The C2 systems are integral for organising information from these numerous subsystems to form a coherent tactical picture for better sense making by commanders.

With the drive towards having first-of-its-kind capabilities in technology, the operational requirements of the C2 systems are becoming increasingly harder to define, especially at the initial stage. Unfortunately, traditional C2 development has been based on paper designs and screen prototypes, which have limited interactions and functionality.

The long development cycle of a complex C2 system also means that there would be a long time lapse between specifying the requirements and testing the requirements. To conduct testing when the system is being implemented, changing the requirements would be costly and refinements to the requirements may have to be limited due to schedule or cost. Thus, there is a mounting need to develop a systems engineering approach to test C2 processes and workflow as early as possible, when the operationalrequirements are unclear or loosely defined.

This is a problem faced by many systems developers in the defence industry. The Emulator-Based C2 Development (EC2D) is an approach designed to address this problem. An assembly of emulators is used to establish the user interface and provide weapon and sensor inputs. Actual C2 modules are used to provide an integrated system for defining work processes. For the case study, a physical mock-up was set up to model the layout of a bridge on board a naval craft. With inputs from operators who are the end users of the C2 systems, ideas were explored and system requirements were refined accordingly. Thus, this approach allows for operation of the C2 system and experimentation with new C2 processes and concepts before the actual system is built.

This paper describes the process of the EC2D approach by describing how it is applied to address challenging issues in a naval C2 project, and in particular, finding the optimal station layout in the bridge and refining the C2 requirements. The paper also highlights the insights gained and recommendations for future work.

BACKGROUND

Joint Modelling and Simulation Environment for Wargaming & Experimentation Labs

The Joint Modelling and Simulation Environment for Wargaming & Experimentation Labs (JEWEL) is a repository of simulation components, models and knowledge, which allows long-term capability build-up. It is an enterprise solution for simulation as it adopts a common architecture for interoperability and reuse.

The JEWEL environment relies on a suite of reusable models and components, which are based on open standards and architectures. These collectively support various services in the Singapore Armed Forces (SAF) for various applications like training, analysis and experimentation.

Combat Management System

The Combat Management System (CMS) is a C2 system that was developed in DSTA, in collaboration with DSO National Laboratories, and is currently on board the frigates of the Republic of Singapore Navy (RSN). It integrates sensors, weapons and decision support tools to provide a coherent picture for decision making by commanders.

Concept of Emulator-Based Command and Control Development

Emulators are a class of simulators built to mimic operational combat systems (such as C2 systems, weapons and sensors) for training and experimentation purposes. Structurally, emulators consist of three layers: the User Interface (UI) for the users to interact with the emulators, a set of emulation logic modules for mimicking real systems behaviour, and the simulation engine and scenario generator to create the necessary stimuli to drive the emulators.

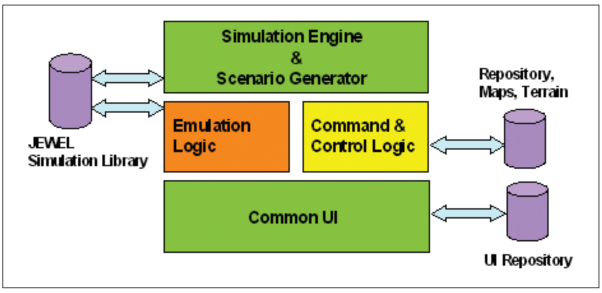

Figure 1. Emulator-based C2 Development framework

In EC2D, emulators are constructed using JEWEL during the inception of combat systems to assist in establishing the UI and defining work processes. As shown in Figure 1, JEWEL provides the simulation engine and scenario generator so as to simulate sensor and weapon inputs. Actual C2 modules were used to provide the C2 logic. The user interfaces are taken from the libraries of JEWEL and an existing C2 system, CMS.

In the beginning, emulation logic was used to effect a desired capability. For example, the users may desire a capability for the C2 modules to analyse the tactical picture and compute a weapon circle around the contact. This can be easily done in emulation for users to test for operational benefits. The real C2 algorithms can be researched, developed and inserted later. Users can experiment to see if ideas meet operational needs and firm up specific requirements, which can reduce costly post-implementation changes. The 'emulated environment' with its scenario generation capability would thus facilitate early and comprehensive testing of the C2 software components.

Eventually when the project is completed, all the emulation logic will be replaced by the actual C2 algorithms (see Figure 2).

The EC2D approach will extend the use of emulators to the entire C2 development cycle, from front-end studies, system definition, system design, to system development and training.

Workflow studies

As described in the previous section, the EC2D concept involves exploring ideas with users early in the development phase. This is done using workflow studies. Workflow is the analysis and documentation of the work that is to be done by human beings to successfully accomplish a goal or set of goals (Beecher, 2005). In the C2 context, workflow studies focus on mission and mission scenarios, command and control of the mission, communication channels, flow of work during a mission, potential bottlenecks as well as collaboration and decision points. Workflow studies are essential in the EC2D approach to engage users systematically during the exploration of design and ideas. Human factors would thus be considered in the early phase of hardware and software design. The case study in the subsequent section, 'Process of EC2D', will illustrate how an understanding of crew workflow led to a better design of the bridge.

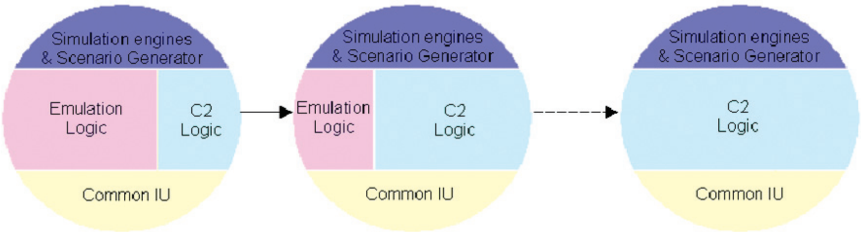

Figure 2. The proportion of emulation and C2 logic with time

The use of Emulation

This section explains the use of emulators in EC2D.

1. Limitations of Simulation. Simulation has long been used to aid C2 system design to give a more quantitative description of the system. However, the use of simulations to design complex technical systems, while long thought possible, has yet to measure up to its promise. This is largely due to shortcomings in software and hardware, which limit the contributions of simulation (Lofdahl, 2005). "Until recently, it has been almost a fundamental article of faith that as we got more advanced technologically and organisationally, we would be able to tame complexity by insightful decomposition and massive amounts of processing power." (Alberts et al. 1999, 151).

Researchers are increasingly aware that the core problem of simulation is not one of more data and computing power but that of abstraction.

A C2 system is highly complex and involves multi-system interactions. It is thus not easy to simulate the whole C2 system accurately for requirements definition.

By incorporating an actual modular C2 system thus obviating the need to emulate it, and focusing efforts on emulating other systems and their inputs to the C2 system, the impact of the limitations on simulation technology to the EC2D approach can be minimised.

2. Benefits of Emulation. We have made a distinction between emulation and simulation: "One system is said to emulate another when it performs in exactly the same way, though perhaps not at the same speed. A typical example would be the emulation of one computer by (a programme running on) another. Emulation is used as a replacement for a system whereas a simulation is used when one desires to analyse it and make predictions about it" (Denis Howe, 1993-2006).

Typically, simulation attempts to analyse the way in which the simulated system actually functions and to predict aspects of the system's behaviour by creating an approximate (mathematical) model via physical modelling, and this is usually done completely by software. Emulation, on the other hand, merely seeks to mimic the behaviour of the emulated system without duplicating the way it actually functions and may sometimes require special hardware to facilitate it.

The EC2D approach using emulation as hardware is used to create a realistic environment for the conduct of the workflow studies.

PROCESS OF EMULATOR-BASED COMMAND AND CONTROL DEVELOPMENT

Selection of a Case Study

A case study was carried out on a specialised first-of-its-kind naval craft. This project posed interesting challenges for three reasons. First, the RSN was prepared for new and innovative ways of managing C2 system on board the craft. Hence their requirements on the C2 system and other subsystems on board the craft were minimally spelt out. Second, as there was no prior experience of incorporating C2 modules in this craft, knowledge of its concept of operations and the crew co-ordinations had to be acquired in order to propose a well-constructed C2 solution that addressed the users' needs. Third, the ship was designed for lean manning. It was thus imperative to introduce an integrated bridge design that would allow a small crew to conduct their operations efficiently and effectively.

The EC2D approach to "operate" an emulation of the proposed cockpit would thus be very useful for assessing the interactions among the crew, as well as the design of the Integrated Bridge.

Requirements gathering

Operators, the end-users of the systems, were interviewed to identify four stations that would be key to the operations of the craft. They were the Navigation station, the Surveillance station, the Pilot station and the Commander station. An analysis was then conducted with the operators to find out the functions the crew needed and the means of executing these functions. With that, an initial layout of the bridge with functions assigned to the different operator stations was generated. For example, the crew operating the navigation station would need a navigation radar display.

Besides creating a 2D plan view of the bridge, a 3D model of the integrated cockpit was quickly developed using 3D StudioMax software to help users visualise the idea and generate discussion. Snapshots of the 3D visualisation are shown in Figure 3.

Figure 3. Initial proposed configuration (3D visualisation)

Integration of Command and Control systems with emulators

Emulators of the Navigation, Surveillance and Pilot stations were constructed using components from the JEWEL simulation library, with close references to the technical specifications of actual navigational and Electro-Optic (EO) devices that were being considered for acquisition.

Unlike the traditional way of emulating the entire system for workflow analysis, the most critical subsystem, the C2 software, was not emulated but adapted from the already tested and feature-rich CMS. The advantage of integrating an actual C2 software is that all the C2 logic is already intact and what you see is what you get.

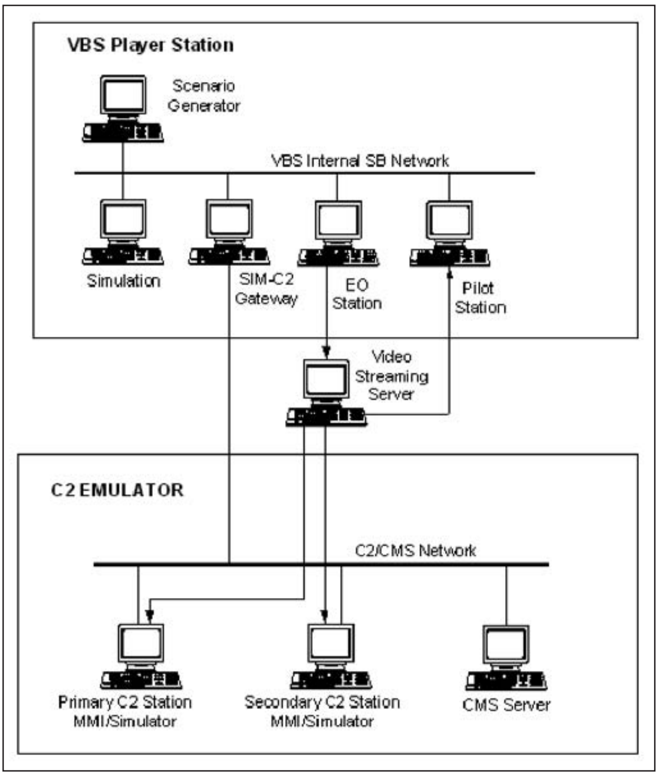

Figure 4. Architectural overview of the EC2D system

Connectivity between the C2 subsystem and the other emulated components was achieved using a Sim-C2 Gateway that was specifically developed to handle the exchange of simulated information and commands (e.g. own-ship location, simulated tracks and target designation commands). Figure 4 shows the architectural overview of the EC2D system.

Leveraging existing software components like JEWEL and CMS, the development time, including the integration of the emulated set-up, was completed within a period of two months.

Workflow study

After the development of the emulated set-up, workflow studies were conducted to gather user requirements effectively.

A physical mock-up of the bridge was constructed at minimal cost using materials like office partitions to mark out the physical dimensions of the bridge. Development computers were used as the bridge consoles. Appropriate lighting was installed to create more realistic lighting conditions inside a bridge. The out-of-the-window view was emulated using projectors.

Stations for different roles of the crew, e.g. navigator and commander, were arranged according to the proposed layout (generated during the requirements gathering phase). The crew conducted missions in this emulated cockpit, with realistic operational scenarios injected to stimulate interactions and responses.

Through observation and interviews, feedback concerning accessibility, applicability and adequacy of features was gathered. The stations were rearranged in a different layout and a new baseline of emulated features was also generated. This cycle of workflow analysis was repeated until the users were convinced of the optimal cockpit layout and features that they would require to operate effectively. Figure 5 illustrates this iterative process.

The workflow study was conducted over a period of three months, before the station layout and functions were finalised.

EVALUATION OF CASE STUDY

3D Modelling

3D modelling was an important step to generate user interest and discussion in the design ideas. Users could visually walk through the confines without actually developing a physical model of the Integrated Bridge. This allowed them to appreciate the complexities involved in integrating the systems.

Crew Organisation

Through operating the emulated bridge, the users were able to experiment with different layouts and configurations of the stations. Decisions on the most appropriate arrangements were made based on required interactions among the crew. For example, it was deemed useful for the commander to be situated in the centre and to have his own station for situation awareness to carry out his roles more effectively. Situating the pilot at the side gave him the advantage of using the side window while steering the ship into berth. Figure 6 illustrates the final configuration that would be considered for implementation.

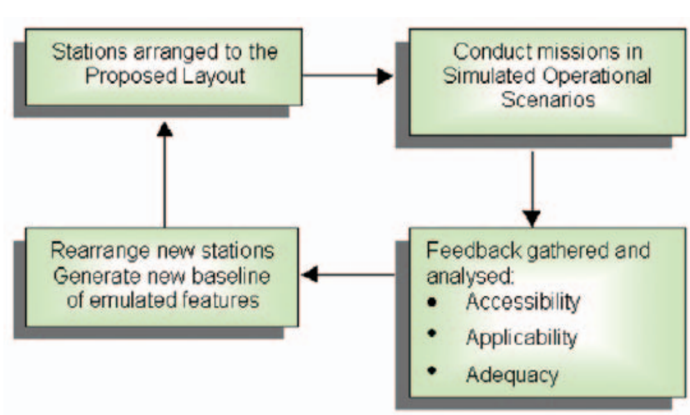

Figure 5. An iterative workflow process

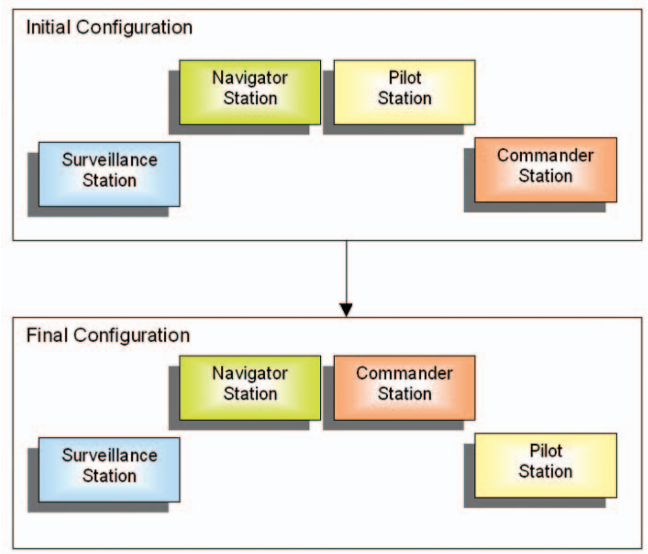

Figure 6. Initial and final configurations of the stations

Functional Features of Stations

Operating the emulated bridge helped to pinpoint salient requirements on the man-machine interfaces (and consequently, the system-system interfaces). The derived functional requirements of each station are listed:

a. **Surveillance Station.** There will be a display for the EO View, for surveillance purpose.

b. **Navigation Station.** There will be two displays, one for the C2 View, and another that can be toggled between the EO View and the Navigation Radar (NR) that incorporates the Electronic Charting System View. This is where safe navigation would be ensured with the navigation systems, and where forward search and surveillance will be conducted with the C2 situational picture compiled.

c. **Commander Station.** There will be a single display to present the C2 View for command and control purposes. Furthermore, CCTV views of the craft's blind-spots will have to be suitably sited for the Commander's visibility so as to facilitate safe steering of the craft.

d. **Pilot Station.** There will be a single display to present the C2 View. The Pilot will need to be aware of the situation awareness to facilitate safe movement of the craft according to the sail plan. Essential navigational information for piloting the craft will also be displayed via the C2 View at this station.

e. **Requirements arising from unique craft platform design.** Difficulties in crew workflow due to the platform design of the craft had surfaced in the EC2D process. This prompted investigations to re-evaluate the craft platform design.

f. **Reconfiguration Capability.** An added advantage of the EC2D approach in the case study is the ease and affordability of changing the screen layout after each review. The design of JEWEL allows the screen panels to be positioned and re-sized based on an Extensible Markup Language screen component set-up file. Generic panels (e.g. buttons, switches and knobs) can be added, removed or adjusted easily before the start of a new scenario. This flexibility allows the users to try out different ideas quickly to determine if the new features can meet their operational needs. Requirements can thus be firmed up before the development phase, resulting in fewer post-implementation changes.

LESSONS LEARNT

A first-time user of this approach would need time to set up the emulated cockpit, particularly to adapt and add on to the JEWEL framework, and to implement the interface between the emulated logic and the C2 logic. With wider application of the approach, the library of components and interfaces is expected to expand and become more standardised, consequently bringing about greater ease of use in subsequent projects.

Recording, Playback and Data Analysis Functions

The addition of an activity recording and replay capability in the emulated set-up would have been helpful as a debriefing tool for both the project team and the users to discuss issues that they might have missed out during the scenario play. This would be particularly useful to capture fleeting actions or incidents that might not be noticeable straightaway but that would surface only through debriefs or repeated analysis of recorded activities.

Application of Cognitive Task Analysis in Process Studies

To tackle the workflow study at a more systematic level, it might be useful to introduce and explore Cognitive Task Analysis (CTA) in EC2D-based projects. CTA is a technique to determine knowledge, thought processes and goal structures that underlie observable task performances. It can be used to model the information needs and flow between various system components, operators and mission requirements. Model-based simulation runs can be executed using the emulated set-up to deduce missing links in the information flow network. The results can be used to resolve information overloading, mismatch between system design and operational needs, as well as co-ordination and competition issues between operators in a team.

CONCLUSION

The Emulator-based C2 Development approach has been beneficial for defining the Integrated Bridge of a naval craft. The key to success of the approach has been the ability to present 3D visualisations of ideas effectively, emulate the perceivable man-machine interfaces, and allow users to operate the emulated stations interactively so as to evolve the system requirements.

On the whole, this approach has been effective in engaging and involving the users early in the design, analysis and definition phase to derive the most practicable Integrated Bridge design for implementation. Concurrently, the approach also allows the users to assess their training needs as the operational requirements are deliberated.

The approach is recommended for future projects with first-of-its-kind desired capability and where crew interactions are time-critical and complex. Additionally, suitable Data Analysis and CTA tools are recommended for more thorough and systematic workflow assessments.

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BIOGRAPHY

Dr Yeoh Lean Weng is Director (C4I Development) and a DSTA Systems Architect. He is also concurrently Deputy Director of TDSI and Adjunct Professor at the National University of Singapore (NUS). He has extensive experience in the development and implementation of Command, Control Communications, Computers and Intelligence systems. Lean Weng received his Bachelor (with Honours) and MSc degrees from NUS in 1983 and 1987 respectively. He further obtained two Masters (with distinction) in 1990 and a PhD degree in Electrical Engineering in 1997 from the Naval Postgraduate School (NPS). He attended the Programme for Management Development from Harvard University in 2003. Lean Weng received the National Day Public Administration Medal (Bronze) in 2001, and the Defence Technology Prize in 1992 and 2004. He received the Defence Technology Prize Individual (Engineering) Award in 2007, in recognition of his outstanding technological contributions.

Chung Wai Kong is Principal Engineer and Programme Manager (C4I Development). He is responsible for the development of Naval Shipboard Command and Control Systems. He received his Bachelor of Engineering (with Honours) degree from Nanyang Technological University in 1997. Wai Kong further obtained a Masters of Science (Computer Science) degree from the NPS in 2005. He led the Combat Management System (CMS) team to win the Defence Technology Prize award 2007, under the Frigate Programme.

Cai Jialing is Senior Engineer (C4I Development). She is a member of the team developing Naval Shipboard Command and Control Systems. She is involved in track management and data fusion engine of CMS. Jialing obtained the DSTA Undergraduate Scholarship in 2000. She received her Bachelor of Electrical and Computer Engineering degree, with first class honours, from NUS in 2004. Jialing is a member of the team which received the DSTA Innovation Excellence Award in 2006. She is part of the team that was awarded the Defence Technology Prize (DTP) 2007, for her involvement in CMS in the Frigate Programme.