Integration Testing of Highly-Complex Submarine Systems

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Synopsis

With the growth in technology, there is a desire to embrace the increased functionality and capability that it can yield. For large control and indication (C&I) systems on a submarine, this translates to monitoring and automation several orders of magnitude beyond that possible on previous classes. As such, system complexity increases significantly.

In addition to ensuring that an individual system operates correctly, it is imperative to ensure that when brought together these complex systems interoperate as intended. Given the spatial complications of a built submarine, and the programmatic implications of correcting defects post-build, it is advantageous to be able to verify and validate correct operation of this super system-of-systems ahead of installation.

The methodology described in this paper relates to the novel approach of shore-side integration testing of complex systems as applied to the Dreadnought build programme.

Keywords: Submarine; integration testing; complex systems

1. Introduction

From an engineering perspective, a submarine is the successful integration of a plethora of highly-complex systems into a small, mobile volume; in essence a super system-of-systems that is subjected to a harsh environment. Of course, other platforms, such as oil rigs, surface ships and aircraft are also a collection of systems, though both the quantity of systems and mode in which these are operated on a submarine is many orders of magnitude beyond these others.

The highly-complex submarine systems include: a Nuclear Steam Raising Plant (NSRP); electrical generation storage and distribution; high energy fluid systems; hotel services; weapon systems; navigation systems; steering and diving etc. Unlike the other platforms, not only does the submarine have to operate for prolonged periods in total isolation from shore support, but the grim reality of systemic system failure is ever present in the minds of the submariner.

As technology has advanced over the years, the shipbuilder is ever keen to embrace the perceived benefits (increased automation, additional monitoring and enhanced “defence in depth”) this may offer. On the flip side, such an approach significantly increases complexity further and introduces an abundance of other second and third-order issues, such as: cost-growth, schedule impact; unwieldy obsolescence and magnitudes of safety due process.

2. Impact of Change

Any large-scale, enduring engineering project will fundamentally be subject to change during the build process; this is compounded further when obsolescence is considered. This change, and the imperative to verify and validate correct inter-operation of complex systems results in cost-growth and schedule delay. Though not unique to defence (for example, this has effected Crossrail, too) history is littered with examples of defence projects dogged with successfully addressing this issue.

A well-known example of failure to successfully prove integration following change was the Apollo 13 accident on 14 April 1970 (Wikipedia (2022a)). Here, a thermostatic switch in an oxygen tank was originally (in 1962) specified to work at 28v. Though the specification was later (in 1965) changed to 65v, the switch

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remained unchanged. No integration testing was undertaken and when the switch was operated *in situ* it overheated, failed and caused the oxygen tank to ignite and its moon landing was aborted. Arguably, had the systems been tested in an integrated fashion prior to the mission, this defect could have been highlighted and addressed.

3. What Makes Submarine Systems Unique?

Many platforms outside the submarine domain utilise complex[2] engineering systems; for example, aircraft and surface vessels. However, the manner in which these are installed, maintained, updated and interrelate are significantly different and far fewer in number than on a submarine, particularly a SSBN. In addition, the consequences of failure are much less severe, too.

Taking, for example, a surface vessel: this typically has much more space to accommodate its various systems. Should these fail then, at worst, the vessel will be rendered dead in the water until assistance, be that from the Original Equipment Manufacturer (OEM) or shore support crews is provided; the, relative, generous space onboard much aids system rectification. Conversely, a SSBN has to accommodate far more systems, including the NSRP and Strategic Weapon System (SWS), into a heavily confined space. Its operational profile mandates that it remains incommunicado for months at a time and, should catastrophic failure occur then the submarine will be lost.

Consequently, it is of the utmost importance that the concatenated, broad collection of complex submarine systems, subject to stringent spatial constraints, operate correctly in all foreseeable modes and are maintainable by the crew, completely unaided, whilst deployed. Historically, Installed Tests were the manner in which such assurance was obtained. Should shortcomings be discovered, it was necessary to rectify the systems *in-situ*, which introduced significant complications, programme delays and injected programme cost.

4. A Novel Approach to Integration on Dreadnought

To avoid the integration issues that affected other projects, Dreadnought[3] commissioned a facility that would allow the most complex systems to brought together and tested ashore in normal, abnormal and combined abnormal modes ahead of being fitted on the submarine; intuitively, it is much cheaper and offers less programmatic impact to address shortfalls ahead of build. This facility is called the Dreadnought Integration Facility (DIF).

In any such large platform it is common for C&I to be provided by one dedicated system and actuation of various devices, such as hull valves, powered separately from the C&I system using hydraulic or pneumatic supplies. Through testing at the DIF it is possible to ensure that the Human Factors and Operability (HF&O) spatial element, both in terms of the user-experience (i.e. the physical layout) and end result (i.e. the correct valve moves when demanded) is not only correct, but displayed in the correct format to attract the desired attention. Though seemingly trivial, the confusion that such poor layout provided were deemed influencing factors in both the Chernobyl (Great Disasters (2020)) and Piper Alpha (Great Disasters (2019)) accidents.

4.1 *Design and Functionality of the DIF*

The concept of the DIF was stood up over a decade ago and a dedicated, classified facility constructed at cost specifically for Dreadnought boat 1. Although a significant investment, this figure is rather small compared to the overall spend of the Dreadnought programme (Dreadnought Alliance (2021)).

A key functionality of this facility is that it replicates, electronically, the submarine platform as far as possible. Consequently, bespoke power supplies together with interconnectors have been installed. Furthermore, cable runs have identical lengths to that of the submarine-fit; this ensures latency is accurately modelled.

4.2 *Second Order Benefits*

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[2] For clarity, a complex system is one that contains a significant proportion of programmable elements, controlling a multitude of critical parameters in real-time, often relating to high-energy systems and spatially distributed across the platform.

[3] Dreadnought class is the replacement for current Vanguard SSBN that provides the UK's strategic Continuous At Sea Deterrent (CASD) (Dreadnought Alliance (2021)).

Rapid Prototyping: Classically, the “V” curve is used to describe the verification and validation activities undertaken in development of a system (Shamieh (2011)), Fig 1. In terms of programme, an abscissa can be superimposed on this curve reflecting the Dreadnought’s build schedule. As is often the case in a large project, challenges associated with verification and validation activities have the effect of extrapolating this curve to the right, in essence risking the delivery dates.

In the DIF it is possible to setup complex, realistic simulations in a very short time, whereas in a built submarine this (alignment of spatially diverse and critical systems) would quite literally take days to accomplish. Additionally, the DIF also affords the ability to undertake “soak tests” in bespoke configurations: this is particularly beneficial as submarines are often operated for a prolonged period in abnormal configurations. Together, this novel testing, in the safe environment of the DIF allows the V curve to be left-shifted, saving valuable programme time.

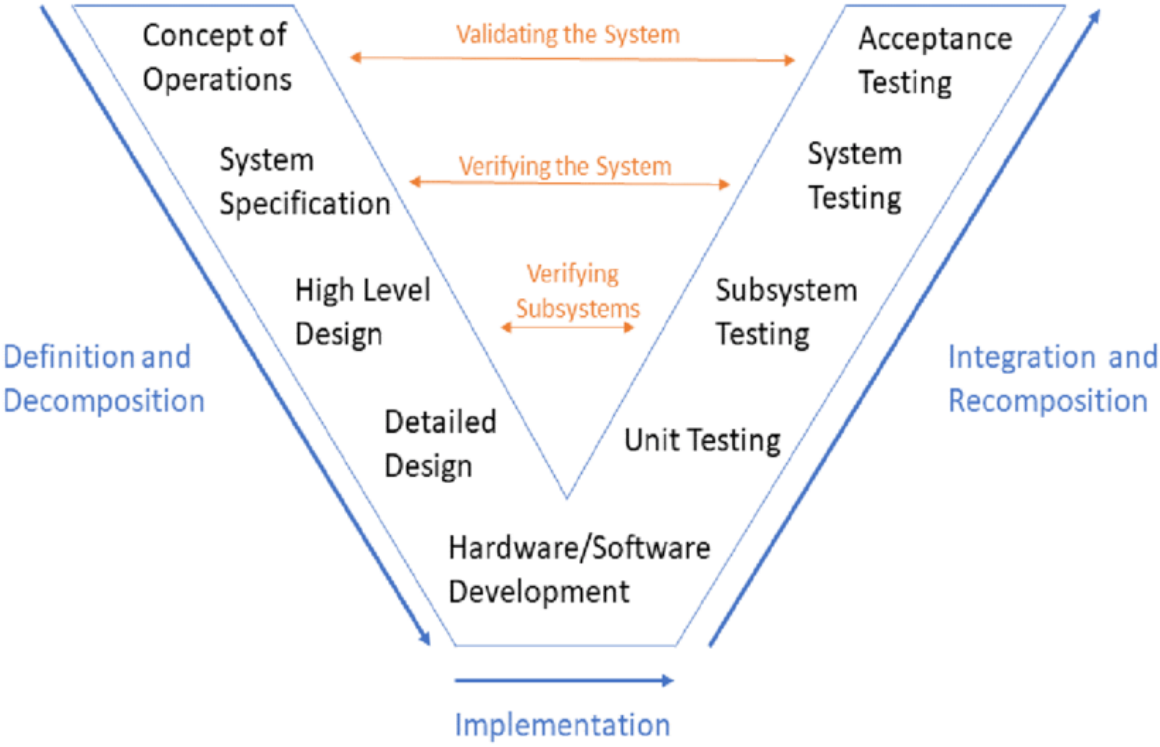

Fig 1. The V Curve

Obsolescence Management. Another significant feature of the DIF is addressing change and validating it. As mentioned, the short product-life of many components has meant that the time elapsed between design, delivery and installation has frequently resulted in certain products becoming obsolete, and in some cases the manufacturer has even withdrawn from the market altogether. Given that the Dreadnought class commission will extend into the 2070s the position of installing obsolescence prior to entering service is clearly not the hallmark of a responsible operator. However, fully qualifying a new product on the platform following installation would put the programme and maintenance of CASD at risk.

Instead, through use of the DIF it is possible to practically validate the correct operation of new components and their interaction with the other complex systems in a safe, shore-based environment. An example of this relates to a Programmable Logic Controller (PLC) which became recently became obsolete. The manufacturer proposed a direct replacement to the Tier 2 supplier, yet uncertainty remained regarding its operability with another system. By testing it in the DIF it was possible to analyse the component quickly and safely. It goes without saying that such an approach is not possible on an operational platform.

Through-Life Safety Case Maintenance. A guiding principle of modern engineering is the use of robust standards during design and the production and maintenance of a safety case to ensure the overall solution meets all its requirements in a demonstrable and safe manner. Each complex system on Dreadnought has its own Safety Case, the Approval of which rests with the appropriate authority: for example the PWR3 Safety Case is Approved by the Defence Nuclear Safety Regulator (DNSR). Bringing together and testing the interoperability of these complex systems, particularly following an update, in a shore environment introduces a further degree of assurance to the V&V process which otherwise could only be provided at sea.

4.3. Operating Philosophy

Initial guidance on the DIF's operating philosophy was taken from the Eurofighter Typhoon (Wikipedia (2022b)) project's integration testing at RAF Conningsby in the 2000s. Due to the differences in system architecture (a fighter jet is several orders of magnitude less complex than a submarine, yet operates significantly quicker, for example) the read across required much modification and adaption, though interaction with Subject Matter Experts (SMEs) provided useful lessons, for example in the simulation regimes.

Development of the operating philosophy of the DIF resulted in a Simulation & Stimulation (SIM & STIM) stimuli being adopted. Put simply, the SIM component is the inputs which the system is subjected to, for example raising the foreplanes to 10º, whilst the STIM is the interaction from other systems, for example a failure of hydraulic pressure, loss of electrical supply and so on. The combination of SIM & STIM provides a powerful, cross-domain (i.e. electrical and mechanical) and pan-system (i.e. the induced parameters from other systems) mechanism to test our complex system in all normal, abnormal and combined abnormal modes. Further, since this is software driven, it is possible to load scenarios in a very short time (minutes). The output from the system under test is monitored by both software against a pre-defined set of parameters and test engineers, Fig 2.

As a comparison, to generate the appropriate SIM for the various systems can vary from several hours to several days, though typically tends towards the former. Notwithstanding the implications to the asset (i.e. Nuclear Safety, Weapon Safety, Watertight Integrity etc.), undertaking bespoke testing onboard would require justified test procedures, Approved well in advance by Subject Matter Experts (SMEs), prevent other military tasking and tie up much resource for a considerable time. The DIF avoids these issues.

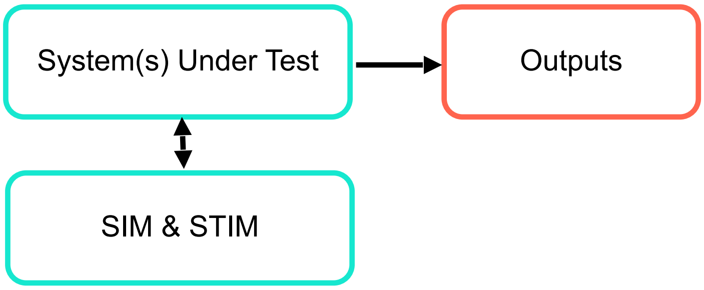

Fig 2. SIM & STIM

5. Success to-date

Through not yet at full operating capability, through integration activities, the DIF has highlighted many quality issues with numerous products delivered into the programme. This has ranged from care and protection issues, where equipment has been irrevocably damaged, through to cabling being incorrect, both in length and type, all of which would deleteriously affect schedule had this been found onboard.

Systems testing has been successful, offering confidence in proof of concept. In particular, the assessment of change due to obsolescence has offered particularly positive results. Given the pace of change, this will play a significant role going forward.

6. Summary

The overriding priority in the Dreadnought Alliance is to ensure the schedule is held such that the submarines can be delivered on time to maintain CASD (Dreadnought Alliance (2021)). Bringing complex systems of system together will, by its very nature, introduce schedule risk, which is only compounded by the short-term and fickle nature of the modern, underpinning architectures. The DIF is providing a credible means of de-risking this activity, thereby allowing the programme schedule to be held.

Naturally, a facility like this is not cheap, but the heretofore programme benefits have been significant. As integration testing ramps up in the coming months, this return on investment is likely to be returned several times over.

Without doubt, integration testing will be of particular use to any complex system of systems project, not just submarine builds. Applying this methodology to future submarine builds, there is a strong argument for developing this further to increase both capacity and scope.

7. References

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