Integrated Model Based System Engineering of the Naval Propulsion Plant and its Control System

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Synopsis

Naval ship propulsion systems are designed to meet very demanding requirements of performance with criteria ranging from high energy density, high efficiency systems and low stealth signatures. With the high cost pressure on defence spending, navies are seeking to meet these objectives with low acquisition and life cycle costs with leanly manned crews for ships. In this scenario, while the complexity of the propulsion system design itself increases, the complexity extends to the domains of the propulsion control systems and human-machine interface. With the lean crew on-board, the complexity further extends to the areas of operation and maintenance of such systems on-board and thus crew training. This paper proposes a domain based integrated Model Based System Engineering (MBSE) to comprehensively address the areas of system design, control system design, operation and maintenance as well as training. The approach is based on development of mathematical model of the propulsion system is developed early during the concept development stage which evolves continuously during the various stages of design. The same framework is then used for dynamic analysis of the system towards development of the propulsion control system, and then integrating into condition based maintenance systems and crew training systems.

Keywords: naval propulsion systems, systems engineering (SE), model based system engineering (MBSE), model based design (MBD), modelling, simulation, propulsion control systems, digital twins, immersive technologies, virtual reality, training systems

1. Introduction

Modern warships have evolved to become some of the most complex man-made systems around (Andrews, 2006). High performance, energy dense, stealthy and efficient systems with affordable acquisition and life cycle costs are the primary design drivers for the present day naval propulsion and power systems (P&PS). To meet the stringent and often contradicting design requirements, the sophistication and complexity of modern P&PS increase, while often operating close to the design limits (Dimopoulos, et al., 2014). The recent trend to design more efficient and versatile ships has increased the variety in P&PS architectures, with architectures becoming more electric. In terms of the more electric architectures, while there have been some major applications of IFEP or IEP for programs like the Royal Navy's QEC aircraft carrier, Type 45 destroyers and USN's DDG-1000 programs, the present trend shows an increased application of the hybrid architectures to naval systems with which provide stealthy, efficient and relatively cost effective propulsion solutions; with the philosophy of 'electrify what needs to be electrified'.

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Some recent examples of such hybrid applications are CODELAG plants used in the USN FFG(X) or the FFG62 program based on the Italian Navy FREMM design and Finnish SQ2020, CODELOG configuration on the T26 program, CODELAD on the German F126 program. On the other hand, combined mechanical propulsion plant configurations like CODOG, CODAG, CODAD etc. still continue to be applied to naval designs with some innovative designs like the CODAG-E developed for the Italian Navy PPA project. Application of such P&PS configurations for ships has lead to increased complexity in design of the propulsion system itself, its control systems and the related system integration work. Such plant designs also throw up some unique challenges in the areas of operation and maintenance. On the other hand, ship building projects face increased cost and time pressures while the manning on the ships continues to become leaner. Further, such complex designs are being executed by ship designers and shipbuilders with rather limited experience and capabilities for executing such complex designs driven by the requirements of 'local content' in naval shipbuilding programs. For a successful ship design, the ecosystem for the development of the P&PS need to address these rather diverse factors in the domains of system design, operation and maintenance.

The design of the P&PS could be viewed as being executed in two primary phases: conceptual and detailed design. The conceptual design phase involves the selection of the propulsion system configuration that synthesizes into the architecture of the overall P&PS, considering the overall design criteria and constraints in iterative loops with the overall conceptual ship design of the ship. This conceptual design is executed in the initial phase of the ship design, where it is estimated that more than 80 percent of a naval ship's ultimate acquisition cost is locked (Brown & M.Thomas, 1998). McIntyre et.al. published an example of such a process used for the selection of the RN Type 26 P&PS design (McIntyre & Gemmell, 2012). The detailed design involves evolution of the architecture of the propulsion and power systems developed during the conceptual design into a working system design with the finally selected equipment. An effective design synthesis process of an optimal P&PS architecture should effectively combine the institutional design, experience and calculation methods of the design agency, in the context of the overall ship design. While the subject of application of available propulsion technology to meet the overall objectives of the ship design is usually discussed by most design agencies in detail, often there is not enough emphasis laid on the detailed process for selection of the most optimal propulsion system architecture with over-simplified coarse estimates of P&PS performance.

Modern warships have additional complexity compared with their counterparts because of the challenging requirements set that they have to fulfil and because of the proliferation of increasingly software based control (Tudor & Harrison, 2019). With increasing complexity of ship propulsion system architectures, the number of variables and drive modes to be controlled escalates to extents that are becoming more and more difficult to manage with conventional control strategies (Geertsma, et al., 2017). On the other hand, often the ship propulsion control systems (PCS) are considered to be primarily 'remote operation' systems that enable the operation of the ship propulsion plant from location/s remote to the engine room. This could not be further from reality, especially in the context of 'combined' plants where the PCS is deeply involved in controlling the system dynamics working together with the individual equipment control systems, and with the power management system in case of electric drives being applied to the designs. In order to improve performance of various propulsion system configuration, intelligent control strategies are required, while mostly conventional control strategies are applied currently (Geertsma, et al., 2017). Hybrid architectures with advanced control strategies can reduce fuel consumption and emissions up to 10–35%, while improving noise, maintainability, manoeuvrability and comfort (Geertsma, et al., 2017).

The design process of the P&PS utilizes modelling and simulation for undertaking various studies such as overall performance studies, dynamic performance analysis, vibration analysis etc. The overall approach is generally to build individual models to address specific areas of application based on various degrees of fidelity and undertake the analysis. The major USN and UK naval shipbuilding programs still use land based test or engineering sites (LBES) to test, prove and de-risk the propulsion system designs before they are installed on board. USN undertook testing of the DDG 1000's IPS at a dedicated LBES, which included testing of the Engineering Control System software with IPS to verify software and hardware compatibility and interoperability (DDG 1000 Program Executive Office Ships Public Affairs, 2011). MoD UK undertook testing of the IFEP for the Type 45 program by establishing the Electric Ship Technology Demonstrator at Converteam's (formerly ALSTOM Power) Whetstone site in Leicestershire, UK (Hodge, 2008) (Mattick, 2004) More recently, RN Type 26 and the USN FFG(X) are using/ plan to use LBES to de-risk the P&PS designs (Capper & Groves, n.d.), (Congressional Research Service, 2022). However, LBES are prohibitively expensive and require a long lead time to set up, and are thus not feasible for most naval ship building programs.

The engineering crew on-board a naval ship is usually required to operate as well as maintain the propulsion, power and auxiliary systems on-board. The design of the PCS and the Human Machine Interface (HMI) plays a crucial part in the operation of the naval propulsion system while the condition monitoring and maintenance support systems on-board are the key tools for the crew on-board to undertake the maintenance activities. The condition monitoring systems are used to trigger a maintenance action while the maintenance support systems guides the crew on the process of undertaking a maintenance task. The designs of these systems are the key enablers for supporting the requirements of reducing crew size on-board, where the crew is expected to undertake a large scope of activities than was traditionally undertaken. With this changing scenario of increasing complexity of systems and lean crew with higher and more diverse individual responsibility in both the domains of operation and maintenance, crew training is a critical factor that needs to be addressed with most effective, efficient and cost effective training solutions.

The aforementioned challenges in the areas of system design, operation and maintenance that the modern naval P&PS face could be potentially addressed by a 'systems engineering' approach. Systems Engineering (SE) is a methodological approach to the design, implementation and operation of complex technical systems, focusing on the interactions of the constituents of the system, how they are interconnected, and what is their influence on the overall behaviour and/or performance of the machinery components (Dimopoulos, et al., 2014). SE aims to ensure the elements of the system work together to achieve the objectives of the whole, by integrating across system elements, disciplines, the life cycle, and the enterprise (International Council on Systems Engineering (INCOSE), 2021). A centreline in SE approaches is the use of mathematical models and computer-based methods and tools that enable better comprehension and management of the embedded complexity in today's systems. This computer-aided approach is often termed as Model-Based Systems Engineering (MBSE). Over recent years, the term MBSE has been used to describe "the formalised application of modelling to support systems engineering," (International Council of Systems Engineering (INCOSE), 2015). MBSE is essentially about placing models in a central and leading role the engineering process to drive requirements exploration, specification, design, integration, validation and operation of a system (International Council of Systems Engineering (INCOSE), 2015). The traditional approach to warship design has largely been predicated on a document-based systems engineering methodology (Tepper, 2010). Tepper presented a vision for a warship development lifecycle underpinned by MBSE that brings together various modelling methods, with targeted emphasis at different phases of the lifecycle, in order to manage such complexity has been presented (Tepper, 2010). A principal outcome of a model based approach is that it enables data-centric systems engineering to be at the core of the design process as opposed to document-centric; this is seen as reducing design risk by removing the issues that documents pose (Buck, 2012). Edmondson et. al. state that MBSE can be used effectively to understand the impact of a change to the specification, but all stakeholders need to understand the impact of that change at a system level and not just at a sub-system level (Edmondson & Twomey, 2018). Sturtevant et. al. explain the application of a digital twin for Integrated Logistic Support (ILS) engineering and asset management standards for naval support systems (Sturtevant, et al., n.d.).

Historically, basic training has been undertaken using classroom tutorials and simulators (along with some generic skill training) before the trainees are deputed on-board ships for 'on-job training'. The major drawback of this method is that it is always a big leap for the trainees to directly graduate from a predominantly theoretical environment to a 'live' operational platform and this may occasionally lead to errors in operation of live equipment at sea. Immersive technologies, a broad term for virtual reality (VR), augmented reality (AR), mixed reality MR and extended reality (XR) technologies, offer cost effective and flexible methods for providing training solutions for complex and expensive systems with a near-live feel for the trainee for the overall system and its environment. Such training systems are being increasingly sought by naval operators to maintain and extend the familiarity and system specific competence of the crew for propulsion systems that are becoming more and more complex (Bunyard, 2021). Martinie et. al. highlight how model-based approaches could provide a for integrating models, operational procedures, training scenarios and interactive system models for dependable command and control systems (Martinie, et al., 2011). However, the current usual practice is to keep the operation and maintenance training activities separated, while the working in a team is rarely considered while developing training systems.

This paper describes the approach that has evolved at RENK, over a course of several development projects, aimed to addressing the areas of design, operation and maintenance as well as crew training for the modern naval P&PS based on an MBSE approach. The paper describes the evolution of this MBSE used for the development of the RENK Propulsion Control System (RPC) which was the trigger for the MBSE approach integrating other product lines using the developed models.

2. Connecting the areas of design, operation, maintenance and training

A key enabler for a combined naval propulsion system is the transmission system, whether mechanical, electric or hybrid, which is designed specifically for a ship design. The transmission system integrates the usually well developed engines to the propulsor system forming the ship drive train. The transmission system developer thus is usually at the centre of the propulsion system design, managing the highest number of interfaces. RENK has been at the forefront of the development of such transmission systems over the last decades, supplying systems for programs such as German F122, F123 frigates, Australian and New Zealand Navy Anzac class frigates, Indian P17, P17A frigates, South Korean KDX-I, KDX-II, FFX-I programs, South African MEKO A-200 corvettes, USN Independence and Freedom class ships, Italian FREMM, the German F125 frigates, Italian PPA ships, Finnish SQ2020 etc. (Hoppe, 2011) (Hoppe, 2012). Based on the knowledge base developed over such projects and driven by customer demands, over the past few years, many independent projects were launched at RENK to develop new product lines in the area of naval propulsion: electric drive systems, propulsion system conceptual design and integration engineering, ship propulsion control systems, condition monitoring systems, immersive training solutions and maintenance management systems.

Recognizing and understanding the needs for a systems based approach for model based design, whilst embarking upon the development of the RPC , the latest in the series of internal development projects, right from the initiation of the project the need for MBSE was made a mandatory requirement, using lean development teams connected functionally by a systems engineering team. The systems engineering team was created using engineers from the propulsion system and the control system engineering teams for the development work. concentrated on the system engineering tasks and development of the control algorithms, while dedicated teams were used to undertake the more focussed tasks of developing the system models, data interface systems, hardware designs etc. A tailored method applying the principles of MBSE to the classical V-Model was developed though the project as shown in Figure 1. Though the same has been done on many occasions in previous works, the method was adapted specifically to the needs of the project.

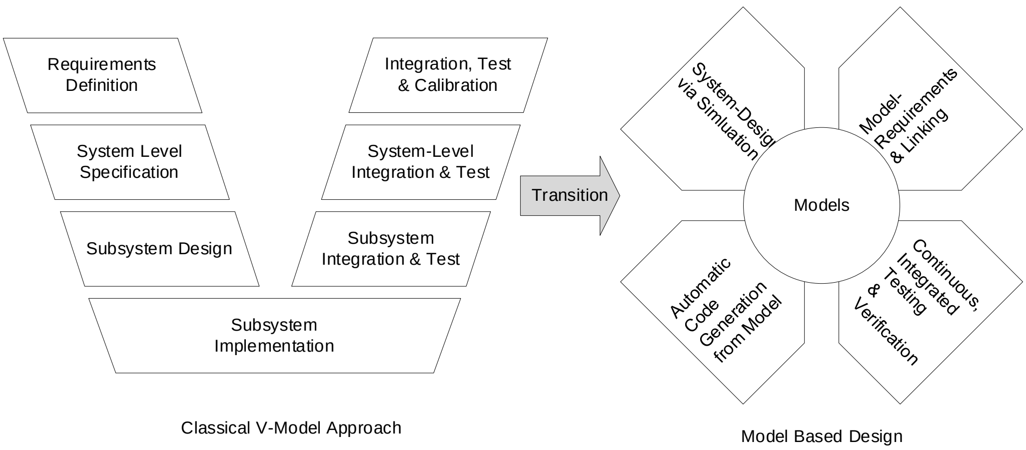


Figure 1: Transition of development-scheme from the classical V-Model to model based design

As the project progressed it was realized that many common elements of models used in other product lines were being used for the models being developed for the RPC. It was thus realized that, with the various performance and design models being the common thread that connects all the product lines, integration of these models across the product lines, would provide a comprehensive P&PS solution that spans across and connects the application areas of design, operation and maintenance. With the overall complexity of the naval ships as highlighted earlier, with MBSE approach at its core, a process of integration these models was initiated to develop a 'digital twin' of the P&PS. Digital twin is defined as: a virtual representation of a physical object or system across its life-cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making. (IBM, 2018). During the integration process, the overall digital twin was functionally divided into the 'performance digital twin' in the form the system performance model of the system and the 'physical digital twin' representing the physical aspects of the system and the included equipment. The digital twin was designed in a manner that it would evolve along with the development of the design of the system, initially used for development of the system design including the design of the control system, studying impact of design changes and then utilization as the 'engines' for the training system, as shown in Figure 2.

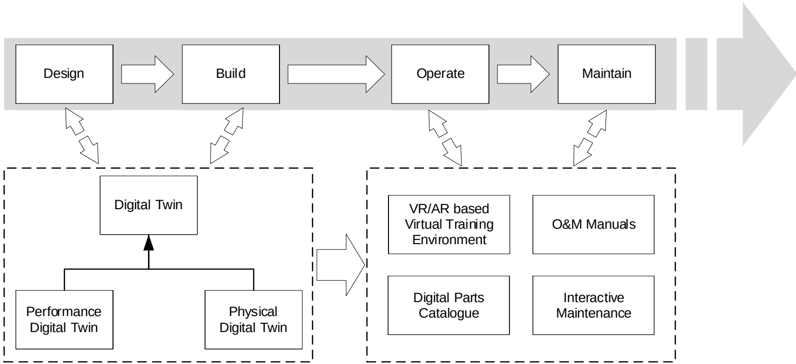


Figure 2: Integration of the digital twin into the P&PS design, maintenance management and training systems

In the overall context of shipbuilding, based on the above explained MBSE based development of P&PS solution spanning across the application areas of design, operation and maintenance, an alternative approach method to system design and integration is proposed. A schematic representation of the proposed division of responsibilities for overall system integration is shown in Figure 3. It is proposed that the ships systems design and integration should be based on system domain expertise rather than the usual practice of shipbuilders contracting the systems more from the point of area of application such as primary system design, control system design, condition monitoring, training simulator etc. Essentially, what is being proposed is that, it is the system domain (eg. P&PS) where very tight integration is necessary and this could be addressed by a single, domain specialist, 'supplier level' integration across the areas of applications of design, operation and maintenance or training systems. This would help the shipbuilders address the overall complexity of the naval platform to be practically addressed by considering the primary ship systems as interdependent loosely coupled heterogeneous systems. The deeper level of integration across the application areas in the systems could be managed by 'supplier level' integration through the application areas so that the shipyard can focus on the higher level system design and integration.

A single entity being responsible for the design of all the sub systems related to the areas of design, operation and maintenance of propulsion and power systems, referred to as the 'Propulsion and Power System Supplier' (PROPSS) in this paper, would provide the shipbuilder the possibility to concentrate its efforts on the higher level integration role. In such a set up we envisage that, the general requirements and boundary conditions for the propulsion system would be defined by the shipyard based on the defined concept of operations. Based on this input, the PROPSS would engineer the best fit system architecture for the given requirements in close interaction with the ship designer. As the ship design would progress, based on the selected system architecture, PROPSS would undertake the entire system internal integration work. PROPPS would also be the developer of the ship PCS, using the domain and project specific knowledge. The PCS would act as the interface between the individual propulsion equipment control systems and the overall vessel level platform management which acts as a 'system of systems', also serving as the primary human machine interface. The PCS would also serve as the human machine interface in case of failures in the overall vessel level platform management, still allowing intelligent control of the propulsion system.

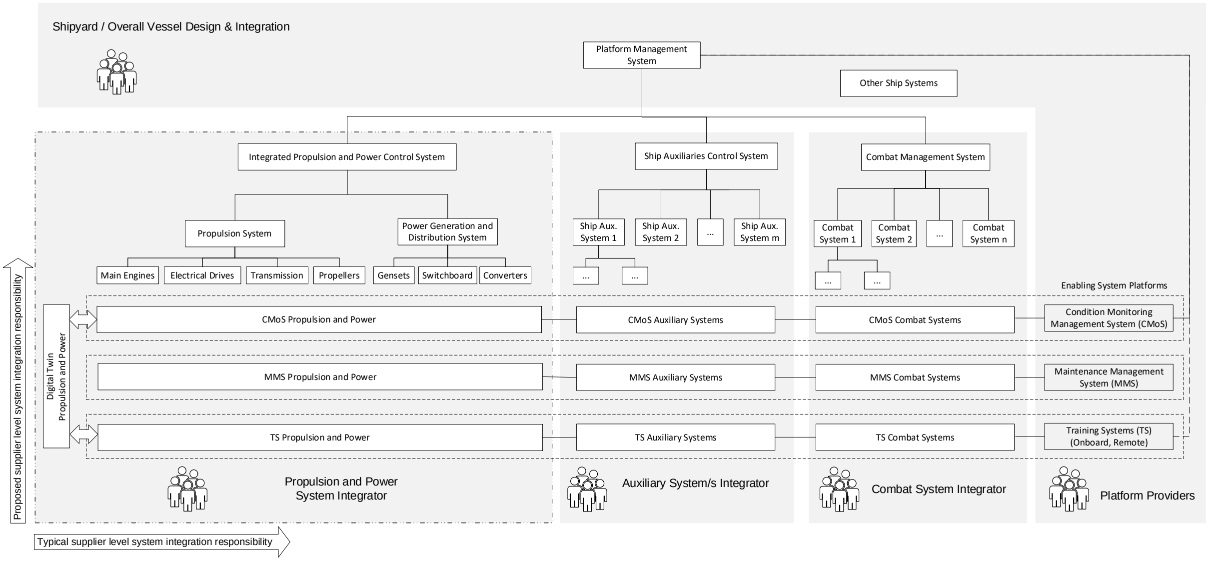
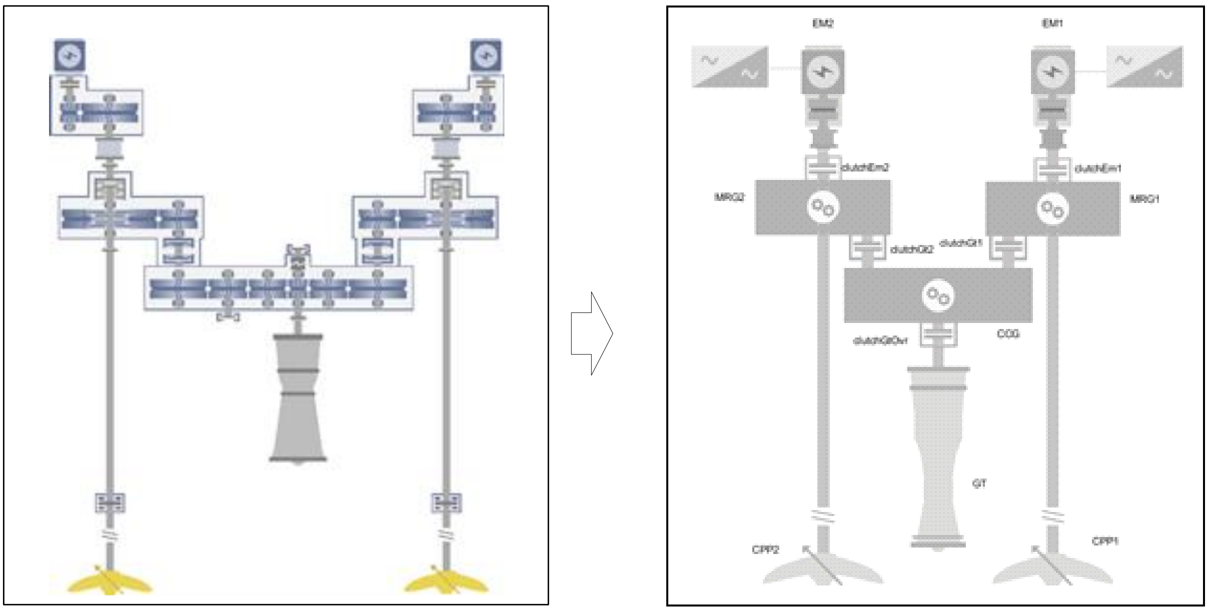


Figure 3: Proposed integration responsibilities scheme for overall naval ship systems integration

3. Application of MBSE for P&PS

This section describes the model based design process that was used for the development of the RPC, which was the template used for the further engineering activities for integration of the various models from other product lines into the digital twin driven MBSE.

For the RPC development process, a complex sample CODELAG configuration, as displayed in Figure 4, was considered. This configuration consists of two shaft lines with Controllable Pitch Propellers (CPP), with a main reduction gear (MRG), a geared electric drive (EM) powered by a variable frequency converter (VFC) per shaft line, a gas turbine (GT) and a cross connect gear (CCG). While these type of systems provide a very large flexibility in operation, modelling them is challenging due to a very large number of propulsion modes (states resulting from various combinations of prime movers to drive the plant) being possible, here 32 modes.



Propulsion Transmission System Scheme

Propulsion Model System Scheme

Figure 4: Reference propulsion system layout used for the development work

3.1. *Defining system requirements, interfaces and algorithms*

For defining the system level requirements and concepts, for both propulsion control and the propulsion plant performance model, a hybrid, document-based approach was used. Initially the general requirements of design, based on the extensive available experience, were captured in a classical way through textual requirements giving the engineers the flexibility to be more descriptive. From these general requirements, functional and architectural requirements were developed in form of graphical modelling diagrams, using the graphical modelling language, *SysML*, as a template. *SysML* was developed based on *UML*, creating a specialized standard targeted towards meeting challenges of systems engineering while reducing the number of diagram types (Holt, 2008). Ideally, a requirements management tool can be used to create, manage and verify system requirements and diagrams, incorporating *SysML*, throughout the development project. Despite the availability of various commercial and open source tools, textual requirements and diagrams were developed and distributed with general purpose text and graphical visualisation editors, allowing a fast ramp-up of the project amongst the various development teams. Further, the diagram templates defined in *SysML* were simplified in such a way that engineers without any background on *SysML* could understand the diagrams and implement the corresponding software modules accordingly, eliminating the need for extensive training. The main simplification of the used modelling rules lies in replacing formal statements, notations and diagram elements by less restrictive descriptions, pseudo-code and generalized visual elements. The most extensively utilized diagram types include:

- block definition diagram –bdd: to show architectural composition of software / system modules including the interfaces
- state machine diagram –smd: to define logic of the controller modules
- sequence diagram –sd: to show the sequence of interactions between software modules / entities/ states
- block diagrams (not derived from SysML) –sbd: to define signal flow for closed loop control structures

However, the increased rapidness of requirements definition and distribution to the project team that comes with the tailored approach described above, is at the expense of requirements accuracy in some cases. In order to cope with that challenge, frequent design reviews were introduced and proved to be highly beneficial for the development engineers as well as for the system engineers, creating a common deep understanding of the developed modules.

3.2. *Approach for defining the propulsion plant architecture and designing the propulsion plant performance model*

A precursor to the development of the RPC development project was the development of a steady state calculation software for comparison of performance of various P&PS architectures during the concept design phase, and thereafter further development of the selected architecture models to undertake steady state calculations for activities such as the development of 'combinator laws' etc. This project was executed using a component based modular approach, allowing rapid development of models closely resembling the actual structure of the propulsion system design. The modelling exercise would involve populating properties of predefined components (drives, engines, gear boxes, clutches and propellers) which would be connected to form the system using mechanical, electrical and fluid connections.

The ideas used for the development of the ship propulsion steady state calculation software, were developed further with the final objective being that a common user interface and models could be used for steady state and dynamic analysis of the system based on the engineering requirement. For the dynamic model of the propulsion system, the component models have been augmented by simplified, discrete logic representation of the propulsion equipment unit controllers. The propulsion equipment unit models are arranged and interconnected in accordance to the actual propulsion system architecture (Figure 4), enabling the engineer working with the model to visually recognize the plant architecture instantly. Further, this component based approach for modelling the propulsion system enables parallel development of unit models, ensures component reusability and simplified testing, flexibility regarding model fidelity and enables the project engineer to analyse the plant behaviour on a system level without having to revisit component model internal processes and interrelations. Thereby the main scope is to model the behaviour of the components which can be observed externally. Providing a specific input, the model shall always give a deterministic system response which is reflected by the output signals in the transient and steady state domains.

While in the early phase of a project design, the overall stationary and quasi-stationary model behaviour as seen from the system level is of highest interest, more detailed dynamic investigations on the component level become relevant in the subsequent stages of a naval project. Given the constraint that the external unit model interfaces remain unchanged, the proposed model architecture allows for further extensions and refinements regarding the component model fidelity and dimension. Finally, the propulsion performance model would comprise of subsystem models with individually selectable model variants, which differ regarding their level of detail and are selected based on the performance study to be conducted. As model precision comes at the cost of computing time, a certain focus on a subset of the overall system can be set, allowing for an optimized trade-off between computing time and model precision where it is needed.

As stated earlier, a major challenge that is faced for modelling of complex P&PS is the very large number of operating modes and simulation of the transition between these modes. Most literature on the simulation of these systems is focused the system behaviour in specific modes of operation but not the transition between these modes. The ability to be able to model and simulate the transition between these modes in the transmission system, consisting of reduction gears, cross-over gear and clutches, was an important achievement of the project. Here, a state-space representation of the system's differential-equations was used to model the rotational mechanical behaviour of the transmission system including the 'stick-slip' behaviour of the disc clutches.

In order to model the behaviour of the propulsion equipment control units, simple logic blocks implemented by using state machine diagrams have been developed. Those logic blocks resemble the signal interface to a propulsion control system or a local user. This enables the controlling instance to issue commands like starting and stopping of engines, engaging and disengaging clutches, etc. and receiving corresponding feedbacks representing the status parameters of the propulsion equipment. This interface also plays a key role for the virtual training system developed in course of the project.

3.3. Designing the RPC and system dynamic studies

The overall architecture of the RPC model consists of multiple levels resembling a hierarchical structure. Initially, the overall system architecture was built using placeholder blocks from the unit models up to the top level model including the initially defined interfaces and connections. Implementation of the individual models was then executed from a bottom up approach, starting with the unit level models. Unit level models are the lowest level logical instance communicating with the actual propulsion system equipment like engines, clutches, etc. by supervising their status feedbacks and issuing the final, discrete commands like start, stop, engage, disengage etc. A rough overview of the overall model architecture is given in Figure 5. On the subsystem-level, functional groups are further integrated into control software modules dedicated to certain aspects of propulsion control. In total, three subsystems have been formed on that level which handle

- control of supervisory and discrete command functions regarding the propulsion equipment
- closed loop regulation control of the propulsion equipment
- control station management for the multiple propulsion control HMI-stations

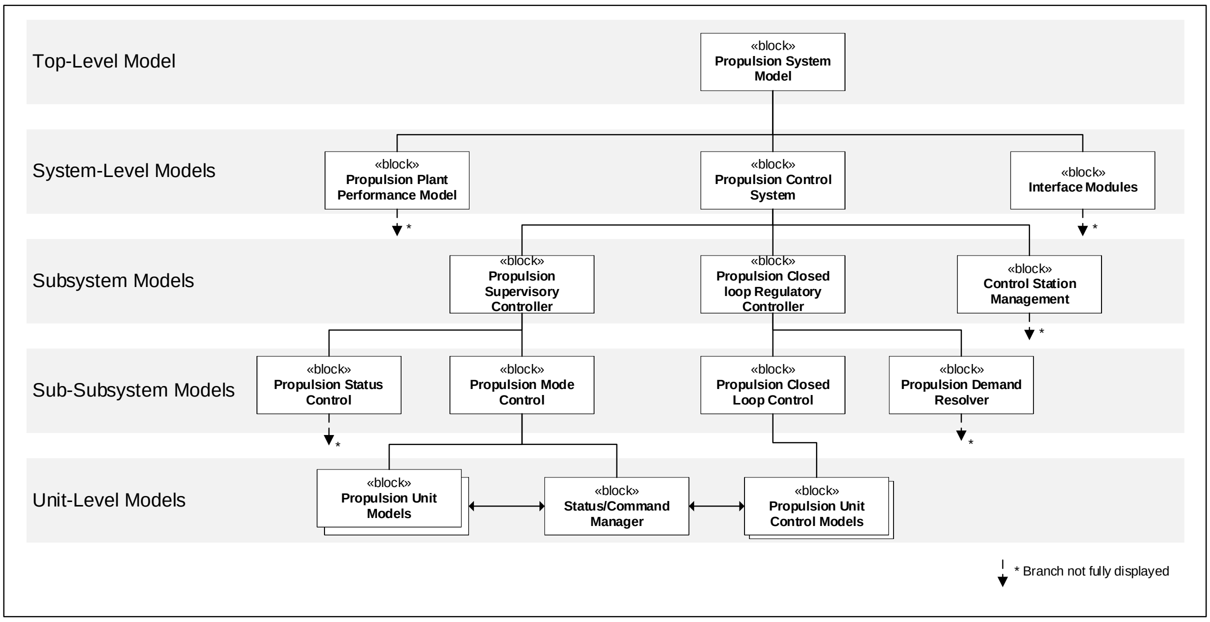


Figure 5: System architecture block definition diagram

The entire supervisory control logic for the system was developed using state machines. The system level engineers developed the control logic algorithms using state machine diagrams, along with timing diagrams where necessary based on which the development engineers created the final implementation of state machines. The control logic developed by the system engineers and their interactive behaviour could be easily recognized in the final implementation of the models. An example state machine diagram is shown in Figure 6. This proves the feasibility of the approach, where a systems engineer can quickly define the control logic on a sufficient but not fully extensive level of detail, enabling the development team to start the implementation work early on.

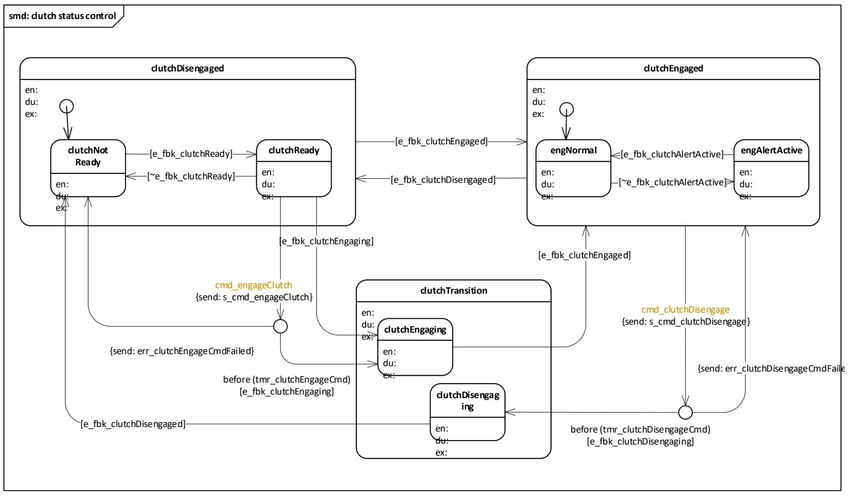


Figure 6: Sample state machine diagram - clutch status control

Extensive testing of the control models was undertaken starting from the unit level and then moving up the design hierarchy. The test cases were defined along with unit model development, covering all reasonable scenarios that the unit models would have to satisfy, including fault-scenarios. Upon completion of a unit model, the defined test cases were executed and documented in an automated manner. Apart from ‘pass/fail-indication’ for the individual test cases, the test coverage was being evaluated, which gives a good hint on whether a sufficient amount of distinct test cases has been defined. The ideas of such testing were drawn from the processes used in automotive industry where such approaches are widely applied, but have barely been incorporated in RPC design. Once the unit level models have been tested and approved, the integration into functional groups was executed. This was achieved by introducing so called ‘status/command manager models’, which interface with the corresponding unit level models, evaluating their status feedbacks, gathering further system feedbacks and thereby observing and controlling compound states of the overall system like ‘propulsion drive mode’. Transitions between such states are controlled based on user input or system events while supervising all necessary feedbacks forming the transitional conditions. Testing of the functional groups at this hierarchy level is conducted in a similar, but less extensive way, as compared with the individual unit models.

3.4. Scenario based integration of the propulsion plant and control system software blocks

The overall software blocks need to be interfaced considering multiple scenarios, ranging form the engineering development phase with MIL, SIL, HIL to the final deployment design as well as integration with trailing systems. Further, despite the parallel arrangement of the control software modules, lateral communication between those has to be implemented, since certain dependencies cannot be eliminated. A descriptive example for that case is the correlation between engine status control and closed loop speed control which has to go hand in hand. This integration step leads to the system level model of the propulsion control software module, implementing an appropriate division of tasks, while maintaining a manageable model structure and high readability.

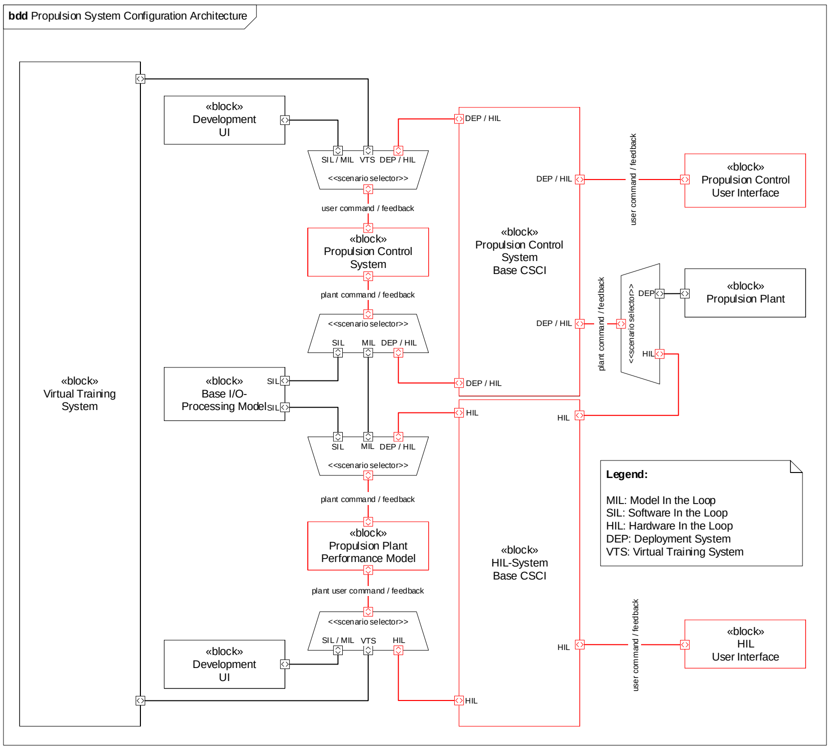


Figure 7: Propulsion System Model Configuration Architecture (Highlighted HIL-Test Scenario)

On the top level model, the propulsion control system model is interfaced with the propulsion plant performance model. External interfaces are managed by a separate software unit which is being referred to as the respective Base CSCI. All interfaces are designed in such a way that the overall propulsion system model can be executed in different usage scenarios. This capability is achieved by introducing so called <<scenario selection>> blocks between the software modules, which act as (de-)multiplexers on the signal bus level and are controlled by the user-selectable scenario. The flexibility, to quickly change configurations also extends to the automatically generated code for deployment on the hardware, where only blocks and signal paths needed for the given scenario are included in the final code.

Each of those scenarios is serving a crucial purpose throughout the propulsion system design life cycle:

- Propulsion plant performance analysis: stand-alone execution of the propulsion plant performance model

- Integrated application development: MIL simulation
- Propulsion control parameter tuning and testing: MIL simulation
- Integrated application development testing including simulated hardware interfaces: SIL testing
- Integrated propulsion system testing on controller hardware with hardware simulator → HIL testing
- Propulsion control software deployment on target hardware & operation in real environment → DEP (Deployment System) scenario
- Propulsion system training for operators (MIL + Training Environment)

The overall design of the RPC was kept modular so that modern control strategies for future smart and autonomous ships and concludes that a combination of torque, angle of attack, and Model Predictive Control (Geertsma, et al., 2017) could be easily integrated in the design. The very expansive model based test procedure developed for the RPC promises to provide significant advantages to the shipbuilder in term of design de-risk as well as reduction of commissioning lead time, HAT and SAT, which translates to direct cost savings.

3.5. 'Virtual Propulsion System Simulator': Model-based training

Utilizing the development of the very comprehensive performance model based digital twin for the propulsion and power system, the current activities at RENK are focussed on the development on the 'Virtual Ship System Simulator' (VPSS), a model-based training solution based on Immersive Technologies. Immersive Technologies based training systems provide multiple benefits over the traditional training methods: increased engagement of trainees, increased accessibility to training, bridging of geographic distances by enabling trainers and trainees to collaborate remotely in virtual environments, no risk to the trainees or equipment, reduced cost for organizations as the system implementation does not require specialized training facilities, high scalability etc. The technology also enables data tracking and analytics by collecting data around metrics, including behavioural data, gestures representing tasks, interactions, and voice recognition. Recognizing these advantages of Immersive Technologies, RENK has already created a product line of VR, AR based maintenance training systems. The development of the VPSS aims at combining the domain knowledge of P&PS, with its knowledge of Immersive Technologies. The VPSS is envisaged to specifically provide advantages over the conventional land based training simulators as: combining operation and maintenance training scenarios, operating scenarios with normal and degraded modes of operation, complex scenarios cleated on the fly by the instructors.

The overall design objective of the VPSS is to provide an integrated operation and maintenance training system based on a high fidelity virtual environment of the bridge, machinery control room and engine rooms eliminating the need for physical mock-up for these compartments. The virtual environments for various control rooms would just include the compartment characteristics but also include the HMI screens, instruments, and levers etc. that the trainee would interact with for the operational training. The parameters for the screens, instruments would be driven by the performance digital twin of the propulsion system. The integrated operation and maintenance training here refers to realistic training scenarios where a maintenance task would undertaken by a trainee that would influence parameter/s in the performance model. The normal modes of operation would be represented by operation of the propulsion system from the bridge or in telegraph mode with operations split between the bridge and machinery control room. The degraded modes would include control of the propulsion plant from the individual controllers of the equipment located in the engine rooms in emergency conditions, without the availability of the central propulsion control system. The instructor could also control the parameters like ambient conditions and sea state that influence the behaviour of propulsion system and the ship. Simulation of these scenarios would be driven by the dynamic performance models of the propulsion system, would provide a very realistic look and feel to the operator.

At the implementation level, the design of the VPSS would utilize the CAD-data, MetaData to create functional VR-Models representing the physical appearance of the control rooms, engine rooms, equipment, equipment control panels etc. and interfacing these models to the propulsion performance model and the propulsion control system running in a MIL configuration. The VR based control rooms would be based on the extensive experience already gained in the developed VR, AR based maintenance systems. The performance model is interfaced to the VPSS in catered to in the design of the system model, as shown by the VTS interface in Figure 7. Using this interface, the functional integration of the digital twin of the propulsion system to the VPSS is already catered for during a project design.

4. Coupling of physical testing requirements with integrated model based systems engineering approach

The model based approach can significantly de-risk the modern naval P&PS propulsion systems, to the extent that LBSE sites could be eliminated. The key enabler for this would be extensive simulation studies that cover extreme scenarios of slam manoeuvres, as well as transition between various modes of propulsion defined by different combination of driving engines, drives. However, a practical integrated test of the overall propulsion transmission system would still be very useful in de-risking the overall design. Such tests are undertaken at the RENK test stand, where the entire propulsion transmission (with the prime movers replaced by testing motors) various modes of propulsion are tested on full load or partial load, based on the test stand constraints, as well as test objectives. An example of CODELAG propulsion system being tested is shown in Figure 8, where the system integrated test was undertaken with electric drives, frequency converters, cooling cabinets, with the gas turbine being the only primary drive being substituted with an electric motor for the test. A constraint, so far faced in such testing is that only steady state drive modes can be tested and not the dynamic transition between various modes, primarily due to the non availability of the PCS during testing and the large effort that would be required to integrate the system for such a test. With the RPC development, this constraint could be effectively addressed. This MBSE based design process for the P&PS, with this supplier based transmission system testing has the potential for significantly reduces the cost of a shipbuilding project by eliminating the need for LBSE sites, whilst still providing a well de-risked design.

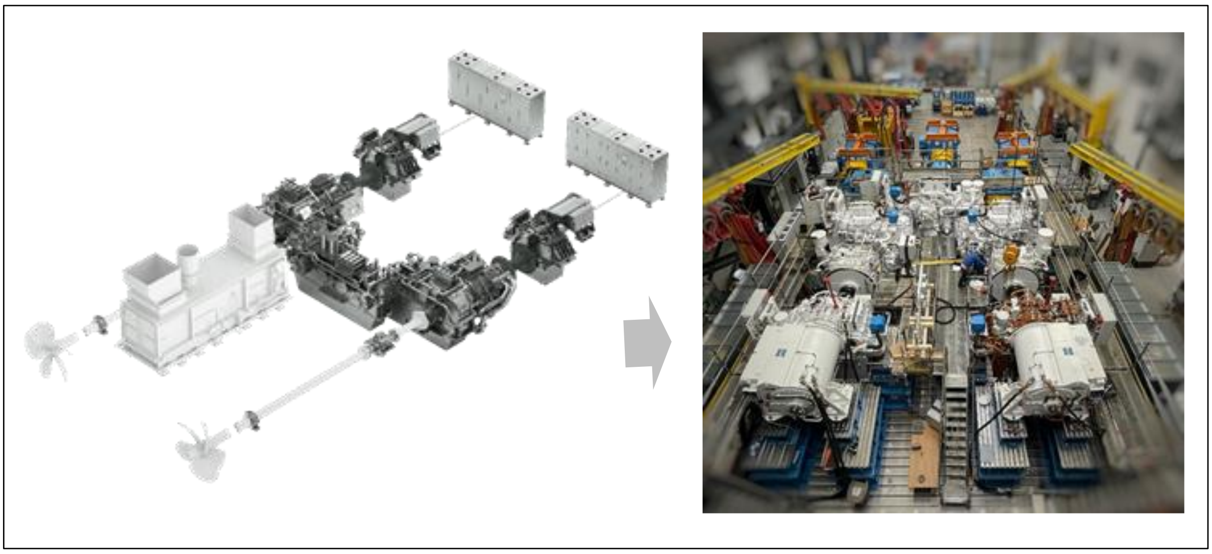


Figure 8: A CODELAG configuration integrated system test at the RENK test stand

5. Conclusion

With the increased complexity of the modern naval P&PS designs, operated and maintained by lean crews on-board, an MBSE approach is the need of the hour. An integrated MBSE process across the system boundaries across the areas of application such as primary system design, control system design, condition monitoring, training simulator etc., has the potential for better integrated systems solutions for the shipbuilders as well as the navies. Based on this approach it is proposed that a single supplier, designated as PROPSS, could be assigned the responsible for the design of all the sub systems related to the areas of design, operation and maintenance of P&PS, enabling the shipbuilder to concentrate its efforts on the higher level integration role. The paper briefly describes the MBSE approach instituted at RENK towards addressing the challenges in the areas of system design, operation and maintenance, training for the modern naval P&PS, with a back drop of multiple undertaken projects. This MBSE approach was extensively used for the development of the RPC, making it the template for the further MBSE engineering activities for integration of the various models across the product lines. The approach focuses on the development of models that evolve along with the development of the design of the system, initially used for development of the system design including the design of the control system, studying impact of design changes and then utilization as the ‘engines’ for the training system. The paper also describes the concept of the VPSS, a model-based training solution based on Immersive Technologies that could the basis of improved training solutions at lower costs. Finally, it is proposed that the overall described MBSE approach for the development of the modern naval P&PS could be combined with the integrated supplier based system testing to engineer a well de-risked design with significantly reduced cost of shipbuilding projects by eliminating the need for LBSE sites.

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Nomenclature

AR: Augmented reality
CCG: Cross Connect Gear
CODOG: Combination of Diesel engine Or Gas turbine
CODAG: Combination of Diesel engine And Gas turbine
CODAG-E: Combination of Diesel engine And Gas turbine with Electric motor

CODELOG: Combination of Diesel ELectric Or Gas turbine
CODELAG: Combination of Diesel ELectric And Gas turbine
CPP: Controllable Pitch Propeller
EM: Electric Motor
GB: Gearbox
GT: Gas Turbine
HAT: Harbour Acceptance Trial
IEP: Integrated Power System
IFEP: Integrated Full Electric Propulsion
ILS: Integrated Logistic Support
LBES: Land Based Engineering Site
UK: United Kingdom
USN: United States Navy
HMI: Human Machine Interface
HIL: Hardware In the Loop
DEP: Deployment
MBSE: Model Based System Engineering
MIL: Model In the Loop
MR: Mixed Reality
MRG: Main Reduction Gear
PCS: Propulsion Control Systems
P&PS: Propulsion and Power System
PROPSS: Propulsion and Power System Supplier
RN: UK Royal Navy
SAT: Sea Acceptance Trial
SE: Systems Engineering
SIL: Software In the Loop
USN: United States Navy
VFC: Variable Frequency Converter
VPSS: Virtual Ship System Simulator
VR: Virtual Reality
VTS: Various Training Systems
XR: Extended Reality