Lessons Learnt for Complex Power & Propulsion Systems Integration

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Synopsis

This paper critically examines the challenges, and exposes the lessons learnt, resulting from the integration of a propulsion system, an integrated platform management system, and a power generation plant for a modern stealthy corvette. The propulsion system consisted of a four-diesel engine plant, exhaust gas system, combining gearboxes and two controllable pitch propellers. The machinery met very demanding requirements for quality, acoustic noise and military shock standards. The paper describes how the system integration activities went about matching all propulsion, automation and power generation components to perform as one unit. This was not without challenges and the paper openly discusses some of the problems and lessons learnt in how to do this efficiently and effectively.

1. Introduction

MTU has built up a long tradition as a reliable supplier of complex marine power and propulsion systems including automation. To be a successful system integrator of power and propulsion systems requires the acquisition of extensive naval engineering domain knowledge which can only be developed through the successful delivery of programmes that have complex and competing naval requirements such as: shock compliance; ultra-low noise and vibration; critical electromagnetic compatibility between electronic equipment; special and extended documentation; integrated logistic support; obsolescence management; and providing long term support services. Our experience gained by delivering hundreds of naval projects has not only helped us acquire the right world-class naval engineering technical expertise but also to develop dedicated processes that help us manage the system integrator role, including project management, technical coordination, sub-suppliers qualification, software development and quality auditing. All this accumulated technical knowledge and well-developed processes were applied on a corvette project which we will describe next.

In 2012 our company was requested to quote for an integrated power and propulsion system for a series of corvettes. The scope of supply was gradually refined after technical and commercial discussions and our company was successfully selected as a system supplier of a complex system comprising: four main diesel engines; two propulsion gearboxes; two controllable pitch propellers with its corresponding shafting; four generator sets; an exhaust gas cooling system for each diesel engine; and an integrated platform management system (IPMS) providing functions for control and monitoring of the propulsion system; an electric power management system (EPMS) for generator set operation; ship systems operation and battle damage control.

MTU embraced a long list of responsibilities as the power and propulsion system integrator, including:

1. **Project and technically** manage the mechanical and electrical interfacing work between five major sub-suppliers to ensure the mechanical and electronic interfacing between the different equipment would result in the system acting as one unit across all the ship operating scenarios.

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2. "**One face to the customer**", meaning that all the communications between the shipyard and the rest of key power and propulsion system suppliers within the supplied scope, was done wholly through MTU, which simplified the shipyard coordination efforts.
3. **Single contractual partner**, providing many commercial advantages for the customer such as being responsible for coordinating and arranging payments, arranging deliveries of equipment, undertaking contract change management and for the processing of warranty claims.

The project was not without problems and these have provided valuable lessons learnt that have been used to improve our processes and increase our domain knowledge, but most importantly to develop the overall experience of the engineering project and teams. Therefore, in the next sections we will elaborate and share these learnt lessons.

2. SCOPE OF SUPPLY

The propulsion system selected was a highly integrated CODAD system (Combined Diesel and Diesel), with two independent starboard and port propulsion trains. Each propulsion train was designed to transmit the power from two main diesel engines to one controllable pitch propeller. The following is a detailed summary of equipment for the power and propulsion plant:

- **Four main diesel engines** type MTU 16V1163 including Local Operating Panel, liquid-cooling, four-stroke engines with: direct fuel injection; exhaust gas turbocharging; resilient mounting; engine driven pumps (sea water, coolant, lube oil and fuel); coupling; vibration damper; electronic engine governor; monitoring and control units; filtration elements.

- **Two CODAD gearboxes** with: all necessary pinions and gears; plain bearings; integrated thrust bearing; multi-disc clutches; lube oil cooling system; connections for hydraulic pumps; monitoring and control units; lube oil filters.

- **Two controllable pitch propellers** and their corresponding shafting system with all necessary accessories for the operation of the system, such as: radial bearings; stern tube bearings; strut bearings; bulkhead seals; stern tube seals; hydraulic power packs; oil distribution boxes; flanges for shafting connections; shaft earthing devices.

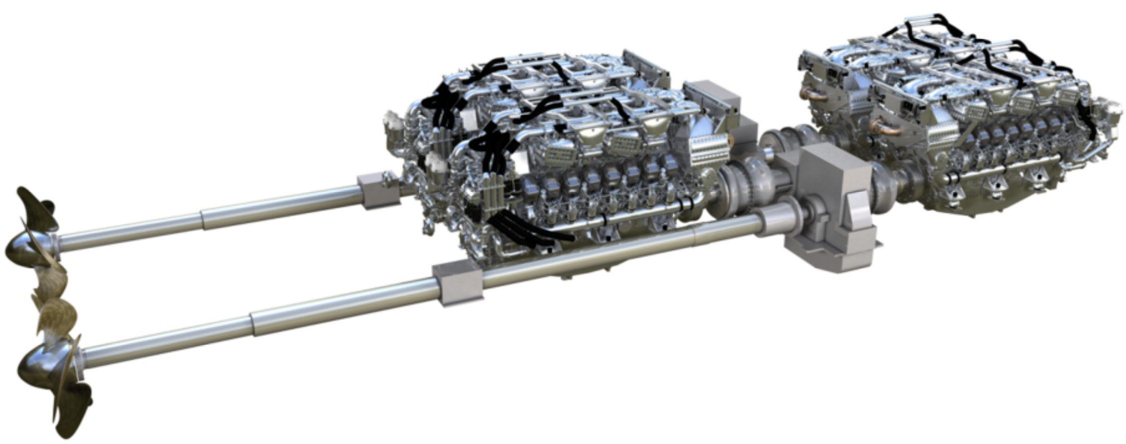

Figure 1: CODAD Propulsion System

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Propulsion Control System (PCS): Each propulsion line has its own RCS-CPP/CODAD Remote Control System (RCS-5). The Remote-Control System is used for automatic speed control of one or both engine lines (depending on the selected operating mode) and of the pitch setting of the Controllable Pitch Propeller.

- The power generation system comprised of four **MTU 8V396 auxiliary engines** including Local Operating Panel, with a marine rated alternator. Both the engine and the alternator are resilient mounted on a common base frame. The base frame is resiliently mounted on the machinery spaces. Therefore the generators sets are effectively double resilient mounted, providing excellent shock withstand and reducing the transmission of structure borne noise.

- The main and auxiliary diesel engines were fitted with an **exhaust gas cooling system** consisting of; Silencers for exhaust gas noise attenuation; Manifolds made of corrosion resistant material; Sea water injectors for the injection of sea water into the exhaust gas stream which cools exhaust temperature down for very effective Infra-red suppression; Sensors and actuators; monitoring and control equipment, sea water pumps and Exhaust flaps.

- **MTU Callosum Integrated Platform Management System** (IPMS) for monitoring, control and operation of the major ship systems, Propulsion, Electrical System, Ship operation and Battle Damage Control. All systems were inter-connected via a dual redundant high-speed fibre optic backbone bus. The key functionality of the IPMS are:

  - Monitoring and Control System for Propulsion plant MCS-5
  - Propulsion Remote control system RCS-CPP/CODAD
  - Engine Telegraph system MTS
  - Electrical Power management System EPMS
  - Uninterruptable Power Supply UPS
  - Duty Alarm systems DAS
  - Data interfaces to all major ship systems, handling in total 6.500 input and control signals
  - Main Control Room Console (shock qualified) with optimized arrangement of the installed equipment according to customer specific ergonomic guidelines, delivered completely wired, tested and prepared for plug-in installation into the ship
  - Damage Control Consoles (Bulkhead mounted style and shock qualified) for Forward and Aft Damage Control section fully equipped with electrical control and monitoring equipment and completely wired and tested

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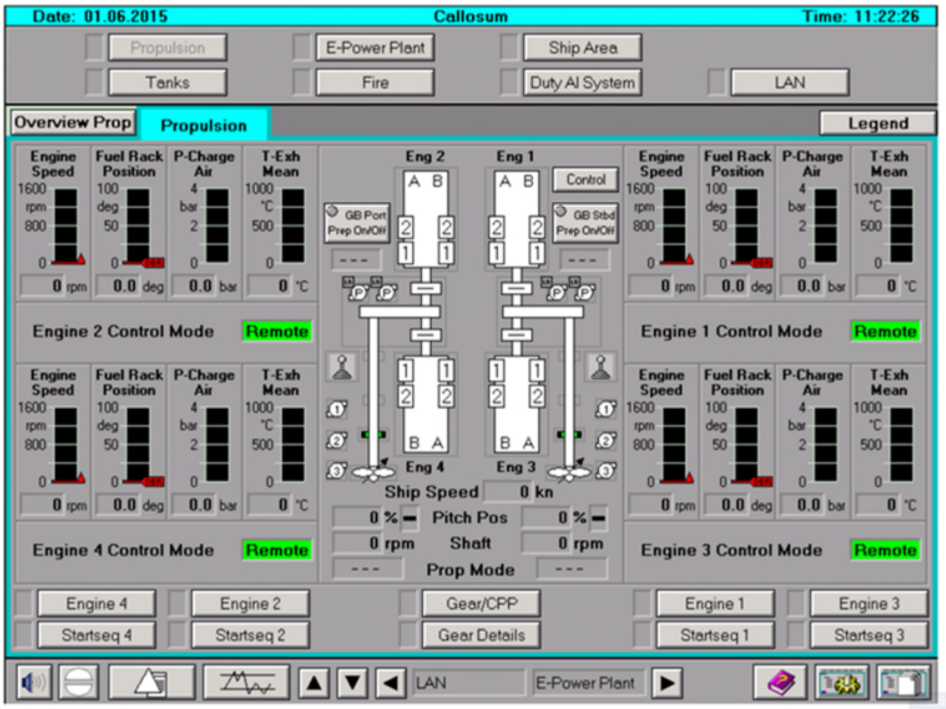

Figure 2: Automation System

3. PROPULSION AND GENERATOR SYSTEM INTEGRATION ACTIVITIES

From the moment that the scope of supply was defined and well before the contract was signed, the project team started working on the system integration. The programme was divide in following phases:

Conceptual design phase: This phase took place before the contract signing. At this stage MTU, CPP system supplier, gearbox supplier and exhaust system supplier worked with the shipyard customer to define the characteristics of the ship performance and each equipment. The technical scope of supply specifications was created, agreed and converted into part of the contractual documents. In this conceptual phase preliminary equipment drawings were drafted and made available to the customer, showing initial dimensions and indicating estimated weights, which enable the shipyard to start the location of primary equipment design of the mounting arrangements.

Preliminary design phase: After contract signing, the project team and its sub-suppliers initiated the design of the equipment. The key interfaces between the following major equipment was rapidly evolved:

- Connection between engine and gearbox input flange.
- Connection between gearbox and intermediate shaft of CPP.
- Connection between gearbox and CPP oil distribution box (OD-Box).
- Connection between engine and exhaust gas system
- Dimensions of power cabling of generator sets.
- Propulsion Engine mounting.
- Generator set mounting.
- Number and distribution of CPP shafting radial bearings

As the design of the major hardware matured, data became available for doing the primary system integration calculations. These are required to certify that the equipment would perform as expected in operation. The calculations that were undertaken by the company and its sub-suppliers included:

- Towing tank and propeller test.
- Torsional vibration calculation.
- Mounting calculation of resilient mounted equipment (shock analysis).

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- Lateral vibration calculation of gearbox input pinion shaft.
- Vessel crash stop simulation.
- Engine clutch-in performance simulation.
- CPP Natural whirling calculations (lateral vibration).
- CPP Natural axial vibration calculations (longitudinal).
- Generator set response in sudden load changes (to confirm the quality power supply).
- Shaft alignment calculations.
- Exhaust back pressure analysis.

Detailed design phase: Once the calculations and studies done in the preliminary phase demonstrated that the design of the equipment was satisfactory, all the equipment sub-suppliers started making their detailed designs and preparing the final working drawings for the shipyard.

Manufacturing and delivery phase: The system was now manufactured and was subject to the approval of the classification society. Acceptance tests took place with the participation of customer, end customer and class surveyors. After successful acceptance, the equipment was dispatched and transported to the shipyard.

Installation and acceptance phase: After arrival of the goods at the shipyard, they were inspected before installation into the vessel. After partial installation of several systems, technicians from our company and our sub-suppliers assisted the shipyard to check the installation. The project team coordinated the participation of technicians from sub-suppliers directly at the shipyard. After completing installation of the systems and after performing all the commissioning activities, the system was started and proved in the harbour acceptance test before the final sea trials.

Warranty phase: During the warranty period and beyond, MTU acted as claims manager, collecting the arising warranty claims for engine, generator sets, gearboxes and CPP system.

4. AUTOMATION INTEGRATION ACTIVITIES

As soon as the shipyard requirements and scope of supply for the IPMS was known, the project team started working on the system integration to check that the IPMS would fulfil the technical requirements. The design activities followed an identical design phase approach as the power and propulsion system:

Conceptual design phase: This phase took place before contract signing. The project team, with the customer and its sub-suppliers developed the project specific requirements, taking into account the complexity and functional integration of each individual systems developing the primary interfaces in order to prepare a preliminary IPMS system architecture. This formed part of the contract documentation.

During the **preliminary design phase** the shipyard had to define the major third party equipment to be considered for integration into the MCR consoles. This is a critical activity that has a major impact on the final design (dimension, power consumption, heat emission/cooling) of the consoles which was why it was needed to be defined at this early design stage.

Design phase: After contract signing, the project team and the sub-suppliers commenced the final design of the system by creating an complete plant wiring diagram to show the equipment cabling requirements. Interface details including signal list for all systems, including:

- (Redundant) Power supply 24DC Main Power distribution and AC Distribution.
- Electrical and control interfaces to Propulsion plant engine and gearbox.
- Electrical and control interfaces to shaft line and CPP propeller.
- Electrical and control interfaces to generator set engine and generator.
- Electrical and control interfaces to exhaust gas system.
- Electrical and control interfaces to ship side monitoring and control systems.

Other crucial activities included:

- Preparing the project specific mimic pages for the IPMS screens that had to meet the ship's operating philosophies

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- Creation of measuring point list for the I/O-signals
- Definition of the software functions to be implemented into IPMS for the individual systems
- Definition of all data interfaces to the IPMS subsystems

Production phase: After the design phase was finished, the mechanical design of the consoles was frozen. Subsequent modifications after freeze would now affect the delivery date with associated commercial impacts. The detailed drawings (i.e. Installation drawings, wiring diagrams, etc.) were prepared for the customer as final working documents. The functionality of the automation system software was be defined together with the shipyard and system sub-suppliers. Creation of detailed wiring diagrams and contract specific software including the HMI screens.

Installation and acceptance phase: After arrival of the goods at the shipyard they were inspected before being installed into the ship. Testing of the software was done by the shipyard technicians together with assistance from MTU automation commissioning engineers. The functionality of the systems were tested and demonstrated in the harbour acceptance test and sea trials before being accepted.

5. CHALLENGES RESULTING FROM MECHANICAL INTEGRATION

No naval platform goes through its design phases without emergent problems and challenges that have to be overcome. The successful integrating of a complex system depends on the performance of third-party sub-suppliers. So, along the development phases of the project the team faced the following experiences and challenges:

Engineering challenges: Even considering that the propulsion system itself was very complex, from an engineering design perspective, the development of the system was relatively smooth. MTU was delivering engines and generator sets that had been supplied many times before to other naval platforms so these had been well-proven in the field. The propulsion engines were standard products that only required a coupling to be designed. The generators sets were also based on an existing design that were adapted to meet the project related requirements.

The selected gearbox and CPP system supplier for this project, had a long experience providing equipment for complex naval projects, and provided excellent assistance to the project.

The exhaust gas system with its sea water injection sub-system became the most critical part of the project. The exhaust gas system had a high number of interfaces with the engines and with the ship which demanded a much higher integration effort from the shipyard than originally expected.

Communication challenges: The communication between our customer, ourselves and our sub-suppliers, with factories in different countries and time zones, all using different main languages, was often problematic and misunderstandings were commonplace. A major factor why projects can fail is through poor communications, so as the project went along we had to apply additional efforts to improve communication and transparency to ensure the project stayed on track.

Scheduling challenges: One of the most complex problems that the project team faced at the beginning of the project was the scheduling of delivery of drawings and documentation. At the beginning of the project, the company was put under tremendous pressure to supply equipment drawings, so that the shipyard could commence the detailed ship design. At the beginning of the design phase, some suppliers needed information from other suppliers to start designing the system. Nevertheless, some of the required data was just not available. So, the backlog of drawings that were not available at the right time grew larger. Inevitably this caused some suppliers to start to threaten delays to the delivery of their equipment as the design work could not start as was originally scheduled.

Quality challenges: Considering the complexity of the design of equipment, only minor quality issues occurred. Some of them required discussions with the classification society and customer, to get concessions in order to be overcome.

Commercial challenges: From the commercial point of view, it was difficult to coordinate all the payments that were necessary for each delivery of equipment. For each shipset there were six major deliveries (main engines,

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gearboxes, CPP, gensets, automation and documentation) and a total of three shipsets, which equated to 18 individual deliveries. Many of the deliveries needed to be linked to a bank guarantee. We supplied the items in accordance with INCOTERM CIF of an Asian harbour, so we had to coordinate the international transport and insurance to an Asian country. On top of that was the need to obtain the correct export control licenses. Logistically and administratively prepare and issuing the invoicing of 18 separate deliveries, obtaining export control licenses and the corresponding bank guarantees, with all shipping documentation turned out to be a major effort.

Visa challenges: In some cases, the testing of the engines was postponed at short notice due to the availability of the test benches at our factory in Germany. The visas expended to Asian customers and End User representatives for the participation on the corresponding factory acceptance tests, did not give the possibility to extend or adjust the stay period in Germany of this persons. So, this added a new dimension to coordinating the participation of the shipyard customer and end navy customer at the factory acceptance tests.

6. CHALLENGES RESULTING FROM AUTOMATION INTEGRATION

The success of integrating a sophisticated IPMS depends receiving interface definitions and sub-system data on time. This is a huge coordinating task between many different suppliers in the ship, some under our control and others under the direct control of the shipyard or even the end user. Hence, along the development phases of the project, the team faced the following challenges:

Engineering challenges: MTU was delivering the monitoring and control system for propulsion plant, generators and ship side systems. Even though the **propulsion plant system** itself was complex from an IPMS design perspective the development throughout the project was relatively smooth despite the fact that the combination of OEMs that made up the propulsion plant equipment with engine, gearbox, shaft line, CPP propeller and exhaust gas system was completely new for automation system so, apart from the engines, the interfaces were unproven.

The main gearboxes were equipped with their own monitoring and control unit which had a serial and hardwired interface to the automation system. The implementation of the interface was relatively straightforward with good assistance from the supplier..

It was a similar story for the CPP system which had an hardwired interface to the IPMS and the implementation was made without problem with good assistance from supplier.

The exhaust gas system with sea water injection was the most critical part of the project and had an electrical hardwired interface. As discussed previously the exhaust gas system had a high number of interfaces with the engines and the ship which demanded a higher integration effort from the shipyard than anticipated. Fortunately a good working relationship between our company, supplier and the shipyard overcame the challenges and enabled the interfaces to be properly defined.

The **Propulsion Control System for a CODAD** configuration had been proven many times in the in-house RCS system. Nevertheless, each vessel needed specific adjustments, which resulted in quite a few rounds of clarifications with the OEMs and the shipyard customer.

The **genset plant** with the electrical power management system EPMS was a standard application and the interfacing to the generator and engine was straightforward. The specification of the electrical power management system EPMS was developed with good assistance from system sub-supplier and the shipyard customer.

The **ship area systems** with their many hardwired I/O signals and serial data interfaces was a big challenge. These required detailed attention and frequent discussions with the shipyard customer and their sub-suppliers to get all the required information for I/O list, alarm lists, HMI screens and software development. Because the ship systems were defined very late in the ship building process, the time to react and update the software accordingly became a big headache for the IPMS team!

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7. EXPERIENCES AND LESSONS LEARNT

So, drawing upon the challenges described in sections VII and VIII, the project team can share with you what we learnt during the development of the project:

1. **Supplier Selection**: The company had a large and complex scope of supply and we could only successfully develop the corvette power and propulsion system because the main suppliers selected were highly professional and world-leaders in their respective fields. MTU could rely on these suppliers to deliver high quality products and work collaboratively with us. However, this still required good supply chain management
    - Each sub-supplier needed to be qualified and subject to appropriate quality audits.
    - The work of each sub-supplier still needed to be checked, in order to prevent quality escapes and inconsistencies in the project documentation.
    - Supplier selection based on lowest price alone without considering product quality would have had bad consequences for the project.
    - As the power and propulsion system integrator we had to take accountability for the consequences of any arising quality problems caused by our suppliers and work closely with them to find a solution.

2. **Project Management and Personnel**: Having an MTU project manager dedicated completely dedication to the corvette project from the concept stage to post warranty stage ensured that the project was a success. This consistency in key people working on the project also contributed to its success.

3. **Contract Documentation**: Before the contract signing, the development of high quality technical and commercial specifications ensured that each party knew exactly that they were being contracted to deliver and when. This really did help with the smooth running of deliveries and ensured that there were very few gaps in the scope and the design activities. This was especially relevant in the definition of the role of IPMS supplier with its extensive reliance on the shipyard to provide timely data.

4. **Risk Management**: The project team did a thorough programme and technical risk analysis at the beginning of the project to identify which aspects of the system integration and deliveries would be critical and to define mitigation strategies for each risks. This was a continuously updated process to manage the unexpected problems that occurred.

5. **Commissioning**: Our company installed a full time coordinator at the shipyard to coordinate our own and sub-supplier field service support for the commissioning, harbour and sea acceptance tests. This significantly helped to improve communication with the shipyard customer and all the involved parties as well as achieving an efficient utilisation of service technicians during this critical stage of the project.

6. **Communications**: Line of communication were clearly defined in the contract and respected, but due to the complexity of the IPMS, many technical interface meetings with each of the shipyard's sub-suppliers had to be coordinated by shipyard. Depending on the complexity of interfaced systems, we found it more efficient to have direct contact with the shipyard sub-suppliers to solve open issues even though the commercial contract was between the shipyard and the sub-supplier. Trust and openness helped make this a collaborative and efficient means of progressing the IPMS design.

7. **System Testing**: Especially for the serial data interfaces, system integration tests with the system sub-suppliers proved immensely helpful by checking the software well before shipboard commissioning. This saved a lot of time during the commissioning phase by solving interface problems and miscommunications in advance. However, this had to be accounted for in the project costs as additional travel and test equipment is needed to facilitate system testing at suppliers' factories.

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8. CONCLUSION

The project was complex but successful. However, it was a powerful demonstration that power and propulsion system integration is not a trivial undertaking and requires careful considerations before contracting to take on the risks. From a business perspective it is a high reward with high risk business activity. It was enabled through the accumulation of specialist technical, programme management and logistics skills along with having experienced people, effective communications and choosing reliable and experienced sub-suppliers.

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