The Autonomous Machinery Design of Tx Ship

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SYNOPSIS

Today's naval platform procurement processes are dominated by both fiscal and manning pressures that result in lean and ultra-lean-manned technologies being integrated into vessel design. Concurrently there has been huge advances over the last 5 years in 'systems automation' and platform autonomy. The vessels that make up tomorrow's navies will be a force mix of manned, un-manned, or 'optionally-manned' platforms.

The Transition Ship (Tx Ship) is a Thales concept for the future development of naval warfare: an optionally manned trimaran that introduces the option of unmanned warships whilst retaining the alternative of keeping the man onboard during early maturation of its systems. The design showcases the benefits of optionally manned assets and offers commanders a flexible platform for anti-submarine warfare, mine countermeasures or intelligence gathering missions, with its technologies also helping reduce manning on conventional ships through state-of-the-art sensors and effectors.

Critical to realising optionally manned vessel operation is fully autonomous management and control of the ship's mission systems and machinery systems. A manned Engineering Department traditionally keeps the vital systems on board available enabling Command to fight the ship, these include monitoring the performance of machinery system for extended periods, routine equipment maintenance and battle damage control. On Unmanned Surface Vessels, these functions are still very relevant but now need to be undertaken without humans onboard.

This joint paper by Tx Ship consortium members Thales, Steller Systems and Rolls-Royce, discusses the design practices surrounding power and propulsion system and auxiliary systems design considering the lean manned and unmanned missions. Central to this is the selection and optimisation of these systems with respect to availability, rather than more traditional metrics in order to enable the unmanned mission. These systems are fully integrated with the autonomous machinery controller which operates the marine systems in support of the vessel's mission, calculates the vessel capabilities and impact of health events to assist with mission planning. The control, maintenance, and battle damage concepts designed for Tx Ship's Marine Engineering systems address the unique challenges of supporting unmanned vessels and contribute to the vessel's unique autonomous mission capability; these challenges will be outlined in this paper.

Keywords: Autonomy, Autonomous Shipping, Unmanned, Optionally-Manned, Tx Ship

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1. Introduction - The Tx Ship Concept

The Tx Ship is a modular multi-role trimaran concept capable of performing a wide range of tasking, whilst allowing the navy to transition from a lean manned to an unmanned autonomous vessel. The concept is an exciting opportunity to understand the potential value of autonomy as it is phased into our traditional manned fleet, in tackling the challenges facing navies today. For autonomous vessels to be effective the platforms themselves need to understand and self-manage their own performance and limitations. Should failure, damage, or the need to conduct critical maintenance occur, the platforms must adapt their subsystems and components' functionality to enable continued capability and safe return to port without human intervention.

In the immediate future, operators will begin to learn how the manned/unmanned team would augment into the existing fleet in an optimised manner. To develop operator trust, people will need to be 'in/on the loop', protecting assets from non-desired outcomes and 3rd party threats, leading to an initial need for a manned capability. However, as this trust is developed, and the various AI algorithms that govern the autonomous decision-making process are validated and proven, fewer people will be required to supervise the platform.

To enable this, Tx Ship approaches ship design from a different perspective, one which departs from more typical design processes. Typical design cycles focus on maximising cost effectiveness, whereas Tx Ship concentrates on optimising availability and minimising the effect of failures. The concept and the systems within it must have a dynamic understanding of its own health and performance capability. Ultimately, the ship must be self-sustaining, ensuring that the platform does not fail in critical scenarios and the various systems onboard know how long they are able to perform.

The Tx Ship proof of concept has been designed in preparation for the future and forward-looking operators. It is designed as an unmanned platform that can accommodate people onboard as6 required; addressing the future autonomous platform capability as a means to enable the design of a platform to transition into an autonomous platform through its design life.

The purpose of this paper is to explore the design practices surrounding the power and propulsion system and auxiliary systems design onboard the Tx Ship, considering; lean or unmanned missions, the selection and optimisation of these systems with respect to availability, and the importance and effect of the Concept of Operation on this selection.

2. Typical Autonomous Ship Control Layers

Today's autonomous vessels such as US Navy's Sea Hunter, feature a relatively simple power and propulsion system. This will typically consist of a simple diesel-powered propulsion train alongside a modest electrical power generation and distribution system. The control of these systems is relatively simplistic; with most of the vessel's autonomous capability residing within its autonomous navigation system. These systems are vitally important and, via COLREG compliance, form a vital part of the vessel's ability to manoeuvre and operate autonomously in a congested seaway.

In the context of an autonomous naval vessel such as Tx ship, this autonomous navigation system exists alongside the autonomous mission management system. This layer of control, shown in Figure 1, provides mission planning, monitoring and re-tasking capabilities to the unmanned vessel. The mission management system is used to process the mission, understand the constraints and objectives of the task, and control the vessel in order to achieve it's mission; managing sensor fusion and fighting the external battle of the vessel.

Controlling the individual equipment items and sub-systems is the Automation system. Over the last 40 years, Navies have used increasing levels of Automation to allow operators to oversee and supervise the control of many of the platform systems, using an Integrated Platform Management System (IPMS) or equivalent. Control, monitoring, or starting and stopping of equipment as an example, are governed by this Automation system. However, the automation system is a facilitator and does not make autonomous decisions or act according to the goals of mission but typically enacts the decisions of a human operator. As such, there is a requirement for a supervisory control and autonomy layer to manage and configure the entire engineering plant. This autonomous machinery controller sits

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between the Mission Management System, and the automation system layers and replicates the Marine Engineering branch on board a traditional manned warship.

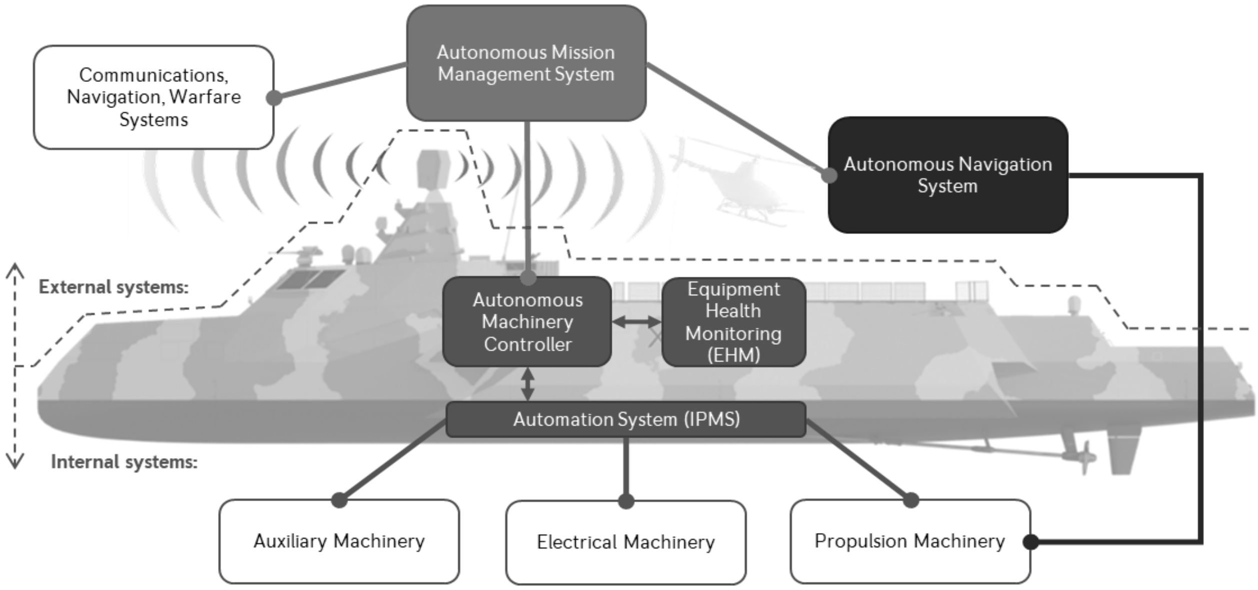

Figure 1 – The various autonomy and control layers for the Tx Ship

Due to the speed, range and multi-role requirements of the vessel, a sophisticated Power & Propulsion system was required on Tx Ship. As such, various decisions regarding plant configuration need to be made to match the relatively complex system capabilities, to command posture, as decided by the autonomous mission management system. In this way, the autonomous machinery controller will need to communicate with the autonomous mission management system to make decisions based on threat state, battle damage, or efficiency. The autonomous machinery controller will then need to consider these drivers alongside systems or equipment health and levels of consumables available on board before planning on how the machinery needs to be reconfigured, then ordering the changes to the machinery, via automation, as necessary.

However, the autonomous machinery controller is one element of enabling the autonomous unmanned mission and will need to be complemented by a new design philosophy, which prioritises availability of the systems it controls. This novel approach to system design has been trialled on the Tx Ship case study.

3. Approach to Propulsion System Design

The Power and Propulsion System, and its auxiliaries, are the most vital systems onboard in ensuring the completion of autonomous missions that may extend to 90 days [2]. As such, a different type of design approach is needed to converge on the optimal design of machinery systems alongside appropriate maintenance and operating philosophies to provide sufficient availability of power and propulsion to reliably perform independent missions of up to 90 days at sea.

Missions of this length are challenging because they typically exceed the intervals of maintenance tasks for the variety of rotating machinery on board, such as daily condition inspections and oil particle checks, whilst the wider supporting systems must be sympathetic to ongoing redistribution of fuels or consumables to maintain vessel stability. Finally, the power and propulsion systems onboard must accommodate equipment which will degrade and fail during the mission. According to Kooij[3] there are several strategies in tackling the issues identified in ensuring that these vital systems are designed appropriate for the unmanned mission.

1) Improving existing component/equipment technologies such as <u>extending</u> a diesel engines MTBF
2) <u>Removing</u> reciprocating machinery and creating a propulsion system based on systems less mechanically complex than a typical diesel engine

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3) Reduce the effect and/or manage the impact of an engineering casualty by increasing the redundancy of the propulsion plant.

The Tx Ship Power and Propulsion system design adopts this final strategy in that it aims at minimising the effect of an engineering casualty on the overall system. However, whilst redundancy alone will enable autonomous power and propulsion system functionality, solely building in large degrees of redundancy in small sea frames results in a platform that is not optimised for carrying the array of sensors and mission systems that make the autonomous ship desirable. As such, optimising the power and propulsion system with respect to availability, analysing the failure modes of key equipment items, and subsequently minimising the reduction in capability that equipment failure may bring is a more prudent strategy to excessive levels of redundancy alone.

To do this effectively in a naval platform, the design process will also need to consider traditional military drivers such as minimising Underwater Radiated Noise (URN), dealing with the threat of underwater shock events, platform range and speed, as well as statutory regulations relating to emissions etc. The resulting system would also need to be feasible, from a physical and functional integration perspective, into a narrow, 90m trimaran hull form. Subsequently, the system design process for the Tx Ship Power and Propulsion system departed from typical down selection techniques.

3.1. Fault Tree Analysis

Considering the overarching requirement of system availability, the system was designed with input resulting from an availability modelling tool, based on Fault Tree Analysis. Firstly, failure cases were derived which would result in Tx Ship not being able to fully complete its mission. The fault tree was then populated with a variety of differing system topologies with a typical example illustrated in Figure 2. Fault Tree analysis (FTA) was selected as it is useful in determining and identifying the conditions and factors that could potentially cause the system to fail. As such, FTA can be used to; understand the logic leading to the failure event, demonstrate compliance to reliability requirements and, importantly, drive improvements into the various system of systems to optimise for availability.

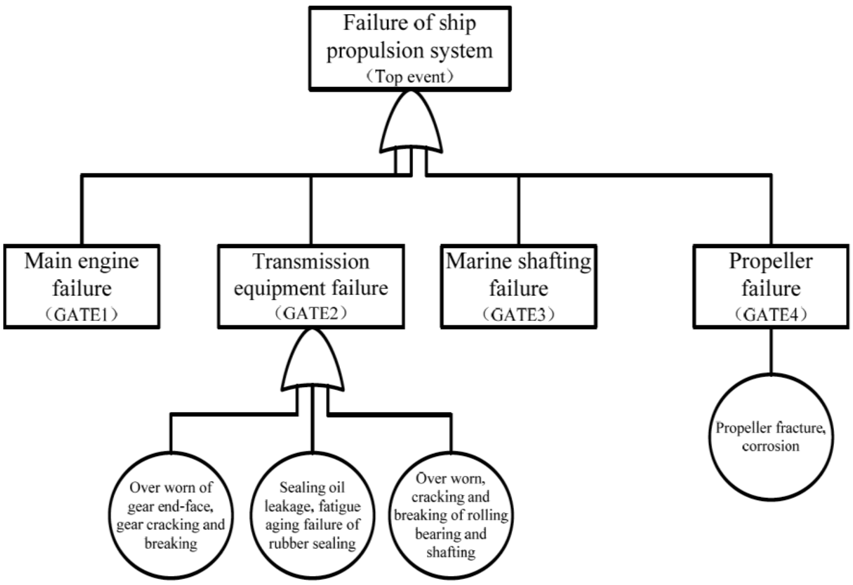

Figure 2 - A typical marine propulsion system fault tree [4]

In order to understand the top-level failure event, a variety of scenarios were analysed which would result in Tx Ship failing to fulfil its mission. These relate to two key events;

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3.1.1 Electrical Power Generation or Distribution Failure

Security of supply for electrical systems and prevention of Total Electrical Failures (TLF) are key risks that impact increasingly electrified naval vessels and one that requires careful consideration with respect to electrical system design and layout[5].

Subsequently, maintaining electrical supplies, at least to vital consumers such as navigation and autonomy systems, firefighting and propulsion is imperative if Tx Ship is to maintain any of the float, fight and move functions required for it to fulfil its mission. As such, electrical systems availability, including the number and location of the Main Switchboard(s), the resilience or redundancy of supply feeders and the supply to consumers must be adequately considered in order to minimise the probability of this event.

3.1.2 Loss of Propulsive Power

In order to maintain the move function on board a vessel, the main propulsion system; that is the main shafting, and propeller should be capable of delivering power. This can be delivered via electrical machines, or mechanical prime movers – or a combination. As such, it is vital to consider the optimal blend and rating of these prime movers, generators, or electrical machines, in order to ensure that availability is maximised.

3.2. Systems Availability

Availability is a function of the number of hours that a system can be expected to be operational for compared to the time it is unavailable for, termed, ‘down-time’. The various relationships between availability (A), reliability (λ), Mean Time Between Failure (MTBF), and Mean Time To Repair (MTTR) are;

$$MTBF\ [h] = \frac{Operating\ Hours\ [h]}{Occurences} \qquad \text{[Equation 1]}$$

$$A = \frac{MTBF}{MTBF+MTTR} \qquad \text{[Equation 2]}$$

$$\lambda = \frac{1}{MTBF} \qquad \text{[Equation 3]}$$

Crucial in achieving a design optimised for availability is convergence on what level of performance degradation corresponds to failure of the autonomous mission, and what is an acceptable likelihood of this series of failures occurring during the mission. In this way, it is important to understanding what the minimum threshold levels of performance are for the two key capabilities (as identified in 3.1.1 & 3.1.2); propulsive power and electrical generation and distribution capability. Anything below this minimum threshold capability would represent ‘failure’ and the mission would have to be abandoned.

In addition, a range of acceptable probabilities of the autonomous mission failing as a result of the vessel being unable to deliver these threshold performance values, is required to populate the top-level failure event. With this information, the requirements for the various MTBF rates of the subsequent equipment items can be derived via FTA that will result in a vessel being available to fulfil its mission.

For the Tx Ship case study, the maximum permissible failure requirements have been assumed to be a 5% probability that the vessel will not be able to deliver at least 12 knots via its main propulsion capability (a safe return to port thruster was provided). Additionally, a lower, 1% probability was seen as acceptable that the vessel is unable to generate or distribute electrical power to critical consumers (sized at 500kWe). As such, the following fault trees therefore need to be created for each P&P system architecture,

- Availability modelling against full operational capability of the plant for propulsion and power generation
- Availability modelling against the minimum acceptable, 12kt propulsive power requirement
- Availability modelling against a minimum acceptable, 500kWe electrical power requirement

By following the availability-centred design approach, two P&P system topologies were down selected from a range of mechanical, hybrid and Integrated Full Electric Propulsion (IFEP) power systems. These two candidate

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designs were then refined into concepts for Tx Ship – an optimised hybrid system and an IFEP power and propulsion system. These designs were sized to meet the Tx Ship's derived power requirements and then improved in parallel, using fault tree analysis.

3.2.1. Hybrid System Option

In order to derive a number of candidate hybrid propulsion options a number of key system design decisions were:

- Main diesel engines rating and type,
- Number and rating of diesel generators,
- Electrical Machine (PTI & PTO) rating,

MTU brand diesel engines and generators from Rolls-Royce Power Systems were used to provide indicative power ratings in addition to validated Mean Time Between Failure (MTBF) and Mean Time Between Overhaul (MTBO) figures. To assist with design of the power generation system, some basic sizing analysis was performed between Rolls-Royce and Steller Systems to determine what the optimum number and rating of the Diesel Generators and electrical machines were given the constraints of system availability alongside Naval Architecture considerations. This process investigated a range of electrical machine ratings in addition to two, three or four MTU Diesel Generator options with loading, redundancy and control aspects all investigated.

Next, each variant of the P&P system was modelled using FTA to determine at what point the overall system availability targets were achievable. This was an iterative approach, considering different combinations and arrangements of the system and investigating the sensitivity of the electrical distribution system in particular on overall system reliability. The final version of the hybrid concept, as shown in Figure 4, set realistic MTBF targets for each of the components and met the availability targets without consuming unnecessary volume. This was considered against a 40 day mission, rather than the original 90 day mission which was derived via a series of nominal CONOPS derived between Steller Systems and Thales. The resulting 40-day mission completion probabilities are shown below:

Probability of completing the mission with enough propulsive power to reach the vessels top speed:
P_{Prop}Max = 92.7% (Example illustrated in Figure 3)

Probability of completing the mission with enough propulsive power to reach the minimum threshold speed of 12kts: **P_{Prop}Min = 99.90%**

Probability of completing the mission with enough electrical power to reach the minimum power requirement of 500kWe: **P_{Elec}Min = 99.996%**

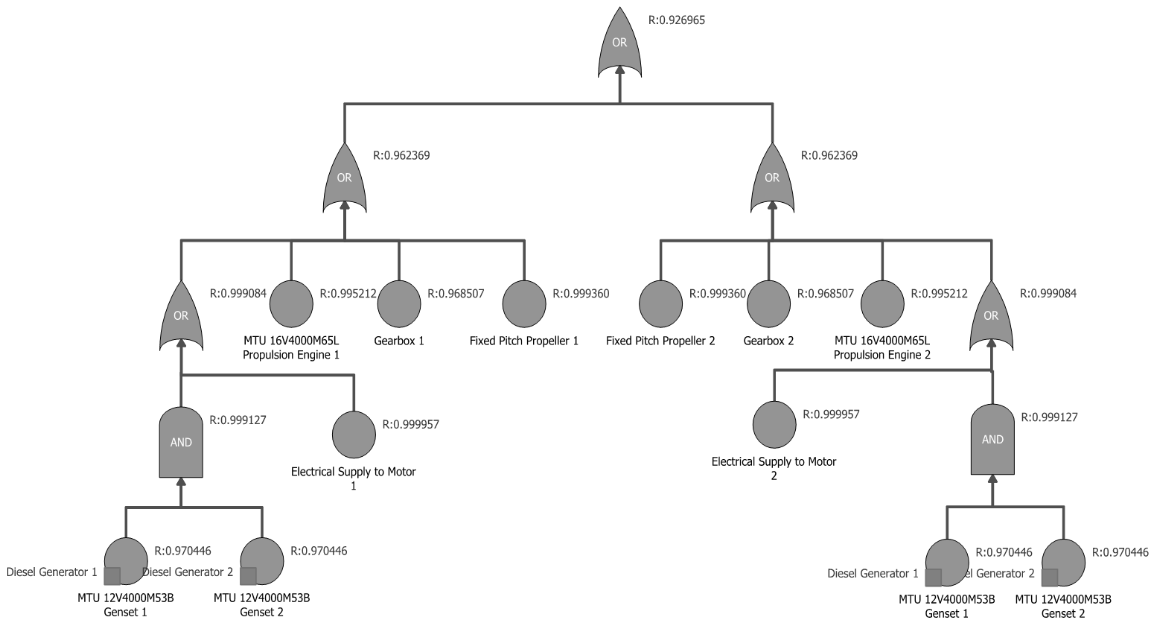

Figure 3: Example Fault Tree for Hybrid P&P System to achieve maximum propulsive power

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A noteworthy consideration of the Hybrid propulsion design is that, by providing a system with a sufficiently powerful PTI/PTO to convert power from/to electrical to/from propulsive power, the overall system availability is considerably improved. As such, the probabilities derived above exceed the anticipated mission requirements, assuming a given operational profile, electrical system design and maintenance requirements are met.

3.2.2. IFEP System Option

The IFEP version of the P&P system was developed with a similar method to the hybrid. The key system design decisions are:

- Number and rating of diesel generators,
- Number and rating of electric propulsion motors,
- Required electrical distribution topology.

The resulting sizing study between the design partners showed the validity of using two to five Diesel Generators in the system, in addition to the required ratings. The propulsion motor was sized directly as a result of the vessel's power speed characteristics and assumed a twin shaft line arrangement.

It was concluded that, due to the rating of high-speed diesel generators, and the resulting poor loading conditions, a two Diesel Generator solution was sub optimal. Systems that feature three and four Diesel Generators can only be met if relatively large (16+ cylinder) Diesel Generators are used whereas a five Diesel Generator solution is possible with smaller (12 Cylinder) units but would represent an integration challenge given the constraints of the 90m vessel. This therefore gave two different options to explore using FTA with the most appropriate balance between volume and availability being optimum for the Tx application.

The final version of the IFEP concept, used three large Diesel Generators, owing to their lower overall volume without compromising availability. This achieved the following 40-day mission completion probabilities:

Probability of completing the mission with enough propulsive power to reach the vessels top speed: **P_{Prop}Max = 90.8%**

Probability of completing the mission with enough propulsive power to reach the minimum threshold speed (12kts): **P_{Prop}Min = 99.997%**

Probability of completing the mission with enough electrical power to reach the minimum power requirement of 500kWe: **P_{Elec}Min = 99.993%**

This IFEP concept had a slightly lower chance of reaching the availability for top speed since it was highly dependent on the availability of all prime movers and the electrical distribution system reliability. However, since the power generation capability needed for the 12knot minimum threshold speed was comparatively low, there was a good degree of availability in the system for this requirement. These probabilities, again, surpassed the derived mission requirements.

4. Resultant Design Outcomes

After consideration of the physical and functional integration aspects of both down selected systems using both Rhino 2D and 3D CAD programmes, it was decided to integrate the Hybrid system into the Tx Ship hull-form. The resulting system was of CODLAD design and offers the autonomous machinery controller a flexible power and propulsion topology that demonstrably optimises availability as well as volumetric power density. The design is inherently simple and, given that the overriding objective of the Tx Ship programme is to de-risk autonomy the CODLAD system was also seen as a lower risk and an inherently reliable solution. Subsequently, focus can be placed on integrating simple, well proven equipment that can then be augmented with new, supplementary technologies such as Li-Ion batteries to support the wide range of missions envisaged.

Whilst the equipment selection and system topology were selected via the analysis shown above, it has been integrated into the ship design using more typical design methods, alongside traditional rule sets. The integrated solution features ample zonal separation with respect to its geographical layout within the hull form. In this way, a qualitative survivability assessment can be considered alongside quantitative methods of ensuring availability - the resulting system layout offering compliance to the PSML* notation within the Lloyds Register rule set. This offers continuation of propulsion and manoeuvring services after the loss of an entire compartment.

The resulting Tx Ship system derived in Section 3 is show in Figure 4 and features two main MTU 20V4000M93L Diesel Engines which provide power for ship speeds at 16 knots or above. These are augmented by two 740kW DRS Leonardo supplied, permanent magnet electrical machines which provide the low speed cruise plant. These are powered by two 1.64MWe MTU 12V4000M25S Diesel Generators, one of which is sited above the water line, and is configured to act as the emergency generator as well as providing reduced vessel underwater radiated noise (URN) during Anti-Submarine Warfare (ASW) operations.

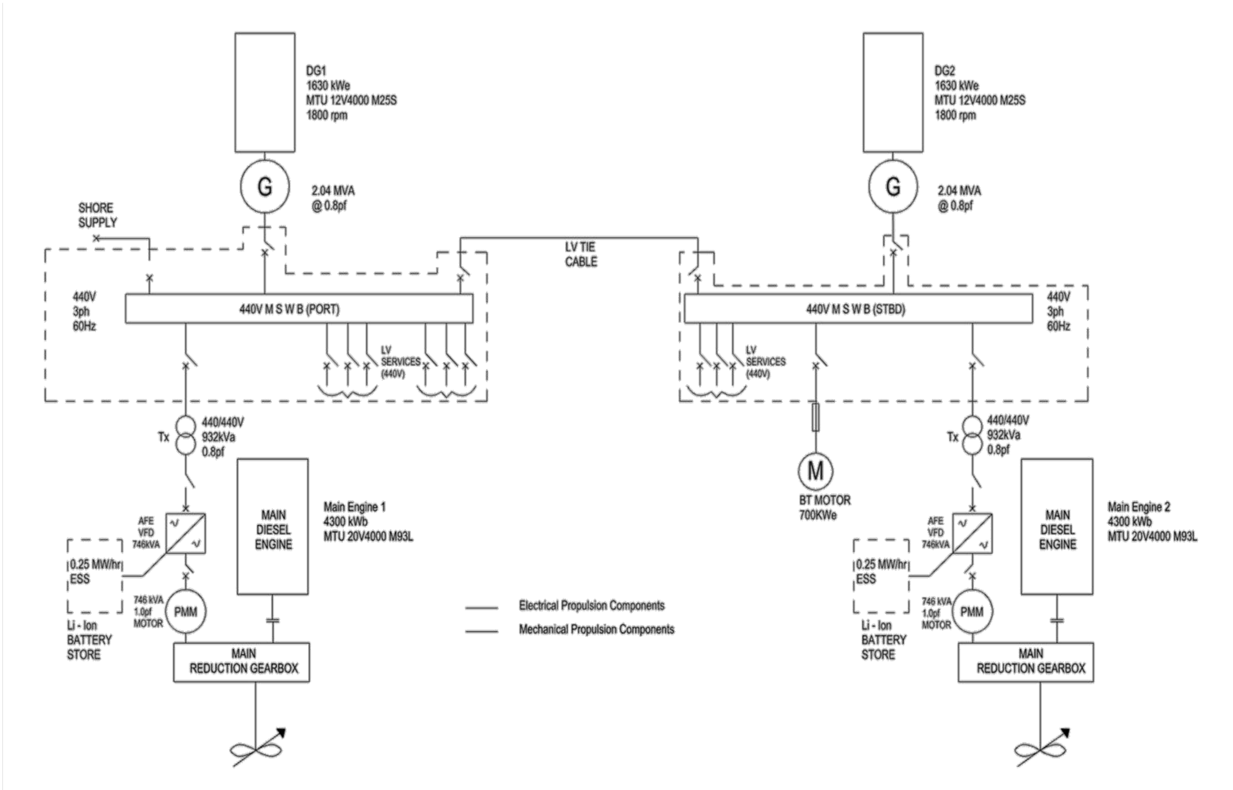

Figure 4 - 1 Schematic Diagram of the Hybrid Electric Propulsion System

The ability to run the electrical machines, via an active front end power converter in both Power Take In (PTI) and Power Take Out (PTO) enables all prime movers, regardless of whether these are diesel engines or generators, to generate both electrical power (via generators or gearbox mounted electrical machines) or mechanical shaft power (either via gearbox or gearbox mounted electrical machines). This offers the autonomous machinery controller the maximum amount of flexibility resulting in a system that can be tailored to a command posture commensurate with equipment health or unavailability, battle damage or efficiency.

The power converter also acts as the interface between a Li-Ion battery storage system (which did not form part of the overall availability assessment) and the vessel's 440V low voltage AC distribution system. Two 250kW/hr Commercial-Off-The-Shelf (COTS) energy stores are fitted to help smooth load variations, improve availability and act as a centralised Uninterrupted Power Supply (UPS) to allow system recovery in the event of critical generator failure or prevent blackout. The energy storage system can be charged while the vessel's electrical demand is low and discharged during high power peaks, optimising generator loading which improves efficiency but also reduces load fluctuations which could otherwise cause premature wear on the Diesel Generator systems.

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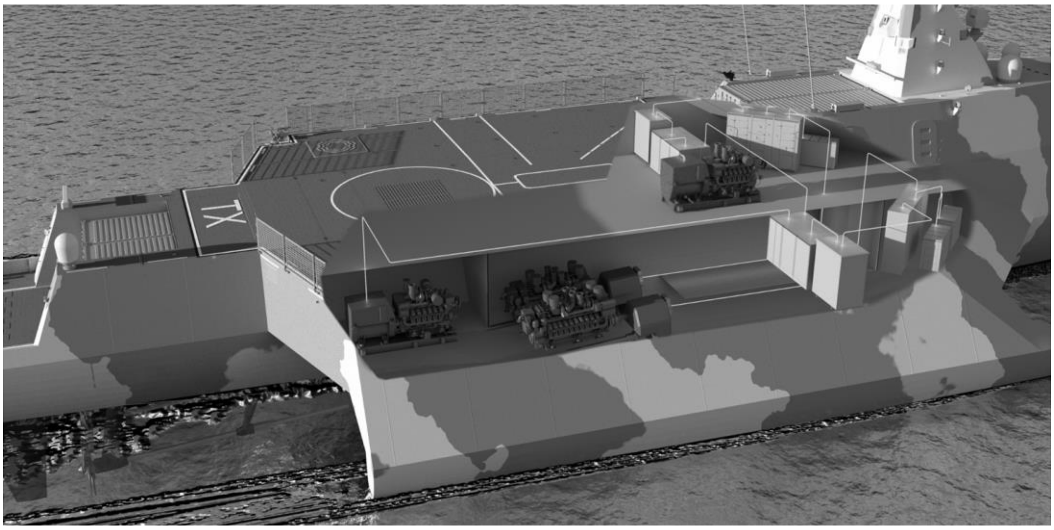

Figure 5 - Illustration of the CODLAD propulsion system within the Tx hull-form

5. Auxiliary Systems Design

An available propulsion system is only as reliable and robust as the dependent systems that provide vital services to it. As such, important consideration should be given to ensuring the system is adequately supported by a range of fully resilient and available ancillary systems. Derivation of these systems is a key dependency in enabling the integration of the autonomous machinery controller which controls all these systems within the Tx Ship hull form.

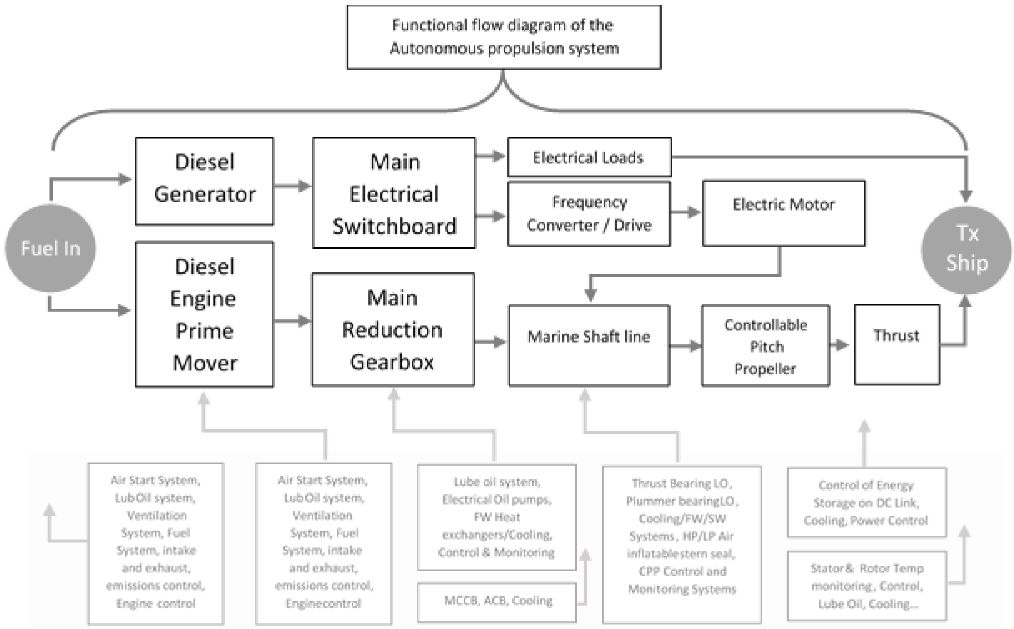

Figure 6 – A flow diagram illustrating the various components of a proposed CODLAD power and propulsion system with its various dependencies

As shown in Figure 6 there are a huge range of interdependent systems which ensure correct power and propulsion system operation. These systems will need to be subjected to the same design processes; centring on reliability and deriving the optimum level of redundancy and resilience to failure via a range of centralised, or de-centralised arrangements.

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5.1 Example - Fuel System Concept

The fuel system is an example of a vital fluid system on board Tx ship and will need to be designed in a manner that ensures fuel supply availability to each prime mover. The fuel system is a candidate for a zonal layout with distributed pumps and cross connections servicing emergency power generation, main generation, and propulsion. Such distribution and cross connections are vital in minimising the effect of failure of an individual valve or pump unit within a system. This system differs from some of the other fluid systems onboard in that fuel is a strategic resource that cannot be replenished easily during the autonomous mission and may be prone to leakage in the event of equipment or component failure. Other systems such as seawater or freshwater cooling circuits can mitigate this by replenishing their working fluids and discharging any subsequent leaks overboard.

In such a cross connected, distributed system, whilst the likelihood of individual equipment failure may be higher, the system's ability to manage the failure, without loss of fuel is increased. As such, decentralised architectures in this instance offer the highest availability where a subset of the machines are fed from one zone and another subset are fed from a different zone. Cross-connections are implemented to allow fuel transfer in the event that one zone is taken out of action, to isolate leaks, or to provide reversionary feeds to other prime movers. This arrangement, via an intelligent fluid control system, built into the autonomous machinery controller provides clean, filtered fuel to all the main prime movers that make up the Power and Propulsion system.

As the maturity of the vessel design increases and more requirements becomes available the fidelity of the design solution for the fuel system, and other fluid systems will increase. An example of this will be the need for availability modelling of coalescers or stripping services as well as further conditioning or redundant filtration stages.

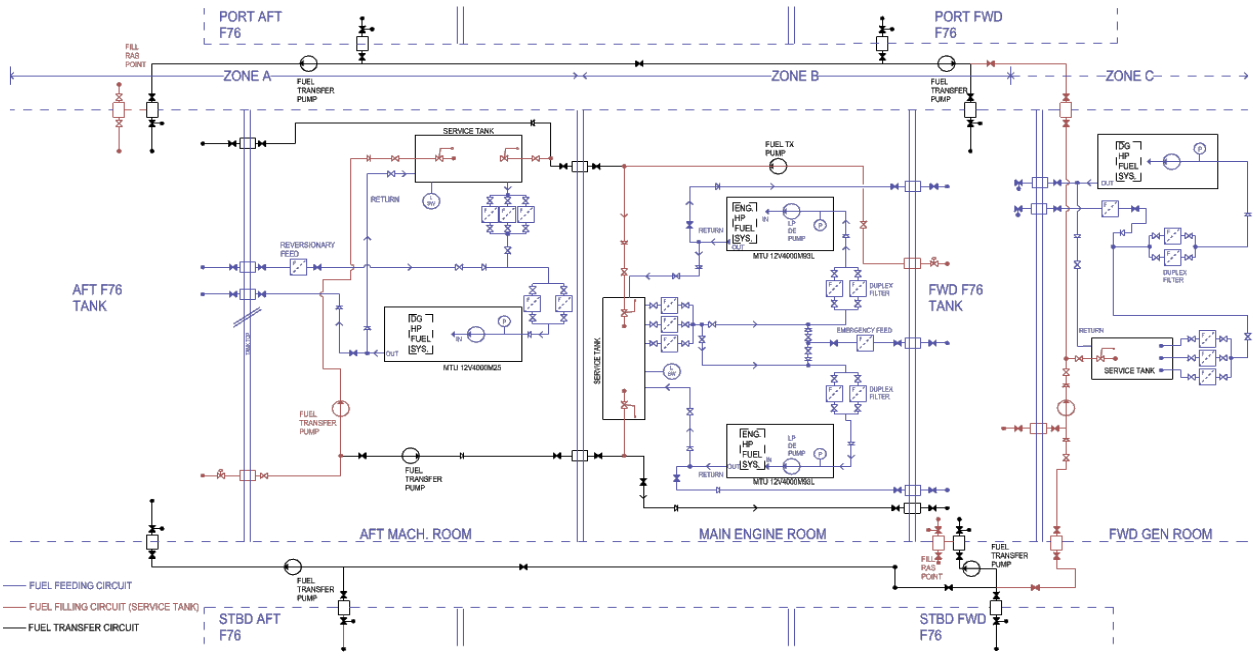

Figure 7 - Main Fuel Filling, Transfer and Feeding Circuits

5.1 Example - Cooling System Concept

A further dependency on prime mover availability is the vessel's cooling system. The cooling medium in the case of propulsion equipment is a combination of sea water, and freshwater systems – both replenishable. This is therefore a key consideration for the cooling system – unlike the fuel system, the severity of failure is reduced if the chosen cooling medium can be replenished easily during the voyage and any leak is either not hazardous or can be mitigated by being pumped overboard. Two fault trees were created to calculate the impact of cooling failure on propulsive power availability: one modelling a distributed cooling system to each machine, and another where each machine depends on a centralised cooling system. If all other failures of the machinery are ignored, then these two fault trees

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calculate the effect of just cooling pump failures on the overall platform availability and can therefore be used to trade between the two systems options as shown in Figure 8.

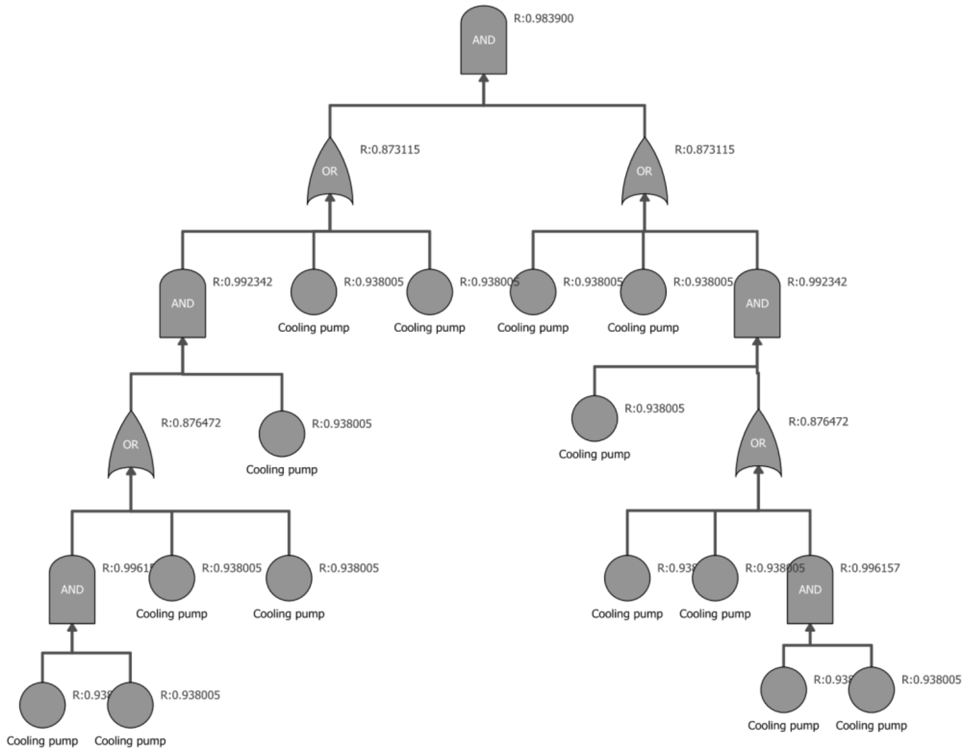

Figure 8 - Fault Tree for Hybrid propulsion failure with distributed cooling

Probability of completing the mission with minimum propulsive power, considering only failures of a distributed cooling system: $\mathbf{P_{Prop}Min = 98.39\%}$ (from Figure 8)

Probability of completing the mission with minimum propulsive power, considering only failures of a centralised cooling system: $\mathbf{P_{Prop}Min = 99.62\%}$

Based on this analysis alone, the centralised cooling system has superior availability; it is also easier to improve this availability further by adding a third redundant cooling system. Such analysis shows the importance of undertaking the analysis of each fluid system in turn rather than applying a blanket approach to centralising, or decentralising fluid systems design in the autonomous vessel application.

6. Maturing the Autonomous Machinery Controller

There are demonstrable diagnostics and health monitoring technologies already in service in current warship systems. In addition, small autonomy driven platforms such as those delivered by Thales' MMCM programme are currently in development and due to be delivered to the Royal Navy in 2020. To develop trust in the larger Tx Ship platform, the intention is to progress through autonomy levels, from remote controlled to complete autonomy over time, adapting the Lloyd's Register suggested autonomy levels[1] from AL0 which denotes human operated functions, through AL6 which describes full, unsupervised autonomy.

The transitional or phased functional maturation approach to autonomy allows command and control of the platform to remain with a 'man onboard', until the various systems are proven, trusted, and deemed appropriate for the platform to perform autonomously. As the vessel moves through each autonomy level, it will also need to satisfy a variety of trustworthiness levels, relying decreasingly on the human operator[7]. The Tx Ship will, during an extensive autonomous trials period, demonstrate the ability to perform in each operational scenario, at the appropriate autonomy level for that task, 'in line of sight' operations before heading 'over the horizon'.

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As trust develops in the systems, crew will no longer be required. Tasks such as daily maintenance rounds, health monitoring and systems reconfiguration will be performed on the availability derived systems highlighted in this paper, by the autonomous machinery controller that supervise these systems. It is expected that in the long term the manning onboard the Tx Ship is mission specific and will not interfere with the day to day running of the Tx Ship. In this way, the manning will be similar in fashion to embarked forces in the current fleet, onboard as required, for the set task only, rather than the running of the vessel.

With respect to physical maturation of the autonomous machinery controller and its integration within Tx Ship, the vessel design benefits from various provisions of Size, Weight, Power and Cooling (SWAP-C) for the various autonomy-based systems on board. These have been specified alongside Rolls-Royce to accommodate the autonomous machinery controller’s processing, HMI and server cabinets as well as the communication nodes within the system. As the TX Ship design matures, further effort will focus on maturing the design integration of the autonomous machinery controller solution in the TX Ship.

7. Conclusions

This paper has investigated the evolving drivers in power and propulsion system design in the context of the optionally manned Tx Ship application. Traditional metrics such as fuel burn, operating costs, and efficiency, whilst still a vital consideration on a military platform, are studied alongside ensuring systems availability, robustness and equipment maintenance when the human operator/maintainer is no longer on board the vessel. This was achieved via consideration of a series of minimum threshold system performance criteria for propulsion and electrical power and assessing the likelihood that the system will be capable of delivering these attributes in order to achieve command aim despite systems degradation across a 40 day mission. The study utilised fault tree analysis and a tailored whole system design process which identified where to place system or equipment redundancy. This is applicable to not only the power and propulsion systems, but perhaps, more importantly the various auxiliary and platform systems that the power and propulsion systems depend on for vital supplies.

The paper concludes that unmanned vessel P&P and auxiliary system design is integral to achieving the autonomous mission and that this must be complemented by a dedicated autonomous machinery controller which analyses both system and equipment health alongside the needs of the mission. This autonomous machinery controller will then send commands to the vessel’s automation system in order to configure the power and propulsion system in accordance with scenario. In the future, this work will be built upon by the authors to improve the maturation of the autonomous machinery controller solution and its integration into the Tx Ship design.

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