From Cruise Ships to Combat - Evaluating Power and Propulsion Technologies for a Lean Warship.

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Synopsis

This paper examines technologies around Power and Propulsion (P&P) systems including design requirements, training, maintenance, and operations exploring how recent advances in these systems can help facilitate a lean crewed warship. The paper draws on the authors experience in the cruise industry and how crewing challenges have been addressed commercially with existing and emerging technologies. The paper challenges the current techniques of P&P analysis and proposes alternative processes for analysing conflicting requirements such as equipment acquisition costs, lean crew objectives, redundancy, and systems efficiencies. Associated risks, opportunities and regulatory framework of a lean crew are investigated. The role of automation, remote condition monitoring and virtual reality is explored. Some recommendations are made for how these technologies can be adopted while still maintaining safety, resilience, and capability.

Keywords: Lean crew, power and propulsion, design out maintenance, equipment health management, virtual reality,

1. Introduction

Over its history, the maritime industry has undergone many significant technological transitions that have impacted the size of the crew onboard. The transition from wood to iron hulls allowed for the accommodation of steam engines. The transition from coal to oil then cut the engineering department and gave improvements through higher energy density. The adoption of a standardised container has dramatically reduced shipping costs through reduced loading times (Stopford, 2008). These, amongst more recent changes such as implementing integrated automated control systems, have led to highly efficient crew levels per cargo carried. In 2003, the world's largest cruise ship was the Queen Mary 2 at 148,527GT. In 2023, the largest cruise ship has ballooned to 248,663GT (Wikipedia, 2024). Despite the 67% surge in tonnage, the technical crew has remained a similar size. Cruise ships share many similarities with modern warships such as complicated survivability requirements, sustaining hundreds of seafarers onboard, high power demands and objectives of balancing capability with an efficiently sized crew. Valuable insights can be obtained from examining how commercial strategies have facilitated an efficiently sized technical crew on cruise ships.

Further radical transformations in the maritime industry are currently leading to an upheaval in crewing training and numbers. 2022 to 2027 looks to introduce disruptive commercial emission policies such as the IMO's introduction of the Carbon Intensity Indicator rating (IMO, 2023) and the EU's Emission Trading Scheme expanding to shipping (European Commission, 2024). Decisions made because of this legislation will have a direct effect in interconnected sectors, such as defence, where commercial shipping will start to coalesce around alternative fuels and prime movers. These decisions and technologies will not only influence the design of the ship but also require an upheaval in maintenance and operations potentially requiring an overhaul of crew skill sets. Disruptive technologies pull crewing requirements in the opposite direction in the form of automation and digitisation. There have been many digital technologies adopted in adjacent sectors to defence such as predictive maintenance through remote equipment health management, virtual reality-based training, and remote-controlled fluid systems.

The methods of enabling a lean crew explored in this paper do not aim to compete with or replace seafarers. Instead, the paper aims to outline some technologies around the P&P systems to move duties ashore, increase reliability of equipment and reduce repetitive tasks to maintain capabilities with a shrinking pool of seafarers.

Authors biography

Edward Penn is a Marine Engineer specialising in Naval power and propulsion systems for Rolls-Royce PLC where he provides systems engineering support for the business development team. He has a decade of engineering experience in the maritime sector and holds an STCW unlimited chief engineers CoC. Before joining Rolls-Royce, Edward spent several years as a seafarer working on new build cruise ship projects, one of which was optimising and verifying the Integrated platform management system on behalf of the owner. He also spent several years operating and maintaining cruise ships power and propulsion equipment.

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2. The Requirements, Opportunities, and Risks of a Lean Crew

2.1. The Requirements

Minimum crewing levels are determined by the flag state of a merchant vessel. All UK flagged commercial vessels above 500GT are required to hold a safe manning certificate which specifies the crewing requirements. The IMO issues guidance for flag states and the capabilities they should consider such as the capacity to train personnel onboard, ensure safe navigational or engineering watches and provide medical care (IMO, 2011). Some principles are applied to naval vessels where a minimum level of crew is determined by a countries naval command. These requirements give forward thinking navies the opportunity to lead lean crewing technologies as the decisions are made in house and not subject to an external party such as a classification society or flag state.

2.2. The Opportunities

Reducing the crew onboard will reduce the number of personnel exposed to a high threat environment. Conflict in the red sea at the beginning of 2024 has illustrated the serious risk to life for seafarers in commercial shipping and defence maintaining these critical corridors. A reduction in crew need not necessarily result in a reduction in capability if balanced with adequate risk assessment and thoroughly tested technologies.

Another major advantage of reducing crew numbers are reductions in operational costs (OpEx). A reduced crew not only reduces the salary associated costs but also the travel relating to boarding and repatriation, hiring costs and training costs. The accommodation spaces and life supporting equipment, such as freshwater generators, can be reduced which leads to reductions in fuel and maintenance associated expenses. The reduction of food further reduces storage space and refrigeration capacity. Ships can allocate the space gained from accommodation and supporting equipment to additional cargo, additional mission critical systems or a reduction in size of the vessel. The reduction in size can lead to a positive design spiral where smaller ships have a lower power requirement further reducing the total size of P&P equipment and crew required to maintain them.

While not directly explored in this paper, some of the discussed P&P technologies may be viable for enabling fully uncrewed autonomous ships. A lean warship could act as a gateway to assessing the feasibility of the technologies more novel to Navies such as remote equipment health management and the associated obstacles when transmitting large amounts of data from ship to shore.

2.3. The Risks

A lean crew also presents several risks. Sufficient crew to conduct on the job training and crew turn over should be factored into the minimum crew numbers. Failure to properly analyse crewing requirements can lead to increased risks of a major incident. An example of this is the HNoMS Helge Ingstad which had adopted a Lean Crewing Concept (LCC) with a high reliance on automation. In November 2018, the frigate was involved in an incident with an oil tanker where mistakes eventually led to a collision and sinking of the Helge Ingstad. The consequent Norwegian Safety Investigation Authority Report (NSIA) detailed a high crew turn over before the incident leading to a lack of sufficient training and an over reliance on automation (NSIA, 2021). When the LCC was introduced, a doctrine was created to reduce the associated risks of a lean crew. Training was a key factor in the doctrine. The successful implementation of the LCC concept on other Norwegian vessels demonstrates that the LCC can be successful if procedures are strictly followed.

Risks of a lean crew have more recently become evident in the red sea as the French navy has announced its intention of increasing crew sizes by almost 20% likely due to the fatigue induced by a continuous elevated threat state (Meta-Defense, 2024). However experienced and motivated the crew, if overloaded, fatigue can lead to compromising on safety and dissatisfaction. If sustained over long periods, an overloaded crew can lower retention rates and result in workload redistributions (Academy of Management Journal, 2023).

In terms of P&P equipment, historic data can be used to optimise and estimate the maintenance tasks and workloads. Time outside of planned maintenance and fixed emergency drills will be allocated to training, ship improvements, or unplanned maintenance. Repeated unplanned maintenance through untested or unreliable equipment contributes to an increased workload and in some cases can reduce planned maintenance, decrease time available for training, and overload crew.

One method of reducing crew is relying on automation to conduct repetitive and analytical tasks. Depending on the system security, automation systems can be subject to external interference and disruption. Commercial shipping companies have opened automation and control systems remotely to allow for system updates, real time data analysis and remote trouble shooting. This brings risks associated with malicious actors manipulating the systems to cause damage, gaining unauthorised access to demand ransom, or stealing confidential data. Systems must have sufficient security and redundancy built in to mitigate cyber security risks. The UK MoD has engaged with industry under the Defence Cyber Protection Partnership (DCPP) and releasing DEFSTAN 05-138. This standard incorporates a risk assessment, risk profiles and associated controls for suppliers. (MoD, 2019). Automation and control systems with numerous interfacing networks and thousands of data points also bring incredibly complex IT systems. The rate of adoption has meant the seafarers onboard are sometimes not equipped with the necessary training to troubleshoot and rectify issues.

3. Design Considerations

3.1. P&P Systems Lifecycle and Viability Analysis

When selecting the P&P equipment for a vessel, both naval and cruise ship design teams carry out a life cycle and viability assessment. Priority is often given to the amount of fuel various systems will use and the capital expenditure (CapEx) of the system. Data from operational profiles or itineraries are combined with power speed curves to determine the most efficient propulsion system. The volume and mass of equipment are analysed to determine if integration is viable. Redundancy and additional capability such as underwater signatures for naval vessels or engine vibration for cruise ships are factored into the P&P system analysis. The future resilience of the system should be considered, particularly with the introduction of direct energy weapons and compatibility with future fuels. Consideration is sometimes given to running hours and associated planned maintenance tasks. It can be difficult to quantify unplanned maintenance even if an operator has experience with the equipment and extensive historic maintenance records.

There are various techniques for selection of the equipment through multi-criteria decision making. The analytical hierarchical process has proven successful in the past but great care must be taken to avoid any bias. Another method of assessment, where possible, is to assign monetary values to the options over the predicted lifetime of the vessel. When calculating the total expenditure, a monetary value can be assigned for fuel costs, spare parts, maintenance hours, capital costs and even physical space. If using a financial basis for the multi-criteria decision making, historical data should be used to estimate the inflation rates of the OpEx. It is important to estimate the actual cost of a seafarer including the potential cost reductions discussed in section 2.2.

In the cruise industry, a financial value can be assigned to a specific volume through the additional revenue of added passenger cabins. In the past, cost modelling has been carried out comparing power dense, P&P equipment which enables additional passenger cabins. In defence, the value of additional volume gained by selection of power dense equipment can be difficult to determine – either facilitating additional mission systems or a reduction in vessel size.

3.2. Redundancy

There are several methods of achieving the survivability requirements to sustain propulsion in a modern warship. Spatial redundancy has been adopted and proven effective in hybrid or Integrated Full Electric Propulsion (IFEP) vessels. Mechanical systems can also adopt some spatial redundancy by offsetting gearboxes and main engines in different machinery spaces. Redundancy can also be achieved by duplicating P&P equipment. The US Navies optionally crewed ghost overlord fleet are fitted with five mechanically driven water jets and three gensets – a total of eight engines. Engines have been adapted to increase the operational unmanned periods at sea such as installing three oil filters instead of one (Seapower magazine, 2022). While these measures increase the unmanned period, the maintenance burden during refit is increased with a larger number of components to overhaul.

To reduce the maintenance burden, operators in the cruise industry, have opted for a redundancy of power instead of a redundancy of components. Here the total number of diesel engines are reduced often from six to four opting for a higher cylinder output and reduction in total number of cylinders. In these setups, the maximum power of all engines outstrips the maximum propulsive and service loads. Operators of this redundancy philosophy normally use 25% to 50% of the vessels power generating equipment. Peak demands from the propulsion and service loads cannot exceed 75% by design. This allows for one engine to be overhauled in service and still gives capacity in the form of breakdown of another engine for most operations and itineraries. A more traditional P&P arrangement would have six smaller engines installed, still achieving normal operations with the allowance for two out of service engines. The six-engine design when compared to the four-engine design equated to a significant increase in the maintenance burden as the total running hours were higher and number of components were higher. Further benefits were also realised as supporting systems such as cooling water and fuel delivery were optimised for four engines further reducing the maintenance burden. Despite the larger individual volumes and mass, the

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cumulative size of all engines and associated systems was reduced, facilitating a reduction in overall size of the vessel or additional passenger cabins.

3.3. Prime Mover Selection

One method of reducing onboard maintenance to enable a lean warship is to consider the maintenance philosophy of the equipment. Equipment employing the design out philosophy aims to reduce failures to a minimum and eliminate the need for maintenance. Equipment achieves this by observing failure patterns and eliminating them where possible, reducing repairability and employing advanced materials. Electrical systems such as moulded case circuit breakers or variable frequency drives have proven a successful example of employing this philosophy as in the unlikely event of failure, they are designed to be replaceable. Removing the option to overhaul this equipment onboard increases the reliability, reduces repetitive tasks for the technical team and creates a safer environment as the opportunity for mistakes are reduced. Some equipment can be offloaded and overhauled in specialist facilities.

This maintenance philosophy can also be applied to P&P equipment through modular removal and replacement. One example of this is the major overhaul of the MT30 gas turbine core where the maintenance philosophy differs dramatically from a traditional marine engine. At the major overhaul periods, the 6.5 tonne engine core is removed from the ship either through the inlet down take or via the enclosure side. The core can then be shipped to an overhaul facility with the entire removal process taking between 48 and 36 hours (Rolls-Royce, 2019). Many in service maintenance tasks such as balancing, and blade redressing can therefore be designed out of the engine equating to an average of less than two hours of planned maintenance a week. This is enabled through a twin spool design where the resultant reduction in shaft length, reduces the amount of shaft sag and allows for reduced blade clearance.

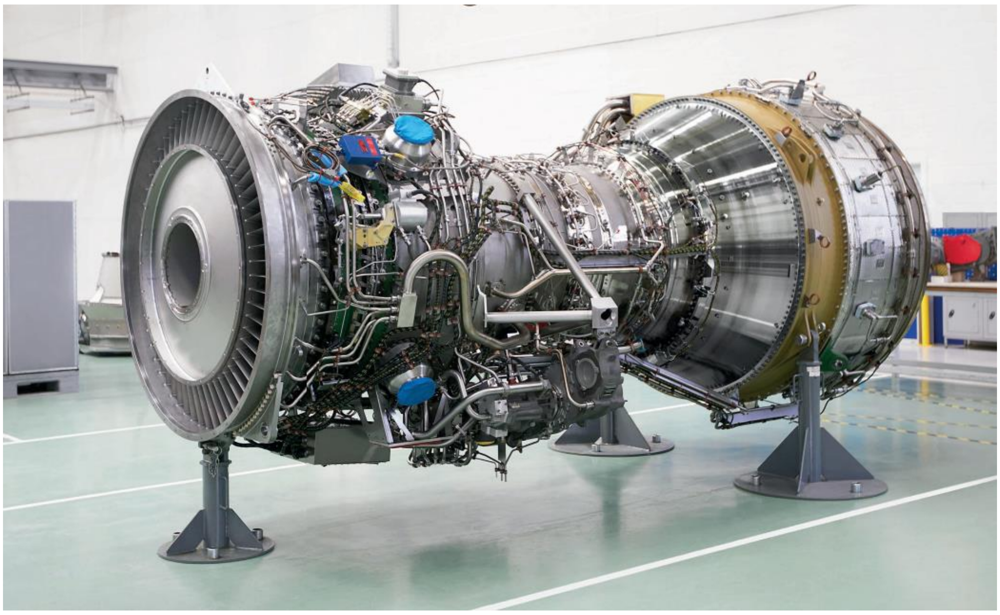

Figure 1 - MT30 core

3.4. Environmental Supporting Systems

The number of supporting and additional systems interacting with diesel engines exhaust systems have grown dramatically over the past decade. To meet MARPOL annex six legislation, NOx abatement Selective Catalytic Reduction (SCR) systems have been installed in the engines uptakes. Merchant navy operators look to waste heat recovery to improve efficiency and ships associated EEDI rating. To prolong the use of cost-efficient high sulphur fuels but still comply with 2020 sulphur legislation, some commercial shipping operators have opted for exhaust gas SOx abatement equipment. The latest exhaust gas treatment to be mooted is Onboard Carbon Capture (OCC) (DNV, 2023). These technologies, while having emissions benefits, also bring dramatic CapEx and OpEx increases. Crew must have adequate training to operate, maintain and manage the chemicals consumed by the systems. The added complexity increases maintenance tasks and the burden for engine room watchkeepers.

While MARPOL legislation does not directly apply to naval vessels, navies often adopt commercially required pollution prevention technologies. Taking NOx abatement as an example, the type 26 P&P system has opted for SCR systems to be installed on the MTU series 4000 diesel engines (Navy lookout, 2019). The cruise industry has opted to mitigate use of the SCR systems through adoption of LNG. In LNG's current form, it is unlikely this fuel will be adopted in next generation warships. To avoid certain exhaust treatment systems, Navies could look to alternative prime mover technologies such as relying on batteries for low loads and gas turbines for boost as the levels of NOx allows exemption from abatement systems.

4. Control and Monitoring

4.1. Integrated Platform Management System (IPMS) Integration

If a holistic approach is adopted when designing the IPMS, automatic planned maintenance can be integrated which can yield huge benefits for reducing maintainers interaction with equipment. One example is implementing remote controlled, automatic cleaning cycles for power generating equipment. Systems which interface with exhaust gases such as heat recovery heat exchangers, SOx abatement systems and turbo chargers often require some form of chemical or water cleaning system. The level of automation adopted in the cleaning system can vary from, complete manual control, a mixture of human input and automation or a completely automatic and remote system. The latter will present risks of introducing more equipment and the complexity of these systems with additional CapEx. By eliminating the number of manual operations, technical crew will be able to conduct maintenance more frequently, remotely and carry out multiple maintenance tasks in parallel. A reduction in maintenance is one of the many benefits of a close cooperation between equipment suppliers, IPMS integrators and the end user.

An IPMS system can also be used to reduce maintenance tasks of the P&P subsystems. To reduce running hours, IPMS controlled ventilation fans, cooling water, and fuel pumps can be automatically started and stopped depending on if the P&P equipment is running. VFD seawater cooling pumps can be set to regulate on temperature which reduces flow rate and biofouling over strainers. Machinery space ventilation can regulate to pressure and temperature to ensure optimum equipment conditions. It is important to consider the threat state when designing an IPMS system. Stopping of P&P subsystems may give maintenance and fuel improvements but could potentially decrease the standby capability of the P&P equipment. Adoption of modes such as normal, low threat and high threat states would allow systems to operate either efficiently or with elevated redundancy through pre-starting subsystems or running numerous engines.

Due to advances in data storage, modern IPMS systems can record vast amounts of information assisting with troubleshooting and watchkeeping. Users can create automatic reports which can replace traditional manual paper logbooks. Observing the thousands of equipment sensors can quickly overload operators and over long, uneventful periods may cause operators to disengage. Some thought in the merchant sector has been given to gamification of the interfacing systems particularly around the aesthetics, ease of navigation and user interaction. This keeps operators engaged in lull periods but also familiar with the system so able to quickly react in emergency situations. CCTV systems can be integrated into IPMS systems and can be a useful tool to reduce watchkeeping teams. If for example, a main engine fuel leakage alarm is triggered, a tactically positioned CCTV camera can be used as a first response tool.

4.2. Condition Monitoring

Monitoring of equipment can be further improved by transmitting data remotely in real time directly to equipment suppliers known as remote condition monitoring or equipment health management. These manufacturers can anonymise and collect data from many operators of equipment. The data pool can be used to create a proactive rather than reactive approach to maintenance. Civil aerospace has been using real time engine condition monitoring where data is transmitted from air to ground since the mid-1980s (Aviation today, 2022) . The maritime industry has been slower to adopt these technologies mostly because the nature of a ship allows for reactive maintenance to be conducted in service.

Adopting real time condition monitoring technologies could yield huge benefits to naval operators. If remote transmission systems are utilised, equipment suppliers can use the various data points to detect trends and malfunctions. The data can be used to inform the ship to apply load limits or carry out preventative maintenance. This can yield reliability increases through preventing downtime or damage to equipment. The data can also be used to accurately predict overhaul periods decreasing unnecessary time-based maintenance. The remote transmission element will eliminate the need for on-site data retrieval. If data collection frequency is increased, it is more likely underlying issues will go undetected. Training of naval staff to analyse condition monitoring data can also be considered. This can result in a compromise reducing the frequency of collection but mitigating some of the cyber security concerns around transmitting data to external parties.

The cruise industry is beginning to adopt some remote communication and condition monitoring technologies. One example being the novel exhaust treatment systems where Suitably Qualified and Experienced Personnel (SQEP) onboard remains low. To advance the SQEP onboard, system specific, instant messaging communication tools have been created in collaboration with equipment suppliers to encourage conversation between vessels which share the same equipment and the suppliers. As well as offering troubleshooting and training, these systems can bridge the knowledge gap which can be created between vessels of the same class.

5. Training Considerations

Some of the most comprehensive and effective training for technical crew is practical on-the-job experience. There are several reasons for why this kind of training is not always possible or unfavourable. A pool of SQEP must be sustained onboard with relevant experience of all equipment. The SQEP pool must be given adequate time to pass on experience through on-the-job training. Varying operational requirements and staff turnover can lead to situations where experienced personnel are unavailable. Vessel operators are also responsible for accommodation, living conditions, travel, repatriation, health, and safety for all seafarers onboard the vessel. These additional costs create an expensive training environment.

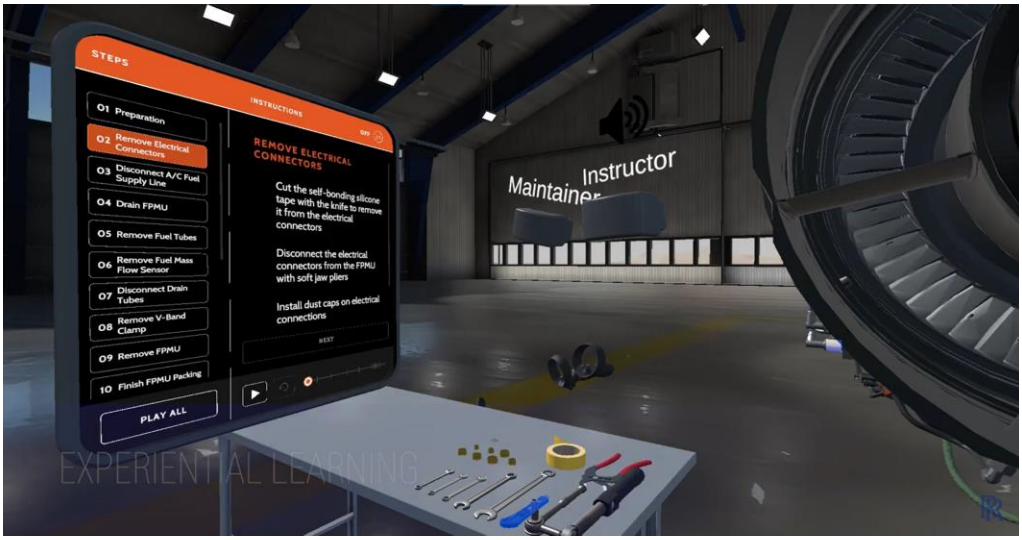

Figure 2 – Virtual reality training – tooling and maintenance instruction

One method of reducing crew onboard is making more training available in shoreside facilities. Advances in virtual reality have allowed training facilities to provide complex engine space and control room simulators such as the facilities in HMS Collingwood (Royal Navy, 2023). An advantage of this type of training facility is the virtual reality environment can be adapted as systems develop such as the adoption of alternative fuels or propulsion systems. Equipment suppliers are also developing solutions. Rolls-Royce for example has developed virtual reality maintenance training software (Rolls-Royce, 2023). The training method has some advantages over traditional on-the-job training as it allows for advanced visualisation of the engine internals, limiting downtime of equipment, and experimentation without the risk of damage. Traditional skills such as the familiarisation with specialised and standard tooling has been considered.

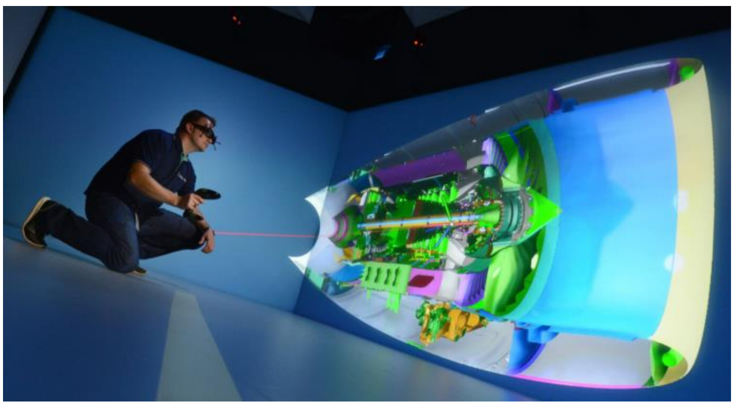

Figure 3 – Virtual reality training – visualisation of engine internals

6. Conclusions

This paper suggests many methods of reducing crew onboard however a holistic approach is required to ensure future warships can operate safely and effectively. Crewing doctrines must be updated frequently with changing technologies and abided by strictly to ensure the associated risks are mitigated. The objective for a lean crew will compete with other priorities but if vessel operators are committed to the objective, it should take priority as early as possible in the design phase. Lean crewed P&P systems favour minimal and reliable equipment, reducing the planned and unplanned maintenance burdens. While this may seem to contradict some survivability requirements, warships could embrace P&P designs adopted in the commercial sector such as a redundancy of power concept. Adoption of remote condition monitoring and autonomous systems remains a viable and established way of reducing technical crew but there are still concerns to alleviate around cyber security.

The aim to reduce crew requirements is a common goal shared between the defence and the commercial sectors. Reducing human error, crew salaries and increasing the space for cargo or mission equipment are driving investment into research. There are advantages for defence to lead this change as personnel exposed to high threat states are reduced and Navies have more autonomy from classification societies and international legislation. There is still room for collaboration between industry, commercial shipping, and defence to ensure knowledge is shared, systems are better integrated and common goals can be achieved safely.

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