Autonomous Machinery Control Systems for Naval Unmanned Surface Vessels

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Synopsis

Advancements in automation, artificial-intelligence, robotics, motion-control, satellite based communications, geo-spatial positioning systems, and real-time machinery control systems have enabled ship designers to consider the implementation of totally automated autonomous or semi-autonomous remotely controlled unmanned surface vessels to operate in a variety of marine and naval applications. The possibility of being able to operate unmanned naval vessels poses several operational benefits and cost savings for naval vessel operators while at the same time introduces inherent risks that must be mitigated through robust system safety and redundancy requirements. Unlike manned vessels, on unmanned vessels machinery control systems will need to act autonomously to replicate functions that are normally performed by human operators. This paper will (a) provide a list of machinery control functions normally done by humans that will need to become autonomous, (b) identify key requirement areas that will need to be developed for totally autonomous unmanned naval surface vessel machinery control systems, and (c) provide an update on ongoing efforts to develop standards and requirements for autonomous machinery control systems on unmanned naval surface vessels.

Keywords: Autonomous; Unmanned; Machinery Control systems

1. Background

The U.S. Navy has been increasingly pursuing the development of unmanned surface vessels to support for a variety of missions including surveillance, intelligence gathering, anti-surface warfare, anti-submarine warfare, anti-air warfare, mine warfare, search and rescue, maritime security operations, and expeditionary warfare. Unmanned surface vessels (USVs) are being developed to operate in fully autonomously modes where a mission is pre-programmed into the USV which then carries out the mission with no human intervention (CRS 2019). USVs are also being developed to be operated in a semi-autonomous mode where a land or ship based remote control center remains in communication with the USV and send commands to the USV to carry out the required mission. In the case of shipborne remote control centers, one concept calls for a single manned warship to operate with a group of USVs which operate similar to a battle group to carry out specified missions (Fuentes 2024). For all these variations, operating the machinery plant without any human intervention for long durations of time (i.e., 30 or more days unmanned) is a considerable challenge for systems designers of USV machinery control systems. Multiple essential control systems including propulsion, steering, electrical plant, auxiliaries, and damage control must be designed to function with no assistance from human operators for extended periods of time. In this regard, system designers must anticipate every conceivable function normally performed by humans to be performed autonomously without any support from a human operator. These functions include everything from routine daily maintenance to recovery from major casualties and damage events deemed recoverable. This paper will focus on three topics that unmanned surface vessel control system developers should be aware of when considering the Machinery Control System (MCS) design on a fully-autonomous or semi-autonomous unmanned surface vessel as follows:

1. Key Machinery Control System functions to Support Autonomous Unmanned Operation
2. Key MCS Characteristics and Essential Features required for Autonomous Operation
3. Development of Specifications and Standards for USV Machinery Control Systems

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 https://doi.org/10.24868/11156

2. Discussion

For an unmanned vessel, one of the biggest challenges is to automate all the machinery control and monitoring functions that are normally performed by watch standers during normal machinery plant operations as well as special situations such as recovery from casualties and damage events such as fire and flooding. USVs will likely be manned during initial plant startup dockside, leaving and entering port, fueling at sea (UNREP), and during plant shutdown after returning to the pier. Once the vessel has completed restricted maneuvering and has entered open ocean, the machinery plant will need be placed into either semi-autonomous mode with a remote operator in the loop or full autonomous mode and all functions required to keep the plant safely operating will need to be fully automated (Gain, 2020). In many cases, there will be an insufficient level of automation specified or the required level of monitoring is not provided to automate a particular function because they are typically performed by watch standers. For example, the basic USCG regulations (46 CFR, 2024) and classification society rules for periodically unattended engine-room (i.e., ABS ACCU, DNV-GL E0, and LR UMS notations) are all based on the capability to leave the machinery plant unattended for up to 24 hours. Things like automatic standby pump changeover, propulsion machinery automatic safety slowdowns and shutdowns, automatic fuel oil transfer, and automatic power management are all standard features for periodically unattended engine-room. However, human intervention is still required for many functions such as performing routine maintenance, responding to alarms and taking corrective action, resetting machinery controllers after a shutdown, restarting machinery to recover from casualties, aligning piping systems for proper operation, operating ballast pumps to maintain vessel stability, activating fire-fighting systems upon detection of a fire, and performing dewatering to mitigate flooding. In order to successfully operate in an unmanned fully autonomous mode, the MCS will need to have a sufficient level of automation, control, and monitoring to autonomously perform these additional types of functions with no human intervention.

3. Differences between Manned and Unmanned Surface Vessel Operations

Similar to manned vessels USVs can be equipped with sensors, weapons, or other payloads with the added capabilities to be operated remotely, semi-autonomously, or (with technological advancements) autonomously (CRS 2019). USVs can be individually less expensive to procure than manned ships because their designs do not need to incorporate spaces and support equipment for extended operations with onboard human operators. USVs can be particularly suitable for long-duration missions that might tax the physical endurance of onboard human operators, or missions that pose a high risk of injury, death, or capture of onboard human operators. Consequently, USVs are sometimes said to be particularly suitable for so-called “three D” missions, meaning missions that are “dull, dirty, or dangerous.” (Diab 2014, Robinson, 2015, Marr, 2017).

From a controls perspective, while a manned vessel relies on human operators at various shipboard control stations to make all critical decisions and respond to system malfunctions or damage control events, on an unmanned vessel all of the logic to execute these functions must be performed by an Autonomous Control System (ACS) which has been preprogrammed to execute a specified operational mission for a prolonged period of time. In order to facilitate autonomous operations, the ACS will need to be provided with enhanced monitoring capabilities in order to be able to sense the state of the machinery plant via the Machinery Control System (MCS) and make fully automated decisions which would normally be made by a human operator. Even routine watch-stander actions such as shifting fuel oil service tanks, periodically cycling equipment, or shifting strainers will somehow need to be automated. When responding to machinery casualties or damage events (i.e., fire, flooding), the ACS will need to assess the condition of the machinery, take corrective action, reconfigure the machinery plant to recover from the casualty, and where possible continue on with the specified mission. Consequence analysers, similar to those found on Dynamic Positioning (DP) Vessels to determine if it is safe to continue DP operations after a casualty, may need to be employed to ultimately decide whether or not the vessel can safely continue with an unmanned mission in a degraded state following a machinery casualty or damage control event. Lastly, as there are no maintenance or repair personnel onboard, machinery will need to have a high level of reliability in order to support prolonged unmanned missions without failure. Table 1 outlines the main differences between manned and unmanned surface vessel control system key functions.

Table 1: Differences Between Manned and Unmanned Surface Vessel Control System Key Functions

Key Functions	Manned Vessels	Unmanned Vessels
Routine maintenance	Performed by crewmembers manually	Must be fully automated to be done by MCS or equipment must be designed to be maintenance free for the specified duration of the mission
Equipment monitoring	Roving watch-standers can check on equipment status by visual/audible observations	Requires enhanced system monitoring, more sensors, camera systems, acoustic/vibration monitoring systems
System alignment	Performed by crewmembers manually operating valves and starting equipment	Must be fully automated such that all the equipment and valves are placed in the correct state by MCS to meet all equipment start permissives
Cycling of key rotating machinery to balance running hours	Performed by crewmembers manually, usually once a day	Must be automated such that equipment is shifted by MCS on a daily basis or may be based on running hours
Recovery from machinery casualties	Typically manually done by crewmembers who troubleshoot the problem, reset safety devices, and restart equipment manually	Must be automated such that the MCS can assess if the problem has been resolved and automatically reset safeties and restart equipment once all permissives have been satisfied. Will likely require enhanced monitoring and additional sensors.
Damage control functions	Performed by crewmembers who manually respond to damage events. An operator at Damage Control Central or repair lockers will take manual actions such as activating fire suppression systems, shutting down key equipment such as fuel pumps and vent fans, closing valves, dampers, hatches, and watertight/firetight doors to isolate spaces, and starting dewatering and ballasting equipment	Must be fully automated such that ACS directs MCS to take automatic action in response to detection of damage event such as fire or flooding

4. Key Machinery Control System functions to Support Autonomous Unmanned Operation

The following is a list of key machinery functions that will need to be performed autonomously by the MCS in order to support prolonged unmanned operation.

1. Routine maintenance and monitoring
    a. Strainers and filters - All strainers and filters for machinery systems may be fitted with a means of automated change out or cleaning such that when the system detects a clogged strainer or filter due to high differential pressure alarm, the system is arranged to take automated action clean, change, or shift the strainer or filter. Such action will prevent casualties such as a clogged seawater strainer from causing Main Propulsion Diesel Engines (MPDEs) or Ship Service Diesel Generators (SSDGs) to overheat and shutdown.

 https://doi.org/10.24868/11156

b. Lube oil analysis – Where lube oil quality must be monitored, the system may be arranged to automatically sample and analyze lube oil and where required shutdown machinery and changeout lube oil.
c. Motor insulation resistance monitoring – Online megger reading for key electrical motors may be incorporated to warn that motor insulation breakdown is imminent and initiate automated changeover to standby motor/pump.
d. Vibration monitoring – Built-in accelerometers may be installed on key rotating machinery to provide an early indication of high vibration which would enable automated changeover to standby machinery before the equipment suffers a bearing failure or other damage due to high vibration.
e. Machinery Condition Based Monitoring (CBM) and Trend Analysis – Enhanced system performance monitoring of key parameters (i.e., temperatures, pressures, flow) may be provided to enable an onboard Condition Based Monitoring (CBM) system to perform trend analysis, diagnostics, and prognostics to predict when equipment is prone to failure and take automated action to prevent failures.
f. Provide overall health status of HM&E systems – Data can be recorded and analyzed to enhance system performance and efficiency.
g. A means of automatically lubricating or greasing the propulsion shaft seal may be required where the ability to periodically provide the propulsion shaft seal with lubricant or grease is needed to meet the manufacturers recommended maintenance requirements.

2. Alignment of machinery systems for startup, shutdown, and routine operations – The following functions may need to be fully automated to support unmanned operations.
   a. Prime-mover Startup to ensure that propulsion prime-movers are safely brought online in time to meet speed demand changes or to recover from a casualty.
   b. Drivetrain Alignment may be automated to ensure that the drivetrain (i.e., main engine, reduction gear clutch, shafting, waterjet bucket) is properly aligned before main engine startup and after main engine shutdown to enable trail shaft mode.
   c. Shutdown of online propulsion prime-movers/drivetrains and transition to trail shaft mode based on the current speed/power demand in order to reduce fuel/power consumption and maximize efficiency.
   d. Stopping and locking the shaft when a drive train is required to be shutdown in order to prevent prolonged duration at high speeds from causing damage to gears/bearings in system (MPDE, Gear, Shaft, or Waterjet) due to loss of lubrication.
   e. Automated start, stop and E-Stop for all propulsion and auxiliary equipment.
   f. Opening of key valves in auxiliary systems (fuel oil, lube oil, cooling water) to align them for propulsion machinery startup/shutdown.
   g. Isolation of systems to prevent a single failure from affecting multiple systems/equipment. For example, alignment of fuel oil service system valves serving main propulsion diesel engines such that a fuel leak on one engine does not require shutting down all MPDEs.
   h. Closure of key fittings and valves when equipment is secured. For example, automated closure of air intake and exhaust gas dampers upon diesel engine shutdown to prevent engine damage due to prolonged seawater intrusion when diesel engines are secured.
   i. Fuel oil transfer – The fuel oil transfer system may need to be fully automated to refill fuel oil service tanks by automatically transferring fuel from fuel oil storage tanks.
   j. Pumps may be arranged to automatically shutdown when a low fluid level is detected to avoid damage to the pump.
   k. Lube oil sump level monitoring may be provided for key machinery such as MPDEs, SSDGs, and reduction gear in order to prevent a low sump level from causing damage to engines or gears.
   l. Line shaft bearing temperature monitoring system may perform automatic engine slowdowns/shutdowns when a high line shaft bearing temperature is detected in order to prevent drive shaft damage from occurring.
   m. Fueling at-sea – The fuel oil transfer system may be arranged to automatically align fuel oil system valving to allow refueling at-sea.

 https://doi.org/10.24868/11156

   n. Ballast/Deballast –The ballast/deballast and tank level monitoring systems may be arranged to automatically start/stop ballast/deballast pumps, align ballast system valves, and transfer ballast water in order to maintain the vessel within stability limits.
   o. Machinery Space Ventilation System – may be capable of automatically maintaining proper engine room and generator room ventilation pressure based on engine operation and compartment pressure.

3. Electrical Plant functions – The electrical plant may utilize the following features to enable prolonged unmanned operation.
   a. Power management – full automatic power management to automatically start and parallel SSDGs when the load is increasing to prevent overloading of SSDGs and automatically disconnect and stop SSDGs when the electrical load decreases to prevent low loading effects on engines and maximize fuel efficiency.
   b. Automatic standby SSDG startup to recover from a loss of an SSDG.
   c. Propulsion power limiting – On electric propulsion ships, the system may automatically reduce propulsion power or delay startup of a propulsion motor to prevent overloading of SSDGs upon a generator failure.
   d. Load shedding – automatic tripping of non-essential loads to prevent SSDG overload upon loss of an SSDG.
   e. Recovery from load shedding – automated recovery after a load shed event may be required to restore the electrical plant configuration. The system will need to be able to automatically reengage tripped breakers after sufficient electric plant generating capacity is regained.
   f. Heavy consumer blocking – Automatic start blocking, time delay, or soft starting of heavy power consumers to prevent large inrush motor current from overloading/tripping SSDGs.
   g. Sequential startup – Upon recovery from a blackout, automated sequential startup of essential motors and other loads to prevent simultaneous starting of too many motors from overloading of SSDGs
   h. Blackout recovery – Automated standby SSDG startup and dead bus pickup to recover from a blackout condition.
   i. Automatic Bus Transfer (ABT) switches may be provided for all essential loads to ensure continuity of power to essential systems.

4. Climate control systems – In spaces housing heat sensitive equipment (such as electronic equipment, computers, network switches, and servers) climate control systems maybe fully automated to maintain the required heat and humidity levels to prevent overheating of sensitive electronic equipment. Additionally, automated changeover to a backup climate control system may be provided. For spaces where crewmembers are normally stationed during manned modes of operation (i.e., the bridge), provisions will need to be made to automatically adjust climate control system for prevailing weather conditions.

5. Pollution abatement systems
   a. Bilge housekeeping – The machinery bilge water system may be fully automated to maintain machinery space bilge well levels.
   b. Oily waste water processing – The oily water separator may be arranged to automatically process oily water waste and maintain overboard discharge to within 15 ppm per MARPOL Annex VI (IMO, 2024).
   c. Black and Gray water processing may be fully automated to support manned modes of operation.
   d. Air emissions - where required by MARPOL, automatic changeover between fuel types may need to be accomplished when entering/leaving Emission Control Areas (ECAs) designated under regulation 13 of MARPOL Annex VI.
   e. Sewage treatment – Operation of the Marine Sanitation Device (MSD) and Vacuum Collection, Holding, and Transfer (VCHT) System may be fully automated to support manned modes of operation.

6. Cycling of key rotating machinery to balance running hours – in order to prevent unbalanced wear and tear leading to premature machinery failure, the MCS shall autonomously monitor running hours and wherever

possible cycle between online and standby machinery to keep running hours balanced. The logic sequence will be designed to equalize hours on a periodic basis on duplicated machinery. Examples include:
   a. Propulsion engines (when operating in a trail shaft mode)
   b. SSDGs
   c. Auxiliary pumps (fuel oil, lube oil, cooling water)
   d. Firemain pumps (when continuously running on a wet firemain)
   e. Steering gear HPUs

7. Recovery from machinery casualties – The MCS will need to be capable of performing the following functions automatically in order to recover from machinery failures.
   a. Start/restart of propulsion machinery to restore propulsion
   b. Start/restart of standby auxiliary pumps
   c. Start/restart of standby SSDGs
   d. Reducing speed command upon loss of a propulsion train
   e. Resetting engine/turbine/motor controllers after a safety system shutdown
   f. Resetting motor controllers after a motor overload shutdown
   g. General troubleshooting and analysis of diagnostics

8. Damage control functions – the following damage control features/functions may need to be fully automated in order to support isolation of a fire/flooding event and subsequent recovery/restoration of propulsion and electrical power during unmanned autonomous operation.
   a. Activation of fire-fighting systems in affected spaces upon detection of fire
   b. Intelligent fire detection sensors with polling (heat/optical/smoke) to minimize false alarms
   c. Pump startup and system valving alignment for sprinkling and watermist systems to release sprinkling water or watermist in the affected space
   d. Shutdown of rotating machinery in affected spaces to prevent machinery damage from fire/flooding
   e. Shutdown of flammable liquid system pumps and closure of tank suction valves and bulkhead stop valves (i.e., fuel oil, lube oil) to isolate compartments where a fire has been detected
   f. Shutdown of ventilation of affected spaces to isolate compartments where a fire has been detected
   g. Closure of key fittings such as fire dampers to isolate compartments where a fire/flood has been detected
   h. Closure of watertight/firetight doors to isolate compartments where a fire/flood has been detected
   i. Startup and alignment of dewatering systems upon detection of flooding
   j. Ballast system operation to maintain vessel stability
   k. Recovery from a fire or flooding event
   l. Isolation of firemain ruptures (i.e., by use of smart valves)

5. Key MCS Characteristics and Essential Features required for Autonomous Operation

An area of concern for MCS system designers is defining the key characteristics needed for a machinery control system to support autonomous operations. The following is a list of essential MCS design features needed to support autonomous unmanned operation.

1. System Architecture -
   a. Autonomous Control System (ACS) Interface – The MCS will have redundant interfaces via an autonomy bus to the ACS at the network layer where higher level decision functions may be implemented (NAVSEA, 2019). The ACS may incorporate logic such as a Mission Consequence Analyzer (aka Decision Support System) that monitors the state of MCS machinery to determine if the vessel can continue to carry out the specified mission autonomously upon detection of a machinery plant system or equipment failure. The Mission Consequence Analyzer is to be able to perform calculations to verify that in the event of a single fault there will be sufficient thrust, electrical power, and steering capability available to maintain the required speed and heading to carry out the specified mission.

 https://doi.org/10.24868/11156

   b. MCS Layer - a robust fault tolerant and redundant MCS architecture should be selected to maximize system performance and fault tolerance. MCS functions should be implemented at the control layer to ensure deterministic system behavior and prevent processing delays associated with the network layer from occurring due to jitter, latency, and insufficient bandwidth. MCS will need to report ship speed, heading, and machinery plant conditions to the higher level ACS and concurrently accept and execute directions in return.

2. Autonomy Level – The appropriate vessel autonomy levels will need to be to be specified and defined in the ship specifications in order to support the required unmanned missions. The level of autonomy required will drive requirements for both the ACS and MCS. For example, the American Bureau of Shipping (ABS) Requirements for Autonomous and Remote Control Functions (ABS, 2022) specifies the following autonomy levels:
   a. Smart: System augmentation of human functions. The system provides passive decision support, such as in the form of health or performance anomaly detection, diagnostics, prognostics, decision/action alternatives, and/or recommendations.
   b. Semi-Autonomy: Human augmentation of system functions. System operation builds upon a smart foundation and is governed by a combination of system and human decisions and actions.
   c. Full Autonomy: No human involvement in system functions. The system makes decisions and takes actions autonomously. Humans perform a supervisory function solely, and have capability to intervene and override actions made by the system.

3. Redundancy and Fault Tolerance – The MCS will need to be fully redundant in all aspects to be able to sustain unmanned operations after a single failure. In this regard, the MCS will be provided with features such as redundant control consoles, network data processing equipment, network data communication cabling, and power supplies. Data Acquisition Units (DAUs) and Input/Output mapping will need to be arranged such that a loss of a single DAU does not result in a loss of all propulsion, electrical power, or steering capability.

4. Remote Operation and Autonomous Operation – MCS will need to be able to perform all required functions to support both Remote Vessel Operation where the USV is being controlled by a remote operator on an off-ship location such as another manned vessel or a shoreside control center (i.e., Unmanned Operations Center (UOC) and full Autonomous Operation where the vessel is autonomously carrying out a pre-programmed mission and the ACS is in full autonomous control and is not being controlled by an off-ship operator (DNV 2021). A means of changing modes should be incorporated to enable placing MCS into an autonomous mode where the MCS is being controlled by ACS.

5. Recovery from Machinery Plant Casualties – In the event of a single machinery casualty, it should in general be possible to restore all key vessel functions without assistance by personnel on board. The MCS will need to ensure that any serious malfunctions of machinery systems providing control, alarm or safety functions will automatically initiate corrective actions to put the system into a safe state to minimize the risk to the vessel and crew (LR, 2017). Depending on the failure or incident causing stop of the function, the restored function may have reduced capacity. Restoration of the function may be assisted by a decision support system (such as the ACS) or performed automatically by the automation system (MCS).

6. Recovery from Damage events (Fire, Flooding) – To the maximum extent practicable, the MCS may support recovery from a damage event such as fire or flooding. In this regard an automated means such as a Damage Decision and Assessment (DDA) system may constantly review a comprehensive set of ship parametric data, assess, and make recommendations to the MCS for actions to be taken to mitigate shipboard fire, flooding, equipment, and structural damage, or CBR contamination. The DDA system function may be part of the ACS.

7. Cybersecurity – The vessel design may incorporate cybersecurity measures to ensure development of all autonomous control and communications systems adhere to secure software coding best practices, and that control systems are configured and physically protected in accordance with applicable cybersecurity guidelines.

 https://doi.org/10.24868/11156

6. Development of Specifications and Standards for USV Machinery Control Systems

There are a number of ongoing efforts to develop specifications and standards with detailed MCS requirements for USVs including efforts by the U.S. Navy, International Maritime Organization (IMO), governmental organizations, and classification societies. Some examples of publications that have been developed or are being developed for use on Unmanned Autonomous Surface Vessels include:

1. U.S. Navy
    a. Unmanned Maritime Autonomy Architecture (UMAA) / Architecture Design Description (ADD), U.S. Navy, PMS 406
2. IMO
    a. IMO MASS Code - refers to a goal-based code for Maritime Autonomous Surface Ships (MASS)123. The code is being developed by the International Maritime Organization (IMO) to regulate the operation of MASS123. The code is currently non-mandatory, but it is expected to become mandatory through SOLAS and other IMO instruments, as relevant, upon experience with its application1. The mandatory code is expected to enter into force on 1 January 2028.
3. Governmental Organizations
    a. UK Industry Code of Practice for Maritime Autonomous Systems Ships (MASS)
    b. Norwegian Forum for Autonomous Ships (NFAS) - Definitions for Autonomous Merchant Ships
4. Classification Societies
    a. ABS Requirements for Autonomous and Remote Control Functions
    b. Lloyd's Register Unmanned Marine Systems Code
    c. DNV-GL Class Guideline - Autonomous and remotely operated ships

7. Analysis of Industry Requirements for USV Machinery Control Systems

One of the main challenges for industry in development of USV machinery control systems with autonomous capabilities to support naval/military applications is that there is a gap between what requirements are available from commercial industry and what additional requirements are needed for USVs engaged in military missions with prolonged durations (i.e. 30 days or more). Appendix 1 provides a high-level comparison matrix of commercial industry standards that have been published for autonomous and remotely operated unmanned vessels mainly for commercial applications. From a quick survey/comparison of the guidance provided for commercial USVs from IMO, governmental organizations, and classification societies the main focus of these requirements is on vessel safety, crew safety, and protection of the environment. These are all design aspects that would also be suitable for a naval USV, however, these requirements (in general, existing industry guidance in Appendix 1) fall short of defining key MCS functions that will be needed on an unmanned vessel executing a prolonged military/naval mission. For example, further detailed requirements need to be developed for MCS key functions outlined in Table 1. Until more detailed industry guidance is developed, these MCS aspects will need to be defined in the shipbuilding specification as they are not typically included on commercial off the shelf (COTS) machinery control system designs. Note that NAVSEA is in the process of developing a USV MCS Design, Practices, and Criteria (DPC) Manual to address this gap in the requirements. Until these requirements are made available, based on the survey of existing industry requirements, it is recommended that the following tiers of requirements be invoked for MCS designs on naval USVs:

Tier 1 – Classification Society Rules for Commercial Ships (i.e., ABS Marine Vessel Rules) with notation for unattended engine-room (i.e., ABS ACCU Notation; ACCU = Automated Control System Certified for Unattended Engine-room) – Classification society rules cover the base minimum level of redundancy and safety required for commercial vessels and specify what automation is needed to support unmanned engine-room operation for up to a duration of up to 24 hours. ACCU indicates that a self-propelled vessel is fitted with various degrees of automation and with remote monitoring and control systems to enable the propulsion machinery space to be periodically unattended and the propulsion control to be affected primarily from the navigation bridge by human operators. These requirements are well developed having been in existence for decades and form the foundation for what MCS functions are required to support minimally manned or unmanned machinery room operations.

Tier 2 – Classification Society Guidance for Unmanned Autonomous/Remotely Controlled Vessels (i.e., ABS Requirements for Autonomous and Remote Control Functions) – These requirements will supplement the Tier 1

 https://doi.org/10.24868/11156

requirements and will provide additional requirements needed to support unmanned and autonomous operation. As outlined in Appendix 1, these guidance documents provide detailed design criteria for key functions such as: Autonomy Levels, Internal sensors (platform monitoring), External sensors and sources of data, Data interpretation, Remote (Off-Ship) Steering and Propulsion Control, Autonomous Steering and Propulsion Control, Emergency Stop, Sense and Avoid System (COLREGS) (Autonomous/Remote Navigation), and Cybersecurity.

Tier 3 – Additional Key MCS Design Criteria needed to support semi/full autonomous unmanned vessel operation (i.e., NAVSEA USV MCS Design, Practices, and Criteria (DPC) Manual (in development)) – Such a manual would close the gap in what is needed between a COTS MCS and an MCS capable of supporting autonomous unmanned operation for prolonged military missions. For example, topics outlined in Section 4 and 5 of this paper (not covered by Tier 1 or 2) as well as key functions listed in Table 1 would be addressed in detail. In the interim, these are topics that should be addressed in the shipbuilding specification until industry guidance becomes available.

Furthermore, in order to operate in a military environment and carryout military missions, additional design aspects may need to be considered that are beyond the scope of this technical paper. This could be a fourth tier of design criteria outlined in the shipbuilding specification or captured in a future naval/military standard, specification or DPC manual. For example, while the U.S. Navy is planning for USVs to be low-cost, high-endurance, reconfigurable ships based on commercial ship designs, with ample capacity for carrying various modular payloads (CRS, 2019), in order operate in a military environment and support weapons systems, exterior communication systems, and military sensors (i.e., air search radar, electronic warfare, sonar systems) design aspects such as electromagnetic compatibility (EMC) hardening, vibration dampening, acoustic signature mitigation, heat signature mitigation, radar cross section minimization, and survivability are all examples of things that a designer may need to consider in order to successfully carry out the military mission.

8. Conclusions

While a great deal of progress has been made in the development of standards and specifications for unmanned vessels capable of semi-autonomous (remotely controlled) or fully autonomous operation, further work is needed to identify and automate machinery control system functions necessary to support these modes of operation. Current industry guidance does not adequately cover all of the key MCS functions needed for unmanned autonomous operation. The U.S. Navy is working to develop an Unmanned Surface Vessel Control Systems Design, Practices, and Criteria Manual. Further refinement of standards and specifications for unmanned vessel machinery control systems will be essential to support the increasing demands from industry as unmanned vessels are likely going to fulfill an expanding list of mission roles and responsibilities for both naval and commercial applications.

9. Recommendations

The commercial and naval shipping industries, classification societies such as ABS, DNV/GL, and Lloyd's Register, international authorities such as IMO and IACS, and regulatory bodies such as USCG should continue to refine and publish updated standards and specifications for machinery control systems on unmanned vessels capable of being remotely or autonomously operated.

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Appendix 1 - Unmanned Vessel – Autonomous and Remote Machinery Control Systems Requirements Survey

Requirements to Support Unmanned Remotely Controlled / Autonomous Vessel Operation	**Autonomy Degree** **(See Note 1)**	**ABS Requirements for Autonomous and Remote Control Functions**	**UK Industry Code of Practice for Maritime Autonomous Systems Ships (MASS)**	**Lloyd's Register Unmanned Marine Systems Code**	**DNV-GL Class Guideline - Autonomous and remotely operated ships**	**Norwegian Forum for Autonomous Ships (NFAS) - Definitions for Autonomous Merchant Ships**
Cybersecurity	1-4	2.9 Cyber Security 2.9.3(c) High Risk Level The vessel is to comply with the CS-1 or CS-2 notation requirements in the ABS Guide for CyberSecurity Implementation for the Marine & Offshore Industries (ABS CyberSafety® Vol. 2).	10.6 Cyber security - A Cyber Security Analysis shall be conducted…..	Section 9 - Level of integrity (Software) Lloyd's Register Cyber Enabled Ships – Draft ShipRight Procedure ISO 27032 cyber security certification	SECTION 2 MAIN PRINCIPLES – [11] Cyber security - The design of both the overall auto remote infrastructure and the individual systems should explicitly take cyber security aspects into account. DNVGLCP- 0231 Type approval programme - Cyber security capabilities of control system components	Refers to Cyber-enabled ships, ShipRight procedure – autonomous ships. First edition, July 2016, A Lloyd's Register guidance document.
Autonomy Levels Defined	1-4	4 Smart-to-Autonomy Levels i) Smart: System augmentation of human functions. The system provides passive decision support, such as in the form of health or performance anomaly detection, diagnostics, prognostics, decision/action alternatives, and/or recommendations. ii) Semi-Autonomy: Human augmentation of system functions. System operation builds upon a smart foundation and is governed by a combination of system and human decisions and actions. iii) Full Autonomy: No human involvement in system functions. The system makes decisions and takes actions autonomously. Humans perform a supervisory function solely, and have capability to intervene and override actions made by the system.	Table 2.3: Level of Control Definitions – 6 levels: 0- Manned 1- Operated 2- Directed 3- Delegated 4- Monitored 5- Autonomous	4.1.2 Autonomy 7 Levels (AL): 0- Manual 1- On-board Decision Support 2- On &Off-board Decision Support 3- 'Active' Human in the loop 4- Human on the loop, Operator/ Supervisory 5- Fully autonomous: Rarely supervised operation 6- Fully autonomous: Unsupervised operation	Section 4, Table 1 Levels of autonomy functions (5 levels) M - Manually operated function. DS - System decision supported function. DSE - System decision supported function with conditional system execution capabilities (human in the Loop) SC - Self controlled function (the system will execute the operation, but the human is able to override the action. Sometimes referred to as 'human on the loop'. A - Autonomous function (the system will execute the function, normally without the possibility for a human to intervene on the functional level).	4.2 Operational autonomy levels – proposes four operational autonomy levels: Decision support: This corresponds to today's and tomorrow's advanced ship types with relatively advanced anti-collision radars (ARPA), electronic chart systems and common automation systems like autopilot or track pilots. The crew is still in direct command of ship operations and continuously supervises all operations. This level normally corresponds to "no autonomy". Automatic: Automatic: The ship has more advanced automation systems that can complete certain demanding operations without human interaction, e.g. dynamic positioning or automatic berthing. Constrained autonomous: The ship can operate fully automatic in most situations and has a predefined selection of options for solving commonly encountered problems, e.g. collision avoidance. Fully autonomous: The ship handles all situations by itself. This implies that one will not have an SCC or any bridge personnel at all. This may be a realistic alternative for operations over short distances and in very controlled environments. However, and in a shorter time perspective, this is an unlikely scenario as it implies very high complexity in ship systems and correspondingly high risks for malfunctions and loss of system.

 https://doi.org/10.24868/11156

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Internal sensors (platform monitoring)	2,3	3.4 Monitoring and Alarm System(s) 3.4.1 Goal - This subsection establishes minimum requirements for monitoring and alarm system(s). 3.4.2 Functional Requirements - In order to achieve the goal, the following functional requirements are embodied in the provisions of this chapter: ● Monitoring and alarm system(s) is/are to be provided. ● The Operator is to be provided with the necessary information and awareness of the operation of the function. 3.4.3 Requirements - In order to comply with 5/3.4.2, the following apply. 3.4.3(a) Monitoring and alarm system(s) - The monitoring and alarm system(s) is/are to comply with 4-9-2/7 of the Marine Vessel Rules. Displays for the monitoring and alarm system(s) is/are to be provided at the operator control station(s). 3.4.3(b) Control awareness - Means are to be provided at all operator stations to identify the system which is having present control over the Function.	Section 7.6 - Internal sensors (platform monitoring)- Internal sensors may be fitted for monitoring the platforms' vital functions and safety. This may include a monitoring capability which would normally be provided by crew onboard.	Chapter 4 Control System, 4.1.2 - The control system shall record the sensor output for all sensors on which the control system is dependent and all propulsion and manoeuvring system activities at appropriate intervals over the duration of the mission. This data shall be protected from loss or damage and readily recoverable in all Reasonably Foreseeable Operating Conditions.	SECTION 5 VESSEL ENGINEERING FUNCTIONS [6.4.1] Status and situational awareness - It should be possible to observe real-time operational status, readiness and capacity of the vessel function or system from RCC. [6.4.2] Alerts 6.4.2 - Abnormal conditions and situations should generate alerts that in general are categorised and prioritized.....	Table 2 – MUNIN Main function groups and sub-groups Propulsion Main energy Electric Auxiliary
External sensors and sources of data	2,3	APPENDIX 1 - High Level Goals (Autonomous Vessel) 2.4 Safety of Navigation = The vessel is to navigate based on the principles in COLREG. This includes: ● Maintaining steering capability (refer to A1/2.1 above) ● Communicating with surrounding vessels in accordance with the requirements of the current regulatory regime ● Communicating distress to surrounding vessels ● Weather monitoring and routing ● Notice to Mariners and Navigation reference ● Law of the Seas compliance	Section 7.7 - External sensors and sources of data - External sensors may be fitted to sense and/or measure the environment, surroundings, navigational data, and other platforms and systems,……	Chapter 6 Navigation Systems. 4.1.2 - The UMS shall be fitted with sensors, systems and equipment to provide feedback to the Operator or autonomous control system of the operating state and potential hazards. The feedback should be appropriate for the Autonomy Level, and operating state and environment of the UMS.	SECTION 4 NAVIGATION FUNCTIONS, [3] Condition detection…..Facilities supporting the principles in COLREG rule 5 of maintaining a proper lookout and the subsequent design criteria from SOLAS V/22 shall be a part of the vessel design. These facilities shall serve the purpose of: — Maintaining a continuous state of vigilance by sight and hearing, as well as detection of significant change in the operating environment. — Fully appraising the situation and the risk of collision, grounding and other dangers to navigation. — Detecting ships or aircraft in distress, shipwrecked persons, wrecks, debris and other hazards to safe navigation.	5 Operating design domain- The Automatic DNT will be the set of tasks assigned to the automation system, on shore or on board. This defines the requirements for sensor systems, object detection and classification, anti-collision systems etc.

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Data interpretation	2,3	3.5 Data Analytics 3.5.1 Goal This subsection establishes minimum requirements for constituent systems using data analytics techniques. Data analytics techniques include machine learning, artificial intelligence, data mining and statistics.	Section 7.8 - Data interpretation - - The ability to interpret sensor data on board in a timely manner with regard to its impact on MASS safety and performance and to execute its responsibilities in accordance with COLREG and international law; The ability to transmit sensor data in a timely manner to an off-board system or human operator…..	Chapter 6 Navigation Systems, 4.1.4	SECTION 4 NAVIGATION FUNCTIONS [4] Condition analysis - Facilities supporting the classification of objects detected should be provided. Classification of other vessels should include the ability to distinguish between the following vessel classes - see COLREG Rule 18:	5 Operating design domain - The Dynamic Navigation Task (DNT) – adapted from the "dynamic driving task" defined in [3], will be the sum of all tasks that need to be executed by the ship automation system and/or the human operators to handle all foreseeable operational requirements in the ODD.
Remote (Off-Ship) Steering and Propulsion Control	2,3	SECTION 6 Remote Control Functions 2.1 Criteria - The function is to be clearly identified. The function may reside within a single system or it may be performed by a combination of multiple constituent systems working in concert to deliver the function. The remote control function is to comply with the following criteria: i) The Remote Control Station is to be constantly manned ii) The Remote Operator is to be designated and will have responsibility over the Function being controlled in a remote location. iii) The Remote Operator is to be able to monitor the system and operations under remote control at all times. iv) The Remote Operator is to be able to control the function in real-time from the remote location.	Section 7.9 Control – off-board human operator The MASS shall have the ability to be controlled by a Control System which may be an on-board, off-board system or human operator, or a distributed system involving one or more of these elements.	Chapter 4 Control System, Section 4.2, Remotely controlled control system 4.2.1 The control panel shall be designed using human factors methodology. The controls are to be easily identifiable and are to be arranged in a logical way to reflect their function, means of operation and hierarchy of importance. 4.2.2 The Operator is to be alerted if the UMS is approaching operating range limit. If the UMS exceeds the operating range limit, it shall automatically return into a safe state alerting the Operator.	SECTION 5 VESSEL ENGINEERING FUNCTIONS, [4.2.3.2] Propulsion and steering machinery - The main command location for control of propulsion and steering machinery should be at the location of the responsible engineering watch in RCC.	4.4 Ship autonomy types - Remote control. Same as direct control, however here the SCC is in control of the ship. One can also here argue that this is not really a type of autonomy. However, as communication links normally cannot be made 100% reliable, the ship will in most cases need fallback procedures that can be activated autonomously when communication fails.
Autonomous Steering and Propulsion Control	4	APPENDIX 1 - High Level Goals (Autonomous Vessel) 2 Goals 2.1 Maintain Steering & Propulsion The propulsion system and supporting auxiliaries are to be designed and constructed to provide ● Continuity of propulsion power, ● Continuity of electrical power, and ● Continuity of position/course	Section 7.9 Control - on-board The MASS shall have the ability to be controlled by a Control System which may be an on-board, off-board system or human operator, or a distributed system involving one or more of these elements. 7.11 - Propulsion control - MASS shall have propulsion control as far as necessary to be capable of ensuring that safe operating speeds appropriate to its situation are not exceeded. 7.12 - The MASS shall have steering control as may be necessary to maintain a safe heading.	Chapter 4 Control System, Section 4.3, Autonomous control system 4.3.1 The autonomous control system shall carry out the programmed mission in an accurate and timely manner with an appropriate level of integrity. 4.3.2 The autonomous control system shall react to changes in its environment including other vessels and moving objects. 4.3.3 It shall be possible within a timeframe appropriate for the operational profile of the UMS to override the autonomous control system to initiate a corrective action or activate a safe state. 4.3.4 The UMS shall fail to a safe state in the event of deviation from normal operation and initiate a system to facilitate location and recovery. 4.3.5 The link between the autonomous control system and the Operator is to be as far as reasonably practicable maintained at all times.	SECTION 5 VESSEL ENGINEERING FUNCTIONS, [4.2.6] Automatic operation (AO) - If the propulsion or steering function is arranged to be automatically operated (AO): The automation system should fully control propulsion/steering machinery and supporting auxiliary systems in all defined operational modes. The engineering watch in RCC will supervise the operation and may intervene if deemed necessary. The automation system may be arranged such that the responsible personnel is given a notification or warning in due time before it carries out an order. The operator may then choose abort or modify the order.	4.4 Ship autonomy types - Fully autonomous. Not supervised by SCC. This type of autonomy is generally complicated to implement and will also mean that the owner of the ship has less control of its operation. Generally, approval of this type of ship will require major changes in regulations, mainly because there is no longer any equivalence to the master or other officers on board.

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Emergency Stop	4	2.1.2 Operator and Operations Supervision Level An operator is to be designated and will have responsibility over the Autonomous Function. The operator may be physically located onboard the vessel or in a remote location. The operator station is to be constantly manned. i) The operator is to supervise the function executions either continuously, periodically or as needed ii) The operator is to be able to intervene, override, and take over the operation when deemed necessary by the operator	7.10 Emergency Stop - The MASS shall have a defined condition of Emergency Stop, which must be fail safe under conditions where normal control of the MASS is lost. Under Emergency Stop, propulsion is reduced to a safe level in a timely manner.	Chapter 4 Control System, Section 4.1.11 - An emergency manual control enacted through a high integrity independent system is to be provided in a prominent position on all primary and secondary Operator consoles to activate a safe state.	SECTION 5 VESSEL ENGINEERING FUNCTIONS, [4.2.6] Automatic operation (AO) –…It should be possible to manually intervene and control the propulsion/steering system from the RCC……The engineering watch in RCC should be provided with sufficient monitoring, alerts, diagnostic functions and controls to intervene in case of unexpected events and failures which are not safely handled by the automatic control functions.	5 Operating design domain...It is generally not possible to guarantee that the conditions the ship operates under, always are within the ODD limits. Exceptions can occur, e.g., in cases of major technical failures or sudden changes in weather conditions. To handle such cases, a DNT Fallback [3] must be defined and implemented. The DNT Fallback should take the ship to as safe a situation as is possible under the given circumstances ("Minimal risk condition" [3]). This will consist of different strategies, dependent on the operational condition. Normally, one can assume that the DNT Fallback will be updated from the SCC before the ship's operational context changes significantly.
Sense and Avoid System (COLREGS) (Autonomous/Remote Navigation)	4	APPENDIX 1 - High Level Goals (Autonomous Vessel) 2.4 Safety of Navigation - The vessel is to navigate based on the principles in COLREG. This includes: ● Maintaining steering capability (refer to A1/2.1 above) ● Communicating with surrounding vessels in accordance with the requirements of the current regulatory regime ● Communicating distress to surrounding vessels ● Weather monitoring and routing ● Notice to Mariners and Navigation reference ● Law of the Seas compliance	Section 7.13 COLREG- compliant behaviors and fail-safes - The Control System shall be capable of operating in accordance with the requirements of Chapter 5 and Chapter 10 to a level of compliance with COLREGS appropriate to the MASS class.	Chapter 6 Navigation Systems, 4.1.13 1.1.1 This Chapter covers the systems required for safe navigation of the UMS. This includes systems on board and off-board for the identification and avoidance of navigational hazards and the communication between these, and systems for communication with other vessels to relay intentions. It does not include control of the navigation system itself or the control of systems to carry out avoidance of navigational hazards,	Appendix D - 3.7 Navigation Decision Support system for Collision- and Grounding Avoidance – NDSS CA-GA - To cover unmanned vessels and based on input from the above navigation sensors, a total system for determining the risk of collision and grounding and aiding in execution of a safe voyage plan should be provided. This system should use and process all available information from navigational sensors and systems in a robust manner in order to avoid single failures.	4.4 Ship autonomy types - Automatic bridge. The bridge system controls the ship while crew on the bridge continuously monitors the situation and can intervene at any time. The level of automation may be arbitrarily high, but crew is always ready to intervene. Table 2 – MUNIN Main function groups and sub-groups 2.4 Anti-collision - Detect and avoid other objects in the vicinity that may be a danger to the ship. Use COLREGS where applicable. 2.5 Anti-grounding - Avoid groundings by keeping to safe channels with

Note 1: IMO degrees of Autonomy

Degree one: Ship with automated processes and decision support. Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised, but with seafarers on board ready to take control.

Degree two: Remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.

Degree three: Remotely controlled ship without seafarers on board. The ship is controlled and operated from another location.

Degree four: Fully autonomous ship. The operating system of the ship is able to make decisions and determine actions by itself.

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