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Zero-emission autonomous ferries for urban water transport

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I. INTRODUCTION

Historically, civilization has flourished either in the coastal areas or near the river basins as water is an integral part of day-to-day life for humans. Today, about 40% of the world's population lives in coastal areas and many of the biggest cities are located near the sea or riverfronts. In Norway, a major percentage of people live in coastal areas. There are many water channels such as river canals and fjords in these coastal areas. Constructing bridges in these water channels is expensive and may hinder marine traffic. Therefore, in the coastal cities, urban ferries are much more than a tourist attraction. They are an integral part of the city's multi-modal transportation system and easing road traffic and congestion.

The ferry industry transports 2.1 billion passengers per year, which is comparable to 2.3 billion passengers carried by commercial airlines across the world. To name a few big cities, ferries in London carry about 10 million passengers every year. The ferry rides in New York, Sidney, Hong Kong, and Istanbul are 3 million, 16 million, 47 million and 108 million, respectively. Moreover, as cities expand, and the population grows, the ferry ridership increases significantly. London's ridership is predicted to reach 20 million by 2035 – double the amount today. San Francisco's ferry ridership has grown 74 percent in the last five years and is predicted to increase by up to 900 percent by 2035. Urban ferry transportation systems are undergoing a revival in many of the coastal cities due to the increase in ridership, advancement in technologies, and replacement of aging fleets.

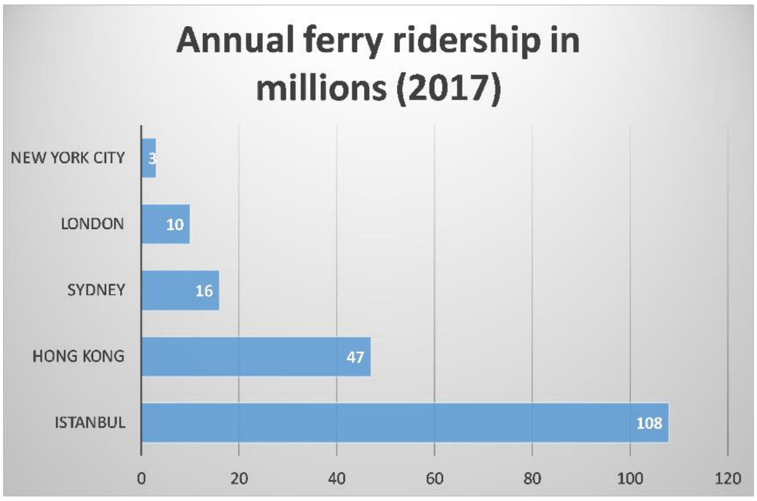


Figure 1. Annual ferry ridership in millions (2017).

The concept of zero-emission autonomous passenger ferries in urban areas is a more flexible, cost-effective, and environmentally friendly alternative than bridges or manned ferries. Autonomous ferries can also be coordinated with, for instance, autonomous buses in an urban intelligent transportation system, enabling reduced commuting time and improved quality of life for people living in cities. Zero-emission autonomous passenger ferries are a promising alternative due to the following reasons:

- Low or zero greenhouse gas emissions.
- Less or no hindrance to marine traffic.
- Economic viability, due to lower life-cycle cost compared with constructing bridges and manned ferries.
- Central supervision of several ships through a control room located onshore.

An autonomous passenger ferry that can see kayakers and boats, and that shows up right when you need it, could be an ingenious substitute for footbridges. However, there are several challenges in designing fault proof zero-emission autonomous passenger ferries. Autonomous systems are complex in nature. Different software, computer hardware, actuators, and groups of people are part of an autonomous system. All these subsystems interact with each other to some degrees and tracing all these interactions across the system is virtually impossible. During normal operation of an autonomous system, this may not be a problem. However, a single failure in one computer may lead to a cascading failure in the software system that produces an erroneous actuator output. This output itself may not be harmful, but with a user not too familiar with the system, this may lead to an accident. Anticipating such interactions beforehand and consequentially eliminating them will not be possible without a systematic, traceable, and holistic assessment process.

Therefore, safety, reliability, and security assessment of autonomous systems cannot use the traditional methods that are focusing on single failure events and with respect to security on single threat events. Security, especially cybersecurity-related considerations, will be different from conventional systems for their autonomous counterparts. Threat agents may exploit the preprogrammed behavior, and detection mechanisms may be insufficient to differentiate between a random encounter and an intentional disruption. The complexity of the system may mask hacking attempts and create vulnerabilities through insufficient and inadequate implementation of a subsystem.

More challenges can be found with respect to the moral and ethical behavior of the autonomous systems. In case of unavoidable accidents, what should be the adequate behavior? Here legislation could give answers. The international maritime organization (IMO) is still working on their code for autonomous maritime surface ships. One requirement that is soon to be universally acceptable is that autonomous ships should be as safe as manually operated ships. The challenge will be to demonstrate that this is the case since very limited experience and data are available on autonomous systems and their operation. Simulations and verification may assist in the attempt to demonstrate safety but need to be accompanied by real trials and tests in the operational environment. Furthermore, autonomous ships may also change traffic patterns, due to different navigational strategies.

The challenges outlined above are to some extent valid for several autonomous segments, such as autonomous ships, autonomous cars, underwater vehicles, and aerial systems. Although there may be differences in the operational environment, the acceptable performance, and the types of failures and accidents that may be encountered, these autonomous systems share commonalities that require new approaches to safety, reliability, and security. In fact, interdisciplinary and inter-industrial approaches are required to solve these challenges. Key enablers for successful and acceptable systems are:

- Recognition and understanding of risks associated with autonomous system operation.
- Implementation of safe solutions from early design phases.
- Monitoring and follow-up of risk levels exceeding acceptable risk levels.
- Establishment of regulations and procedures to assure safe operation.
- Communication with society to establish trust in autonomous systems.

In 2018, the Norwegian University of Science and Technology (NTNU) initiated a pilot project, namely Autoferry, as a platform for research and development platform to address these challenges, with focus on autonomous passenger ferries in urban waterways. The full-scale ferry with a capacity to carry 12 passengers with their bicycles is under construction. This is expected to be operational in the Trondheim canal by 2021. Furthermore, NTNU researchers collaborate with industry to develop autonomous technologies, and with the Norwegian Maritime Authority (NMA) to define the regulations for autonomous shipping.

The NTNU Autoferry project, with a successful demonstration of the full-scale ferry, aims to open new possibilities for both urban and coastal transport. In general, reducing the cost of ferry services using autonomous vessels will enable a revitalization of the urban water transport system and further development of coastal areas. Therefore, autonomous ferries can be transformative both technologically, societally, and in terms of new business opportunities.

This paper presents a less explored opportunity of introducing zero-emission autonomous passenger ferries in order to review urban water transport system and contemporary scenarios. Moreover, the challenges in introducing unmanned ferries in the urban water transport system are outlined. A selected list of existing projects to address the challenges related to zero-emission and autonomous shipping in Norway are presented. Furthermore, possible zero-emission energy solutions, the energy and emission management system, the importance of resilience and survivability in autonomous shipping, and a suitable architecture of the shipboard power system for autonomous shipping, are presented.

II. EXISTING AND ONGOING PROJECTS ON THE ZERO-EMISSION AND AUTONOMOUS SHIPPING

There are several projects focused on developing zero-emission energy solutions and autonomous systems for passenger ferries and, in general, for maritime transportation in the world. Norway as a maritime nation has been at the forefront in developing and adapting pioneering technologies to improve maritime transportation. There are several projects focused on developing zero-emission/autonomous technologies for maritime transportation to strengthen Norway's position as a maritime nation. A few selected projects are reviewed and summarized in this section. At NTNU, a center of excellence Autonomous Marine Operations and Systems (AMOS) started in 2013 with the aim of conducting multi-disciplinary research to create a world-leading research center for autonomous marine operations and control systems. NTNU AMOS contributes to fundamental and interdisciplinary knowledge in marine hydrodynamics, ocean structures, and control theory. The research results are being used to develop intelligent ships and marine structures, autonomous unmanned vehicles (underwater, on the surface, and in the air), and robots for high precision and safety-critical operations in extreme environments.

In 2016, the Trondheim fjord area was designated as the world's first testbed for autonomous vessels by the Norwegian maritime authority in consultation with industry and research organizations. This will boost the research and development in this area and improve the likeliness to make autonomous shipping competitive with road transport for passengers and goods.

Autonomous Ship Transport at Trondheim fjord area (ASTAT) is a project initiated by a consortium of partners including Trøndelag government. This aims to examine possibilities for operating small zero-emission autonomous ship in the fjord at distances ranging from 80 to 90 kilometers. The main objective is to design both bulk and break-bulk shipping-based transport that will be competitive with road-based truck transport. The three selected case studies for this project as shown in Figure 2 are: 1) Transport of containers and breakbulk between Jøsnøya terminal for coastal ships and Trondheim or Orkanger. This will link coastal routes to transport systems in the Trondheim fjord. 2) Lumber from Orkanger to Follafoss or Skogn. The goal is to replace older manned ships and trucks for large volumes of cargo. 3) Gravel from Verrabotn to Trondheim for tarmac production. This will also replace trucks and older ships.

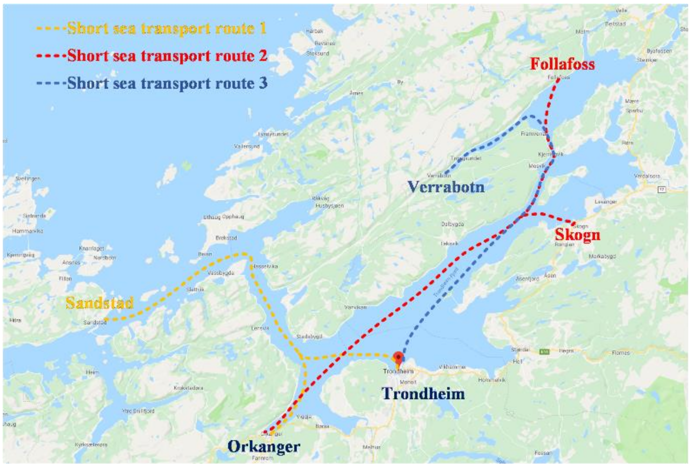
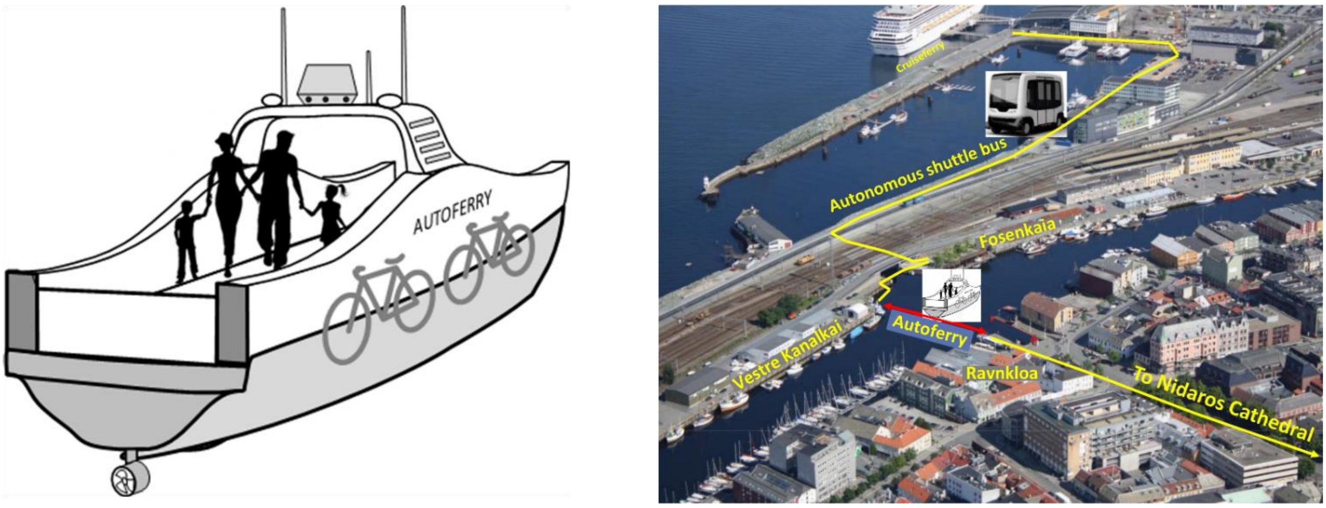


Figure 2. The designated short sea transport routes in Trondheim's fjord area for testing of autonomous ships.

NTNU Autoferry is a pilot project aiming to develop, design, and build a full-scale zero-emission autonomous passenger ferry that is available as a safe and easy urban transport in Trondheim. The main goal of this pilot project is to demonstrate autonomous technologies for passenger ships through a ferry operating in the Trondheim canal. Figure 3 (a) shows the concept design of Autoferry. Figure 3 (b) shows the route map intended for the fully autonomous operation of the full-scale ferry.



(a) (b)

Figure 3. Autoferrey pilot project (a) concept design of the autonomous ferry (b) The intended route of autonomous operation in Trondheim canal.

Yara Birkeland will be the world's first zero-emission autonomous container ship, named after its owners Yara International and its founder, Norwegian scientist Kristian Birkeland. It is designed by Marin Teknikk AS, with navigation equipment from Kongsberg Maritime. It will enter service in 2019 with a small crew on board for trials. Thereafter, it is expected to operate autonomously by 2020. The design prototype of Yara Birkeland is shown in Figure 4 (a). The intended route for fully autonomous operation is shown in Figure 4 (b). With this new autonomous battery-driven container vessel, Yara will replace 40000 journeys of diesel-powered truck haulage from the road to the sea. Thereby, it will reduce noise and particle emissions and improve the safety of roads.

(a) (b)

Figure 4. (a) Design prototype of Yara Birkeland (Courtesy: Gemini.no), (b) the intended route for fully autonomous ferry.

DNV GL ReVolt is a futuristic concept for short sea shipping that aims to build the zero-emission unmanned vessel. The full-scale ReVolt is a 60-meter container vessel with a capacity of 100 TEU and a sailing range of 100 nautical miles on battery power. DNV GL, in collaboration with NTNU, built a 3-meter long ReVolt model ship to test autonomous technologies such as sensor fusion and collision avoidance for autonomous surface vehicles.

Safer Vessel with Autonomous Navigation (SVAN) is a demonstration of the world's first fully autonomous ferry by Rolls-Royce Commercial Marine (now Kongsberg Maritime in Norway) and Finnish state-owned ferry operator Finferries in the city of Turku, Finland. The Falco vessel is equipped with a range of advanced sensors for situational awareness to conduct collision avoidance through sensor fusion during its voyage between Parainen and Nauvo. The vessel also demonstrated automatic berthing with an autonomous navigation system. The situational awareness picture is relayed to a remote-control room onshore, where a captain monitors the autonomous operations and can take control of the vessel if needed.

The Suomenlinna II is a passenger ship in Helsinki city transport. ABB tested a marine pilot control system on the Suomenlinna II to improve the acceptance of autonomous operation systems in the maritime industry. The ice-class passenger ferry Suomenlinna II was remotely piloted through test area near Helsinki harbor, proving that human oversight of vessels from anywhere is achievable with today's technologies.

The Urban Water Shuttle (TUWS) aims to develop a zero-emission fast going vessel that will result in reduced urban congestion, reduced emissions and reduced city infrastructure costs. This could be realized in cities with coastline located close to water and waterways. The concept is therefore relevant for most of the cities in the world. This project has been developed by a joint industrial partnership from the business cluster NCE MaritimeCleanTech. The partners are Wärtsilä, Fjellstrand, Servogear, Grenland Energy, CFD Marine, Sapa, and Norsk Hydro.

Transport: Advanced and Modular (TrAM) is a project funded through the EU's Horizon 2020 research program. The project's main objective is to develop and validate a concept for waterborne modular design and construction with a focus on zero-emission vessels in protected waters, coastal areas, and inland waterways. The project will result in a new fully electric high-speed vessel with zero emissions that will operate between Stavanger and Hommersåk on the west coast of Norway. In addition, new manufacturing methods will contribute to lower production and engineering costs. The vessel will be built by the Norwegian shipyard Fjellstrand.

The Zero-emission Fast Ferry (ZeFF) project is initiated by five cluster partners in Norwegian Center of Excellence Maritime CleanTech and was awarded 10.5 million NOK through the PILOT-E scheme. All partners are members of the NCE Maritime CleanTech cluster; Norled, Selfa Arctic, LMG Marin, Hyon, and Servogear. This project aims to develop zero-emission fast ferries; a battery version for shorter routes, and a hydrogen version for longer routes. Today, fast ferries represent one percent of the oil consumption in Norway, which amounts to 86 million liters of fuel oil per year. The goal of ZeFF is to eliminate these emissions over a period of the next ten years.

MF Ampere is the world's first battery ferry with conventional propulsion, owned by Norled AS and built by Fjellstrand shipyard. The battery-powered MF Ampere commutes daily on a route between Lavik and Oppedal in the Sognefjord.

MF Folgefonn is the first commercial ferry in the world operating with automatic high-power wireless induction charging capability for its batteries. Wärtsila in Norway has developed the automatic wireless induction charging system. MF Folgefonn commutes daily between the islands of Stord, Tysnes, and Huglo in the Hordaland area of Norway.

Stranda municipality in Norway has evaluated the concept of a hydrogen-powered passenger ferry in Geiranger to eliminate emissions in the world heritage fjord. Furthermore, it has proposed Hellesylt Hydrogen Hub to produce hydrogen through local surplus hydropower. Similarly, Sogn og Fjordane district municipality in Norway is supporting the development of hydrogen-powered speedboat. The Norwegian Public Roads Administration awarded a development contract for a hydrogen-powered ferry aimed at long-distance ferry routes, where a battery-powered ferry is not viable. Table 1 summarizes the selected projects presented in this section.

Table 1. Selected projects to develop technologies for zero-emission and autonomous shipping in Norway.

Project	**Goals**
ASTAT (Autonomous Ship Transport at Trondheim's fjord area, 2017-2019)	•Design zero-emission autonomous ship for both bulk and breakbulk transport. •Make shipping competitive with road-based truck transport.
NTNU Autoferry (Autonomous all-electric passenger ferries for urban water transport, 2018-2022)	•On-demand ferry – that is as easy and safe as the elevator. •Zero-emission all-electric propulsion with automatic charging of batteries. •An integrated autonomous system that includes automatic docking. •Safe and reliable anti-collision system.
Yara Birkeland (2017-present)	•The world's first zero-emission all-electric and autonomous container ship. •Move transport from road to sea and thereby reduce noise, emissions and improve the safety of local roads.
ReVolt (DNV GL concept of the unmanned zero-emission ship, 2013 - Present)	•Unmanned zero-emission ship concept for short sea shipping. •Vision to shift congestion from roads to sea by making shipping competitive with road transport.
SVAN (Safer Vessel with Autonomous Navigation, 2018)	•The world's first fully autonomous ferry. •Improving the safety and reliability of autonomous vessel operations.
TUWS (The Urban Water Shuttle, 2017-Present)	•Reduce urban congestion and infrastructure cost.

	•Zero-emission all-electric propulsion system. •Prototype vessel with the length of 25-30 meters, for 180 passengers and an operating speed of 20 knots.
TrAM (Transport: Advanced and Modular, 2018-2022)	•Develop and validate a concept for modular design and production of zero-emission all-electric fast going vessels. • Focus on coastal areas and inland waterways.
ZeFF (Zero emission Fast Ferry, 2019-2021)	Develop a ferry that will: •Operate without CO_2, NOx, SOx and particulate matter emissions. •Have cruise speed between 25 and 45 knots. •Have significantly less energy consumption than current vessels per passenger-km. •Modular for 100 to 300 passengers. •Battery-powered for short-range and hydrogen-powered for long-range.

III. ZERO-EMISSION ENERGY SOLUTIONS FOR AUTONOMOUS SHIPPING

Zero-emission autonomous ships with an all-electric power and propulsion system have generated considerable research and development interest in recent years. The all-electric power and propulsion system in zero-emission autonomous ships is powered by batteries alone or fuel cells as the main energy source in combination with batteries to compensate for the slow dynamics of fuel cells. Fuel cells and batteries have a noise-free operation and reduced requirement for maintenance due to the absence of rotating equipment. Fuel cells and batteries are inherently modular that makes them suitable for improving resilience, redundancy, and easy maintenance, and replacement which are considered very important for autonomous shipping. Fuel cells are being considered for maritime transport applications due to several advantages such as the high efficiency for most of the power range, quiet operation, fuel flexibility, and suitability for air-independent propulsion systems. Moreover, hydrogen has high gravimetric energy density and can be produced from micro- to mega-scale by using renewable energy sources for achieving truly zero emissions. Batteries are preferred over other energy storages devices for transport application due to high energy density and wide power range.

Passenger ships including ferries, cruise ships, and liners must comply with stringent emission regulations as they operate in either Emission Controlled Areas (ECAs) designated by IMO or in urban areas. Therefore, all-electric power and propulsion systems powered by batteries alone or together with fuel cells is the most suitable alternative as it offers emission-free operation. Different solutions to reduce or eliminate emissions are presented in the following subsections.

A. Conventional diesel engine with exhaust gas cleaning system (EGCS) or scrubbers

The diesel engine is the most commonly used power source in about 95% of the ships today due to several advantages: reliability, wide power range, high efficiency, and low energy consumption. The main disadvantage of using diesel engines in autonomous ships is the need for frequent maintenance due to rotating parts in addition to the significant amount of greenhouse gas and particle emissions. Operators of diesel engine-based ships have three main alternatives to reduce emissions. They can modify ships to use liquefied natural gas (LNG) as fuel; they can continue to use high sulfur fuel oil (HSFO) and process air emissions through an exhaust gas cleaning system (EGCS); or they can switch from HSFO to a lower-sulfur fuel, such as marine gas oil (MGO) or low-sulfur fuel oil (LSFO). Each option has its costs and benefits, depending on market conditions and regulatory uncertainty that are inherently difficult to foretell. Moreover, they do not result in zero emissions; merely reducing emissions in urban areas is not enough. Furthermore, with diesel engines, unmanned operation of ships is not possible as the crew is required onboard for maintenance. Therefore, the shipping industry and new ship buyers are looking towards alternative zero-emission energy sources such as batteries and fuel cells that can reduce the requirement of maintenance and enable zero-emission operation.

B. Batteries

Batteries are the most common energy storage in all-electric and hybrid ships. Batteries give significant reductions in fuel cost, maintenance costs, emissions, as well as improved ship responsiveness, regularity, operational performance, and safety in critical situations. Battery cells are categorized into four types for maritime applications.

Lithium cobalt oxide, LiCoO2 (LCO) has many advantages: relatively high gravimetric energy density and volumetric energy density, low self-discharge, high discharge voltage, and good cycling performance. The main limitations for this type are high price, low thermal stability, and fast capacity reduction at high current rates or during deep cycling. LCO batteries are mostly used in consumer electronics where 80% of the capacity utilization is sufficient. Lithium manganese oxide, LiMn2O4 (LMO) has many advantages such as low price, better power capability, and high thermal stability. However, it has lower energy density compared to LCO, and it has short cycle life at high temperatures. Nickel manganese cobalt oxide, LiNi1-x-yMnxCoyO2 (NMC) has higher gravimetric energy density and an operating voltage similar to LCO, while the cost is reduced. It has a high specific capacity similar to nickel. Manganese is doped to improve thermal stability. The composition of nickel, cobalt, and manganese can be changed to obtain a different range of properties such as power and energy density, cost, and thermal stability. Lithium iron phosphate, LiFePO4 (LFP) is known for high thermal stability and high-power capability. The main disadvantage of LFP is low average potential and low electrical and ionic conductivity. These limit the energy density, which is the major limitation for LFP. Table 2 shows a comparison of different type of lithium-ion batteries.

Table 2. Comparison of different types of lithium-ion batteries.

Lithium-ion battery types	LCO	LMO	NMC	LFP
Energy density (Wh/Kg)	195	150	205	130
Energy density (Wh/L)	560	420	580	333
Cycle life	500 – 1000	300 – 700	1000 – 2000	1000 – 2000
Thermal runaway (℃)	150	250	210	270
Safety	Low	Moderate	Moderate	High
Performance	Moderate	Low	Moderate	Moderate

C. *Fuel cells*

In the existing literature, different fuel cell technologies have been evaluated and compared for maritime applications. The most promising fuel cell technologies for maritime applications are proton exchange membrane fuel cell (PEMFC), high-temperature PEMFC (HT-PEMFC), and solid oxide fuel cell (SOFC).

PEM fuel cells are promising energy sources for zero-emission transportation due to low operating temperature, high power density, and modularity (or scalability). The main disadvantage of PEMFC is the requirement of platinum to catalyze the electrochemical reaction at low operating temperature, which increases the price of the fuel cell. Another disadvantage of the low operating temperature is intolerance towards fuel impurities. At present, this is the most used fuel cell, mainly in vehicular applications. High-temperature PEM fuel cells have the advantage of high operating temperature. At a high operating temperature, cheaper catalysts can replace platinum. Moreover, the tolerance for fuel impurities increases significantly. The main problems for this fuel cell are the high price, low lifetime and low power density. They are mainly suitable for high power applications. SOFCs have operating temperatures of 800°C to 1000°C. Though these fuel cells are promising, being in the development stage, mechanical vulnerabilities and high cost hinder the commercialization. The main application of SOFC is stationary power generation. Table 3 shows a comparison of different type of fuel cells.

Table 3. Comparison of different types of fuel cells.

Fuel cell types	PEMFC	HT-PEMFC	SOFC
Power range	0.12 – 5 kW	5 – 250 kW	1 kW – 2000 kW
Operating temperature (℃)	60 – 130	140 – 200	600 – 1000
Efficiency	40 %	40 %	60 %

Cost	Decreasing	High	High
Tolerance to fuel impurities	Low	High	High
Startup time	< 1 minute	< 1 minute	60 minutes
Applications	Transportation	High power applications	Large power generation
Advantages	• Low temperature • Quick startup	• Cheaper catalyst • Quick startup	• High efficiency • Fuel flexibility
Challenges	• Expensive catalyst	• High temperature • Low lifetime	• High temperature • Long startup

Today's zero-emission energy solutions can meet the propulsion power and energy requirements of a wide range of vessels, from small passenger ferries and fishing boats to the large cargo ships in the world. The choice and suitability of zero-emission energy solutions depend on the size of the ship and energy requirements of the mission. For a high-power propulsion system that does not require large energy storage, the size of fuel cell dominates over the size of batteries since the size of fuel cell increases significantly with the increase in power level. Therefore, for small vessels that require high power for short durations, batteries alone are sufficient to meet the power and energy requirements. However, the batteries quickly become much larger compared to fuel cell systems as the required energy storage increases for longer duration missions. This is because the energy density of batteries is less than 1/10 that of liquid hydrogen at the same power level. Therefore, hybrid power and propulsion systems powered by fuel cells as the main energy source combined with batteries are suitable for long endurance missions that require large energy storage. For fuel cell systems, only the size of the fuel tank increases for longer-range missions while the fuel cell itself remains the same for the required power. The available volume onboard of the ship is the main constraint in choosing the type of energy solution, while the mass of the powertrain is not that important as a limiting factor. Considering the extra mass of the hydrogen tank, the overall mass of powertrain powered by fuel cells shall be significantly lighter than the one powered by a marine diesel engine, since the specific energy of hydrogen is about three times that of the maritime liquid fossil fuels. This lower mass may reduce the power requirement, and it can give increased cargo capacity if the fuel cell system takes less volume.

Recently, there has been significant interest in zero-emission ships including battery-powered and hybrid ships. In the past few years, several zero-emission ships of different types have been launched around the world powered by batteries alone. For example, in Norway, the passenger ferry MF Ampere powered by 1090 kWh batteries can sail 5.5 kilometers between Oppedal and Lavik. It has the capacity to carry 350 passengers and 120 cars. Moreover, the autonomous container ship Yara Birkeland (under construction) will be powered by 7 MWh batteries and will have a cargo capacity of 120 TEU and a deadweight tonnage of 3200 metric tons. A study of Norwegian ferry fleet has concluded that it is economically feasible to convert 84 out of 180 ferries to battery-powered propulsion, and 43 to hybrid propulsion.

IV. ENERGY AND EMISSION MANAGEMENT SYSTEM FOR AUTONOMOUS SHIPS

The energy and emission management system (EEMS) is defined as a high-level control system that commands the operation of a hybrid power plant to minimize energy usage and emissions with required safety and resilience while satisfying vessel mission objectives. Hence, it optimizes the performance of the hybrid power and propulsion system by distributing the load power required among multiple energy sources in such a way that each source is optimally used, and overall emissions are minimized. The EEMS controls the dynamic behavior of the hybrid power system that affects the size (weight and volume), lifetime of the components, fuel consumption, efficiency, and emissions. Therefore, the selection and development of suitable EEMS based on the objective function and requirements of hybrid propulsion system are very important. The main objectives of EEMS include minimizing the fuel consumption, minimizing the power losses in system components, improving the lifetime of components and minimizing emissions as shown in Figure 5.

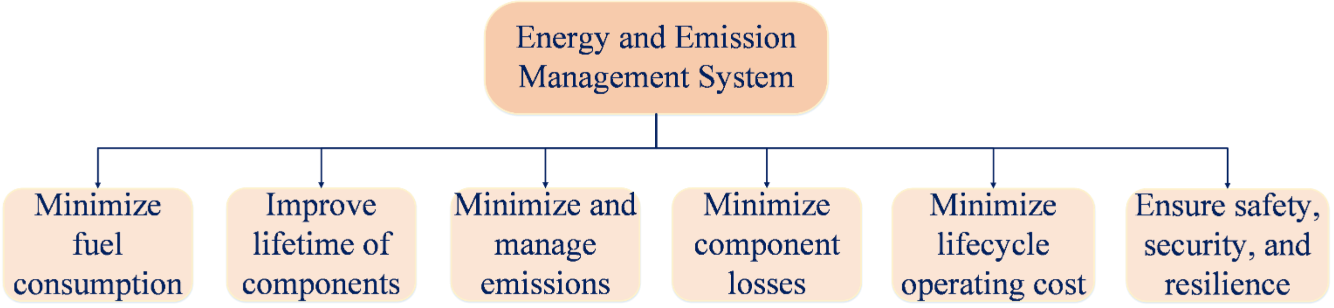


Figure 5. Objectives for energy and emission management system.

Most of the existing research works consider one or some of the objectives mentioned above. However, all the objectives must be considered simultaneously for a real autonomous ship. The energy and emission management strategies, in general, can be classified into three categories as shown in Figure 6: 1) rule-based, 2) optimization-based, and 3) learning-based. The rule-based strategies are classified into two types: a) deterministic, and b) stochastic. The deterministic rule-based strategies operate on a set of predefined instructions, where the power plant is modeled according to physical laws, and uncertain parameters are assumed to belong to certain bounded sets. Deterministic control algorithms are then designed to give stable closed-loop behavior of the plant as well as robustness to parameter variations within the bounded sets. Stochastic rule-based methods, on the other hand, assume that states and parameters are random variables with corresponding probability density functions. Stochastic algorithms are then typically implemented in the form of stochastic filters and state estimators (e.g., Kalman filter, particle filter, etc.) and stochastic control algorithms that provide stability and robustness (and often optimality) on the given probability density functions.

Optimization-based strategies are typically implemented in the form of iterative numerical optimization, such as genetic algorithms or dynamic programming. Optimization-based strategies are mainly classified into two types: a) offline optimization, or b) online optimization. Offline optimization relies on the knowledge of predicted sailing profiles. It is very difficult to predict the real sailing profile due to several stochastic parameters in waterways such as unpredictable weather conditions, factors related to marine biology, and random ocean currents. However, offline optimization is important for the optimal design of a power plant configuration, given a set of likely operation load profiles combined with performance and safety requirements of the hybrid power plant. But for optimal operation of the hybrid power plant in the voyage, online optimization methods are used, where a global cost functional is replaced by an instantaneous cost function. Several numerical optimization methods for EEMS can then be implemented, including linear, quadratic, or nonlinear programming, equivalent cost minimization strategy (ECMS), Potryagin's minimum principle (PMP), and model predictive control (MPC).

Rule- and optimization-based strategies are based on either predefined rules or predicted sailing conditions. These methods are not necessarily adaptive to random system conditions and, thus, may give nonoptimal solutions. Therefore, researchers have gained interest in learning-based strategies, which can be classified into three types: a) supervised learning, b) unsupervised learning, and c) reinforcement learning. Supervised learning is learning from a training set of labeled examples provided by a knowledgeable external supervisor. Unsupervised learning is finding the hidden structure in collections of unlabelled data. These are very good learning methods, but alone they are not adequate for learning from the environment through interactions in real-time. Reinforcement learning is a goal-directed method where an agent learns in real-time by interacting with the uncertain environment.

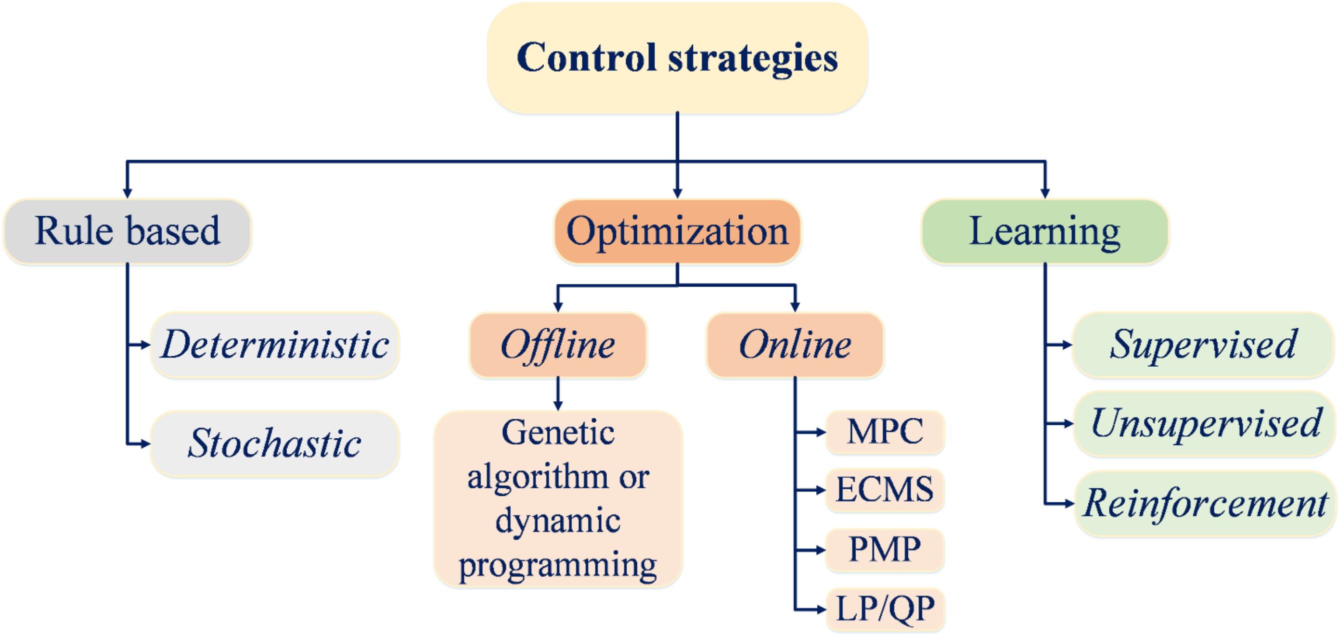


Figure 6. Classification of control strategies.

Figure 7 shows an example of control system abstraction for autonomous ship and its power system. The control layers are classified into three categories: a) mission layer, b) online optimization layer, c) real-time control execution layer. On the top level, there is vessel mission management system, which acts as a mission layer that keeps track of the vessel mission and objectives and commands the lower-level systems accordingly. EEMS acts as an online optimization layer of the hybrid power and propulsion system. The power management system (PMS) is at the next level. It ensures that the load power requirement is met at all the times and provides references to the main power sources and energy storage devices, and it avoids blackout in case of any fault that might happen. Furthermore, there is a battery management system (BMS), which works in parallel with the PMS. The inappropriate operation of batteries, such as over-current, over-voltage, and over-charging/discharging, accelerate the aging process and can result in an unsafe environment including fire and explosion. Therefore, the BMS is necessary to ensure safe and reliable operation of batteries. The real-time control execution is at the lowest level, where the power sources and energy storage devices are controlled individually according to the references provided by the PMS and BMS.

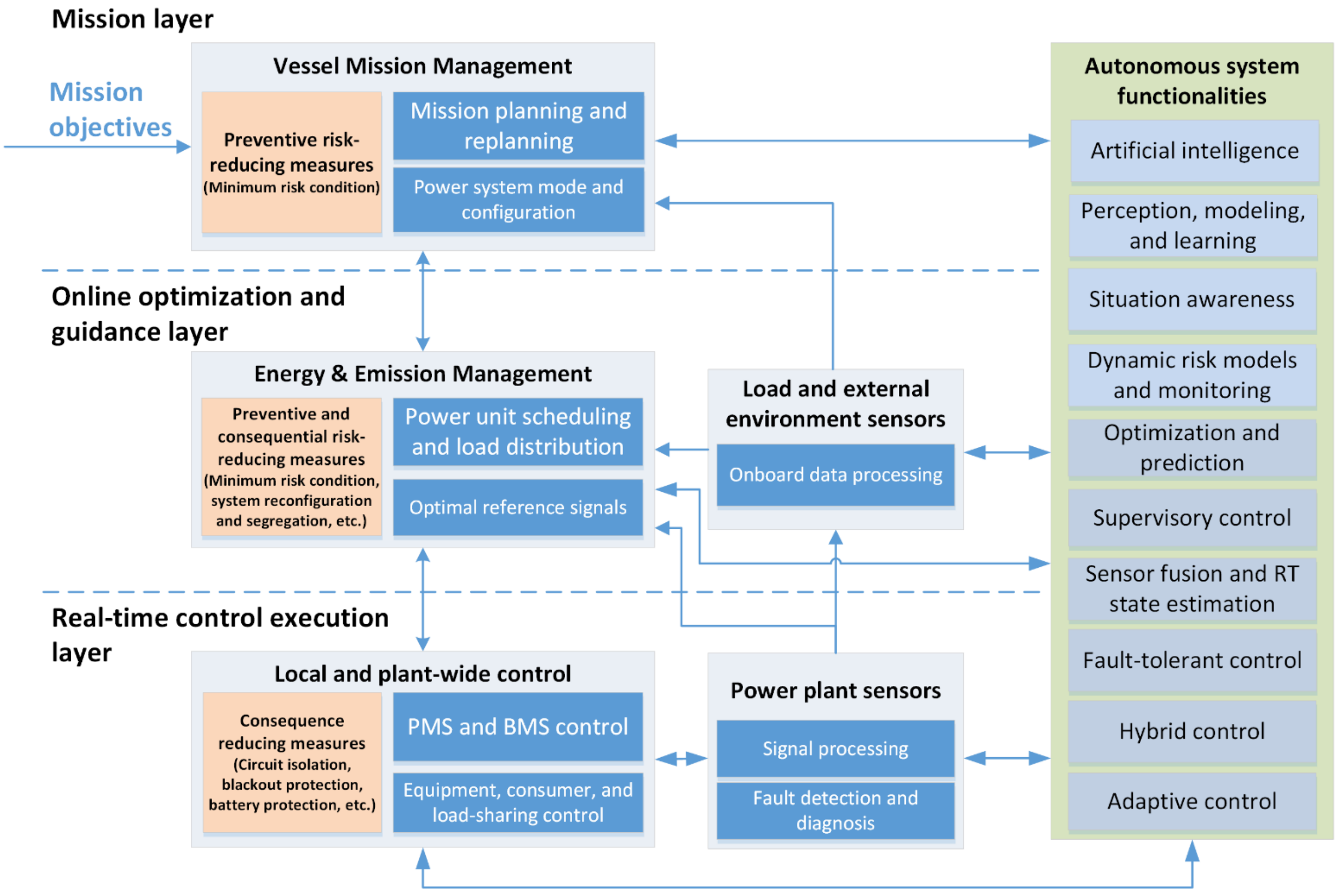


Figure 7. Example of control system abstraction for autonomous ship and its power system.

Figure 8 shows the control and communication architecture for an autonomous ship. The autonomous control system as presented above is implemented in onboard computers. These computers can communicate with a remote control center located onshore through some alternate options such as satellite communication and radio communication. Satellite communication is suitable for ships with long sailing range. Radio communication is sufficient for ships with short sailing range, for example, passenger ships in urban areas. Furthermore, cloud storage and computing technologies can be used for data management and computational purpose. However, this may arise in additional cybersecurity issues.

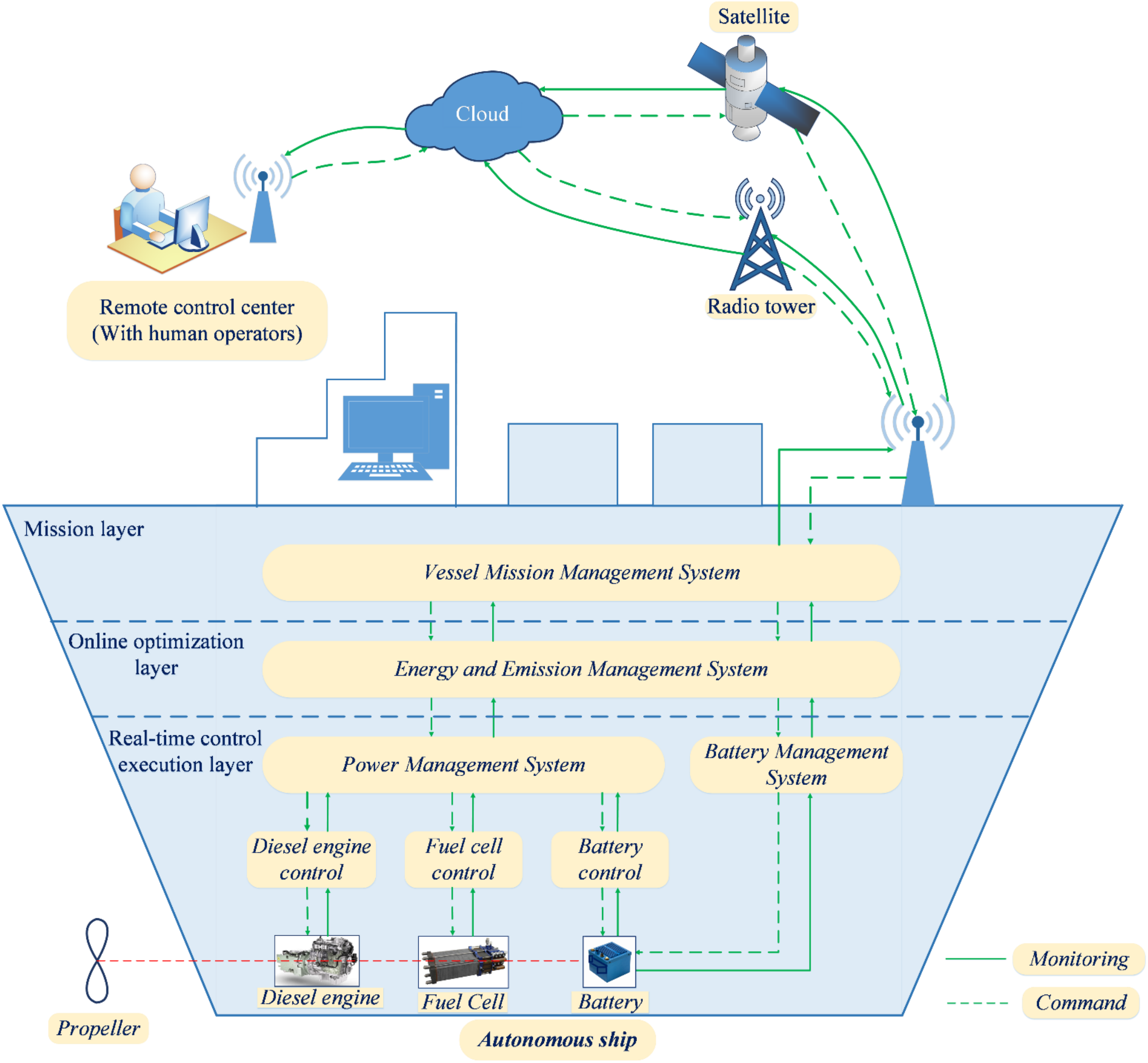


Figure 8. Control and communication architecture for the autonomous ship.

Figure 9 shows different operation modes for autonomous ships. Autonomous ships can be operated in several modes such as semi-automatic operation with crew on board, semi-automatic operation from a remote control center located onshore, semi-autonomous operation, and fully autonomous operation. Here, automatic operation mainly refers to having real-time feedback control systems that typically are commanded by human operators, whereas in autonomous operation the commands are also produced by intelligent algorithms in computers. Semi or fully autonomous operation can be conducted with or without crew on board, where the onboard crew has typically other tasks (e.g. passenger comfort) or more supervisory tasks.

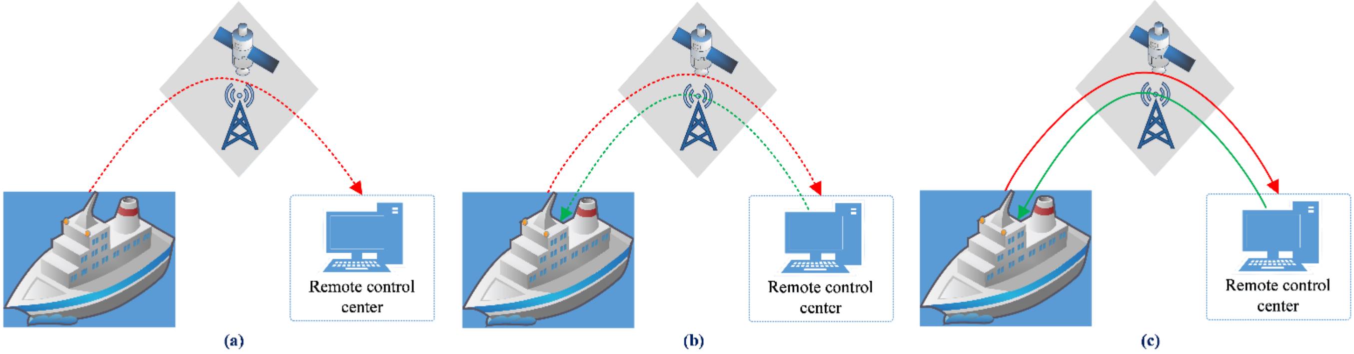


Figure 9. Autonomous ship operation modes (a) fully autonomous operation, (b) semi-autonomous operation, (c) Remote controlled operation.

In most of the shipboard power systems, hierarchical control is used since different levels of the control system are decoupled from each other. However, in hierarchical control, though the low-level real-time control of components is handled by independent local controllers, the system wide real-time control and online optimization rely on the coordination of many local controllers. Based on the coordination among local controllers, the hierarchical control can be classified into three categories as shown in Figure 10, described as follows:

- Centralized coordination control: This is implemented through a central controller and a communication network, as shown in Figure 10 (a). Though centralized control enables system-level optimization, the main drawback is that the whole system fails if the centralized control fails. Furthermore, the ships during autonomous operation are vulnerable to malicious cyber-attacks with centralized coordination. Therefore, this is not very suitable for fully autonomous operation of ships.
- Decentralized control: This is achieved through independent local controllers without any coordination among them as shown in Figure 10 (b). The main advantage of decentralized control is that it offers independence from the communication link and central controller, allowing the continuity of system operation during single-point failure. The main drawback of decentralized control is the limitation on system-level performance since system-level optimization is not possible due to lack of system-level integration/information.
- Distributed coordination control: This combines the advantages of centralized coordination control and decentralized control. In distributed coordination control, the central controller does not exist, but local controllers communicate in order to do system-level optimization as well as maintaining system operation during sing point failures, thereby avoiding system-level failure.

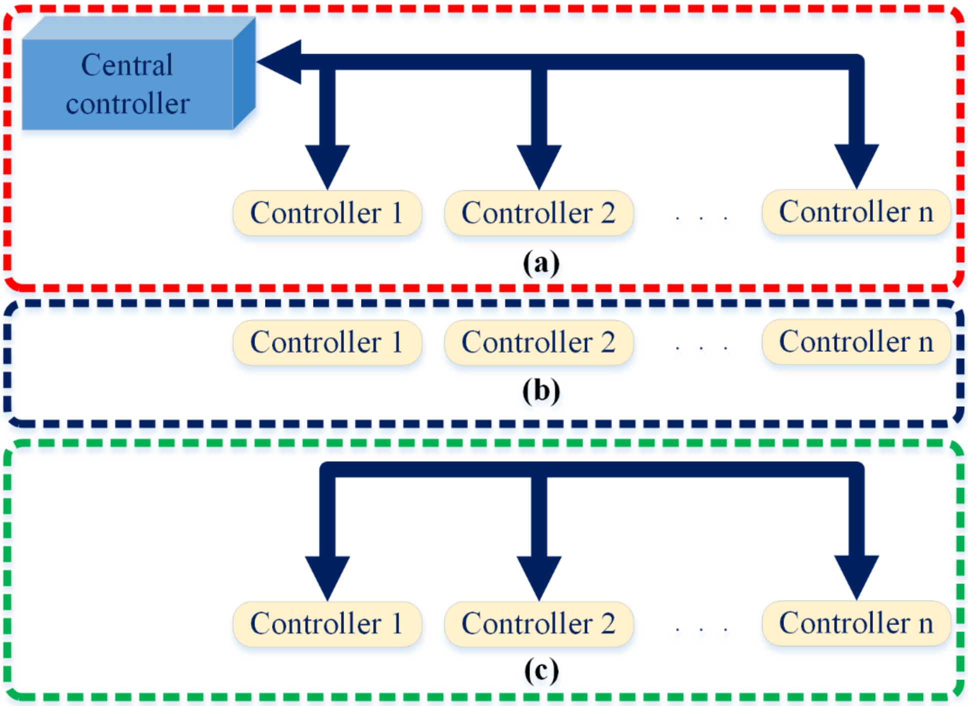


Figure 10. (a) Centralized coordination control, (b) Decentralized control, (c) Distributed coordination control.

Fully autonomous operation of the ships, without crew on board, could enable significantly reduced space, weight, and human safety requirements. However, this will bring in some challenges; the main challenge is to design the whole ship systems to operate with fault-tolerant capabilities. Therefore, resilience and survivability are the most important factors to be considered during the design and operation of the shipboard hybrid power system. For example, the zonal electrical distribution system (ZEDS) architecture could be used as shown in Figure 11 to maximize the resilience and survivability. Here, the shipboard hybrid power system can be divided into several zones that are interconnected with each other through a physical electrical connection to exchange the power and communication interface to exchange the information. Each individual zone is a mini-grid with main energy sources, energy storage, loads, and its own zonal operator (local controller). The main energy sources could be a fuel cell to achieve zero-emission operation or a small diesel engine. In ZEDS, several small diesel engines can be used instead of few big diesel engines used in most of the traditional manned ships today. In this case, a fault in one diesel engine will not have a significant effect on the ship power system except for the reduced redundancy. Hence, blackouts can be avoided, which is essential for fully autonomous operation of ships. Moreover, each small diesel engine can have an integrated battery pack for operating at maximum efficiency with load smoothing. This will not only result in increased resilience but also that all the small diesel engines can be run at optimal efficiency. Moreover, a failed diesel engine generator set (or another power unit) may then also be quickly ejected and replaced at the harbor before a new voyage is conducted. However, studies of life-cycle cost and emissions are necessary in order to investigate the economic viability and environmental friendliness of replacing a few big diesel engines with several small diesel engines. Each zonal operator or local controller can be regarded as an intelligent agent that controls its zone and coordinate with other zones. Combined, these agents form a multi-agent system.

The communication interface enables the system-level integration through communication among all zones and collects the system-level information required for optimization during normal operation. Furthermore, during fault situations, the system will be sectionalized for the isolation of fault through minimum isolation area, thereby avoiding system failure. There are several advantages of using ZEDS configuration including improved resilience. Some of them are:

- Distributed coordinated control can be implemented as a multi-agent system that combines the advantages of centralized coordinated control and decentralized control.
- Self-healing is the most important requirement for autonomous ships without crew onboard. In ZEDS configuration, self-healing can be achieved by isolating the faults through sectionalisation. When a fault occurs, the shipboard power system is sectionalized to achieve isolation of fault and when the fault is cleared, the shipboard power system is reconstructed. The sectionalizing aims to minimize the isolated area while at the same time maintaining the power supply to healthy zones.
- Improved resilience and survivability.
- Modular design and scalability.
- Enabling easier and quicker maintenance.

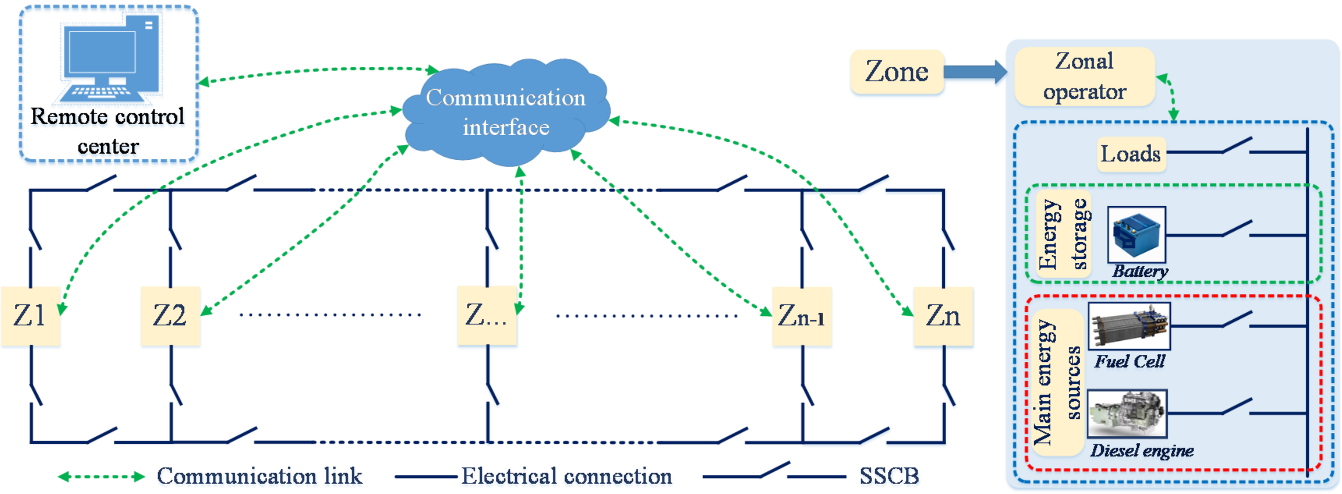


Figure 11. The layout of ZEDS for the shipboard hybrid power system.

However, there are several challenges that need to be addressed before the successful implementation of a ZEDS configuration. The main challenge is that it requires a communication interface for the coordination of the local controllers, where communication time delays and measurement errors may further hamper the performance of the system-level optimization software during normal operation and the protection system during faulty situations. Furthermore, in the case of shipboard DC power systems, protection is a challenging task since it requires precise coordination between the solid-state circuit breakers (SSCBs) and the protective functions. Therefore, it is a protection system challenge to achieve fast and efficient reconfiguration during faulty situations and reconstruction when the faults are cleared. In recent years, a significant research effort has been made to develop the SSCBs using advanced wideband gap semiconductor materials such as silicon carbide and gallium nitride, new power electronic converter topologies, and advanced control techniques. Moreover, measurement errors can be overcome by using outliner data detection and reconstruction algorithms.

V. CONCLUSION

In urban areas, congestion and pollution are growing exponentially due to the increase in population and economic activity. A major percentage of the world’s population lives in urban areas, that are located near the sea or riverfronts, where many water channels such as canals and fjords exist. Reviving the urban water transport system and making it an integral part of the city’s multi-modal transportation system can take away congestion from roads in these urban areas. The autonomous operation of passenger ferries seems to be a promising solution, with the advancement in technologies that will enable increased levels of autonomy and emission-free energy systems. Thus, zero-emission autonomous passenger ferries could solve the problem of congestion and pollution in the urban areas while reviving the water transportation system. Besides the environmental advantages, the autonomous ships offer other benefits to the shipping industry – reduction of the operational costs by up to 30% by reducing crew, increase in safety and reliability especially during nighttime and bad weather, where visibility is poor, optimal usage of fuel and urban water transport network. However, there are several challenges that must be addressed to sustainable transportation solutions by autonomous ferries. Some of the challenges include ensuring ease of access for passengers, situational awareness, sensor fusion, interaction with manned ferries for collision avoidance, and optimal operation of emission- and maintenance-free energy systems. The advanced control strategies for energy management can be used to achieve the optimal operation of shipboard power and propulsion system for the real-time sailing profile.

Norway has been at the forefront of developing and adopting technologies that will ensure sustainable and intelligent maritime transportation. Several research projects and community initiatives have been presented in this paper. Some of these projects and activities are focused on developing either autonomy or emission-free energy systems. However, the time has come to combine these in an autonomous passenger ferry. NTNU Autoferry is established as a pilot project aimed at expanding the research and development in the field and building a zero-emission and autonomous passenger ferry designed for urban transport, which will operate in Trondheim canal. This has the potential to create new markets while addressing several pressing challenges of society. The global commercial freight market alone is worth 208 billion dollars per year. Therefore, the maritime transportation sector with major crew costs presents an unexplored market for autonomous shipping technologies.

VI. FURTHER READING

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