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Is Full-autonomy the Way to Go Towards Maximizing the Ocean Potentials?

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ABSTRACT: Growth prospects for ocean economy are promising because ocean industries are addressing challenges such as food security, energy security and climate change. However, safety and efficiency are the general challenges of ocean operations. Increased automation is believed to solve these problems. This paper discusses the impact of automation on safety and efficiency. A literature review of 'Human factors' mainly from the aviation and maritime industries is presented to untangle the human-machine relationship characteristics when increased automation is introduced to operators. A literature review of Hydrodynamics, Guidance, Navigation and Control (GNC) technologies is presented to introduce the state-of-art and associated limitations. It is concluded that, if the industry's drive is safety and efficiency, then full-autonomy is, at present, not the way to go. Remote control, instead, could facilitate a feasible future, while focused research and development are in need.

1 INTRODUCTION

1.1 *Motivation*

Oceans are resourceful. Ocean operations are vastly increasing the last decades, and so is the interest in unmanned surface vehicles (USV) and autonomous ships. The ocean's extreme weather and far distances can result in high-risk-high-cost work conditions.

The world's economy is mainly defined by three areas: energy, transportation and communication (Rifkin, 2012). Ocean industries push the boundaries of these three areas to the limits. Unmanning of maritime assets by excessive automation and remote control could reduce or eliminate the risk imposed on crew; however, infrastructure cost will increase. A huge safety potential is accompanied with more benefits; by removing crew from the assets, crew related costs are, in theory, removed, costs such as cooling, heating and ventilation. Accommodation spaces are, in theory, no longer required, less power consumption is projected and the chain of promises goes on.

The drivers for unmanning maritime assets are developing into motivations for building and operating autonomous vessels. One example is, Yara Birkeland, a 120 TEU open-top zero emissions autonomous containership, planned launch is expected before 2020, the ship is under construction with Kongsberg technology. Another example is the car ferry Falco that was built using Rolls-Royce technology, launched late 2018.

As operators are moved from the far end of the operation to shore control centers, their experiences are changed, their feelings and senses while on duty from one hand, their toolboxes and control authority on the distant ship from the other hand. The current remote-control technologies and their limitations are subject to discussion. In this paper, the challenges of unmanning maritime assets and the transfer towards full-autonomy will be discussed.

1.2 *Introduction*

This literature review is part of a PhD study with the objective of "evaluation of technology using simulators". Main research area is safety and efficiency of semi-autonomous vessels and the research scope includes Hydrodynamics; simulation and testing; and semi-autonomous maneuvering in close proximity to structures. The simulator facilities at NTNU include a variety of simulators used for teaching and research. The use of simulators enables operators-in-the-loop testing, connecting technology to humans. The author is studying the man-machine semi-autonomous maneuvering problem from both the technology side and the human side. The technology side is broken down to four scientific fields: *Hydrodynamics*; *Guidance*; *Navigation*; and *Control*. Those four fields reflect the state-of-art in ship motion prediction and enhancement of automation level in ship maneuvering. Whereas the field of *Human Factors* (relevant to remote operators) is the field representing the human side of the problem. These five fields are reviewed briefly in this paper. The terms may have multiple definitions, therefore, in this review, the main fields are defined as follows:

- **Hydrodynamics** field in this review refers to methods that describe the motions and responses of a ship moving in water using maneuvering and seakeeping theories such as unified models (Skejic and Faltinsen, 2008).
- Guidance, navigation and control (GNC) is a well-established technical term used in engineering and control (cybernetics) fields in topics related to traveling vehicles; cars, ships, or planes.
  - Guidance module is the brain of the robotic controller that is responsible for trajectory planning, collision avoidance and conforming to protocol (such as COLREG) (Fossen, 2011).
  - Navigation module is responsible for estimating own state, that is, identify own position and motion information using sensors and GNSS signals, as well as estimating *external* situation, including environment perception (wind, waves, water depth, etc.) and obstacle state estimation, that is, identify obstacle position and motion information (Farell, 2008).
  - Control is the translation of guidance (desired trajectory) into actuator instructions that result in an actual trajectory as close as possible to the desired one and provides stability to the vehicle (Pérez, 2005).
- **Human factors** refers to reflections from human operators as more automation is introduced to their operations. Sections below include reviews of each of the fields separately.

2 LITERATURE REVIEW

After the fields of interest were defined, 59 relevant articles were reviewed in those fields of interest. Challenges and conflicts are presented. The literature is found in two ways: Education and search. Education literature is based on relevant courses and their relevant references. While Search literature is based on digital databases search of the following keywords: *Hydrodynamics; seakeeping; maneuvering; ship simulation; semi-autonomous vessels; unmanned surface vehicles; guidance; navigation; control; and human factors.* Search results were filtered based on relevance to the already defined subjects of interest.

2.1 *Topic 1: Hydrodynamics*

Dynamics is broken down by the studies of kinematics and kinetics, the former deals with geometrical aspects of motion and the latter deals with forces causing the motion. This review is concerned with ship dynamics, therefore this section starts with the maneuvering and the seakeeping theories as foundation for ship dynamics models. The former is the study of ship moving in constant speed in calm waters with the assumption that ship motion is frequency independent, that is, no wave excitation takes place. The latter is the study of ship motion at zero or constant speed in waves using frequency dependent hydrodynamic coefficients.

An overview of methods for describing maneuvering and seakeeping are grouped into experimental methods, unified methods, two-time scale methods and direct calculations by Computational Fluid Dynamics (CFD) tools (Quadvlieg *et al.*, 2014). The research is focused on real-time simulations and on including dynamics-in-the-loop for marine control systems, therefore the interest lies in fast mathematical methods such as the unified methods and the two-time scale methods. CFD tools are high computationally demanding and not suitable for real-time simulations. Both examples presented below, *the unified model* and *the two-time scale method*, are suitable for real-time simulations.

The unified model is a vectorial model that describes both the maneuvering and seakeeping ship motions and dates back to 1991 (Fossen, 1991) and is considered by the international community as a "standard model" for marine control systems design. The "standard model" is an upgrade of an earlier model (the "classical model") that represents the ship motion in a component form instead of vector form and is mostly used in hydrodynamic modeling where isolated effects are studied.

The 6 degrees-of-freedom (6-DOF) model is represented as (Fossen, 2011):

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) + \boldsymbol{g}_0 = \boldsymbol{\tau} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave} \quad (1)$$

where $\eta = [x, y, z, \phi, \theta, \psi]^T$ and $v = [u, v, w, p, q, r]^T$ are vectors of position / Euler angles and velocities respectively. $\boldsymbol{\tau}$ vectors are vectors of environment and control forces and moments. The model matrices $\boldsymbol{M}, \boldsymbol{C}(\boldsymbol{v})\, and\, \boldsymbol{D}(\boldsymbol{v})$ are inertia, Coriolis and damping matrices respectively. While $\boldsymbol{g}(\boldsymbol{\eta})$ is a vector representing gravitational and buoyancy forces and $\boldsymbol{g}_0$ is a representation of ballast restoring forces and moments. The model is formulated in the time domain using the *Cummins equation* that considers the impulse response function over the past history of the excitation force, known as *fluid memory effects* (Cummins, 1962).

The two-time scale method was proposed by Skejic and Faltinsen in 2008. It is also a vectorial unified model that describes both the maneuvering and seakeeping ship motions. The time domain of the simulation is divided into two time scales, a slowly and a rapidly varying one associated with the maneuvering and the seakeeping respectively. This method estimates the mean second-order wave loads (that result in lateral drift caused by incident waves and wind) “as accurate as possible and at the same time to be able to simulate real-time maneuvers with acceptable CPU time.” (Skejic and Faltinsen, 2008, p. 374). The model is represented in a 4-DOF (surge, sway, roll and yaw) form as follows:

$$\begin{bmatrix} M & 0 & 0 & 0 \\ 0 & M & 0 & 0 \\ 0 & 0 & I_{44}-Mz_g^2 & -I_{46} \\ 0 & 0 & -I_{64} & I_{66} \end{bmatrix}\begin{bmatrix} \dot u \\ \dot v \\ \dot p \\ \dot r \end{bmatrix}+\begin{bmatrix} 0 & -Mr & 0 & 0 \\ 0 & 0 & 0 & Mu \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}=$$
$$=\begin{bmatrix} X_{\dot u} & 0 & 0 & 0 \\ 0 & Y_{\dot v} & Y_{\dot p} & Y_{\dot r} \\ 0 & K_{\dot v} & K_{\dot p} & K_{\dot r} \\ 0 & N_{\dot v} & N_{\dot p} & N_{\dot r} \end{bmatrix}\begin{bmatrix} \dot u \\ \dot v \\ \dot p \\ \dot r \end{bmatrix}+\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Y_v & Y_p & Y_r \\ 0 & K_v & K_p & K_r \\ 0 & N_v & N_p & N_r \end{bmatrix}\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}+\begin{bmatrix} 0 & -C_{rN}Y_{\dot v}r & -Y_{\dot p}r & -Y_{\dot r}r \\ 0 & 0 & 0 & X_{\dot u}u \\ 0 & 0 & 0 & 0 \\ 0 & -X_{\dot u}u & 0 & 0 \end{bmatrix}\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}$$
$$-\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \int_0^t u dt \\ \int_0^t (v+z_g p+u\psi)dt \\ \phi \\ \psi \end{bmatrix}+\begin{bmatrix} X_R \\ Y_R \\ 0 \\ N_R \end{bmatrix}+\begin{bmatrix} -R(u)+(1-t)T(u) \\ 0 \\ 0 \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ Y_{CF} \\ K_{CF} \\ N_{CF} \end{bmatrix}+\begin{bmatrix} \overline{R_X} \\ \overline{R_Y} \\ \overline{M_X}+z_g\overline{R_Y} \\ \overline{M_Z} \end{bmatrix} \tag{2}$$

The main advantage of the two-time scale model is that it captures the second-order lateral drift phenomenon. It has better performance in incident waves, where the mean second-order wave loads heavily influence the maneuvering behavior. As it considers theories covering the whole range of important wavelengths.

For both methods, the *potential theory* is the main tool for calculating the hydrodynamic coefficients and thus forces. This theory assumes water flow across the rigid body as constant, irrotational, and incompressible. Chapter 5 of Fossen (2011) covers hydrodynamic concepts and numerical approaches. The most common numerical approaches for calculating the hydrodynamic coefficients are;

- Strip Theory; a 2-D theory that considers the flow variation in the longitudinal-section is much smaller than that of the cross-section plane of the ship.
- Panel Methods; 3-D integration method that divides the surface of the ship and the surrounding water into discrete panels, assigned a distribution of sources and sinks that fulfil the Laplace equation.

A comparison of the unified model and the two-time scale method is of interest for this research, because the hydrodynamic differences affecting ship control require further research (Liu *et al.*, 2016). Several examples of unified numerical models have been developed in the last three decades and here is a summary of the latest progress. The method proposed by Skejic and Faltinsen in 2008 was verified and validated for calm water. This method is further developed in a study on ship-to-ship hydrodynamic interaction effects between two ships going ahead in regular waves, it highlights critical maneuvering situations and it still requires experimental validation (Skejic and Berg, 2010). In 2013, the two-time scale model was applied to irregular seas and validated for a container ship (Skejic and Faltinsen, 2013). Hermundstad and Hoff (2009) implemented a time domain unified model on submarines and compared with experimental results. It was argued that the used unified model did not describe the diving maneuvers correctly because the depth dependency of the coefficients was not incorporated. A practical method for ship motion simulation using the two-time scale method is presented by Yasukawa and Nakayama (2009) that derives 6-DOF equations of motion for the high frequency problem and 4-DOF equations of motions for the low frequency problem. Wave induced motions for turning maneuver are predicted for a container ship of geometry S-175 and the predictions resulted in rough agreement with free model tests. Yasukawa, Amri Adnan and Nishi (2010) compared, numerical estimates of hydrodynamic forces and wave-induced motions taking into account lateral drift, with experiments showing that drift effects are not negligible and that the method is able to capture them. Seo and Kim (2011) extended the WISH (computer program for nonlinear Wave Induced load and Ship motion analysis) by coupling the maneuvering and the seakeeping models, and verified it by comparing with published experiment data in calm weather and regular waves. The simulations showed fair agreement of overall tendency in maneuvering trajectories.

Beside lateral drift, the broaching phenomenon is another challenge for hydrodynamic models, it concerns loss of stability while sailing in following seas where the kinetic energy of the ship along the forward axis transfers to roll motion and leads to strong heel, loss of heading, even capsize (Wu, Spyrou and McCue, 2010). Generally, maneuvering in waves is a challenge for both experimental and numerical modelling. For simulating ship motion in waves, forces and hydrodynamic coefficients need to be calculated dependent on wave frequency, ship heading and angle of attack angle between wave direction and ship course (Kim *et al.*, 2014).

2.2 *Topic 2: Guidance*

The guidance system receives information about the world, both internal information concerning the ship maneuvering and engine status, and external concerning the surroundings, environmental loading and nearby target ships and other objects and translates this information into instructions to controllers. Guidance is responsible for path planning, including collision avoidance. Fossen (2011) defines motion objectives categories. The guidance system together with the control system should fulfill the motion objectives according to one of the following categories:

1. Setpoint regulation: heading angle is constant with no consideration of time.
2. Path following: heading angle is variable, following a path, no consideration of time.
3. Trajectory tracking: heading angle is variable, following a trajectory in both space and time.
4. *Maneuvering*: considers the overall feasibility of the path, often with more importance to space than time. To incorporate COLREG, the guidance system shall consider both space and time parameters because velocities of maneuvers are critical.

The guidance system tasks are grouped into two: global and local path planning. The global path planning approach is the deliberate part of the guidance system. It is an optimized plan of the path from starting point of the trip to the end point, it includes known information about traffic, weather forecast, ship properties, land/islands, shallow waters and buoys. This is a multi-objective optimization problem and usually done offline and requires large computational requirements, in which, optimization methods and heuristic search algorithms are the two main methods. While local path (re)planning approach is the reflexive part of the guidance system, it takes charge of planning local deviations from the global plan, in case the navigation system detected an approaching object. A characteristic requirement of local path re-planning is the low computational requirements, where real-time methods such as line-of-sight (LOS) and potential fields are common.

Polvara *et al.* (2018) presented a review of global and local planning methods including a section for advanced computing-based methods. The author stated that almost all of the methods reviewed did not consider uncertainties due to environment loads and vehicle dynamics. A recent review of trajectory planning and tracking review (for autonomous driving systems) concluded that even most advanced guidance and control algorithms, with today's available sensor technology, work well under regulated environments assuming knowledge of surroundings and weather conditions. It also states that the inclusion of vehicle dynamics and environmental loads increases the effectiveness of such controllers (Dixit *et al.*, 2018). Lately, Wiig *et al.* proposed an integral line-of-sight law in the presence of constant ocean currents (2018).

LaValle in his tutorials points out that "the basic problem of computing a collision-free path for a robot among known obstacles is well understood and reasonably solved; however, deficiencies in the problem formulation itself and the demand of engineering challenges in the design of autonomous systems raise important questions and topics for future research" (LaValle, 2011, p. 108)

Polvara et al in their recent review stated the following: "It has been concluded that almost all the existing methods do not address sea or weather conditions, or do not involve the dynamics of the vessel while defining the path. Therefore, this research area is still far from being considered fully explored." (Polvara *et al.*, 2018, p. 241).

2.3 *Topic 3: Navigation*

The navigation system collects data from various sources such as sensors, cameras and satellites, and transfers the data into information of two kinds, state estimation and environment perception. State estimation is information about the ship's motion, mainly location and velocities. Environment perception is weather information, wind, waves, currents, and information about the surrounding as well, including state of target ships and objects. The scope of this system vastly increases as *level of automation* increases; the number of datasets, their resolution, frequency, quality and size are vastly increasing in remotely controlled vessels comparing to conventional ones. Moreover, since making sense of the collected data is considered part of the navigation system, its scope should then include advanced computing methods in order to deliver a fit-for-purpose output. Methods such as machine learning, sensor fusion, computer vision, prediction, and anomaly detection are now used within the navigation system for making sense of the collected data.

On board sensors are susceptible to disturbances that come from the environment, ship motion and other noise sources. The disturbances cause uncertainties in the perception model. This leads to control errors that accumulate over time, and result in undesired control behavior. Therefore, data from multiple sources are correlated against each other to calculate position and velocity estimates as accurate as possible. Data sources involved in a navigation system are:

1. Inertial measurement unit (IMU) is an onboard three-dimensional navigation system that comprises of three mutually-orthogonal accelerometers and three gyroscopes to give the position, velocity and altitude of own ship. IMU is often used with (and aided by) satellite positioning to provide drift-free positioning.
2. Automatic Identification System (AIS) is a very-high frequency communication system used by ships to transmit their identity, position, velocity, destination and other information and in return they receive information of nearby ships. Even though AIS is mandatory for commercial vessels, not all boats have it onboard!
3. GNSS is a global positioning solution system. It transmits radio signals from satellites orbiting the planet to the ship. There are a number of GNSS solution providers including GPS, GLONASS, Beidou and Galileo.
4. Radar, an acronym for radio detection and ranging, uses radio waves to detect ships and obstacles within a long range but its capability of detecting small moving targets is limited. Radar wavelength passes through fog and rain and it provides nearly all-weather data imagery.
5. Lidar, an acronym for light detection and ranging, is a high resolution and accuracy object detection sensor for near-range.
6. Sonar, an acronym for sound navigation ranging, detects submerged objects such as reefs, sunken ships and submarines. The sonar transmits ultrasonic pulses, receives the reflected echoes and displays a picture of the detected objects.
7. Other types of sensors and tools are used for navigation purposes such as cameras, infrared sensors, compass systems, navigation lights and ship whistles.

Most common method for fusing the navigation data as of today is the Kalman filter. The Kalman filter, invented by Kalman in 1960, is a real-time Bayesian estimation algorithm that uses all available measurements over time, and uses knowledge of deterministic and statistical properties of the system parameters in order to provide optimal minimum-error state estimations (Groves, 2013).

Examples of recent perception technologies in navigation systems are:

1 Non-linear observers: Advanced alternatives to the well-established Kalman filter, with proven stability properties and lower computational demands (Fossen and Strand, 1999; Aschemann, Wirtensohn and Reuter, 2016; Bryne, 2017).
2 Extended Kalman filter (EKF) for position and velocity estimation using GPS and compass measurements (Caccia *et al.*, 2008; Bibuli *et al.*, 2009; Tran *et al.*, 2014).
3 Unscented Kalman filter (UKF) for state estimation without previous knowledge of noise characteristics (Peng, Han and Huang, 2009; Vasconcelos, Silvestre and Oliveira, 2011).
4 Inverted Kalman filer (IKF) bounds model uncertainties that come from environment variability (Motwani *et al.*, 2013).
5 The eXogenous Kalman filter (XKF) for providing covariance estimates for the estimated states generated by non-linear observes (Johansen and Fossen, 2017).
6 Wave information perception using camera (Liu and Wang, 2013). Stereo vision system that generate probabilistic hazard maps and provide estimates for speed and heading of target objects (Huntsberger *et al.*, 2011).

2.4 *Topic 4: Control*

The control system is responsible to translate the information collected from the guidance system and communicate it with the actuators as commands. Actuators such as propellers, thrusters, and rudder receive commands from the control system and execute actions producing forces and moments that affect the state of the ship, approaching the desired state. The control system is responsible to make sure that the generated actuator commands are practical for the underactuated ship given the actuator limitations and ship dynamics.

Control literature is rich with control design approaches that extend from the classical proportional-integral-derivative (PID) controllers to the more advanced artificial-intelligence (AI) based controllers. Practical ship control often applies a combination of different control methods. PID control approaches are the most favored, they are, however, suitable for single-input-single-output cases such as heading control (Minorsky, 1922). This approach could suffer severe actuator damage caused by high waves. Simultaneous control of velocity and heading solves this problem. Multivariable control was realized by multi-loop PID control (Lefeber, Pettersen and Nijmeijer, 2003) and fuzzy adaptive control techniques (Le *et al.*, 2003).

Multivariable control has been widely approached by optimal control techniques such as H-infinity and Linear quadratic optimal techniques. Nonetheless, Linear Quadratic Regulator (LQR) controller suffers from the assumption that all states are measurable and known, which is not the case. Linear Quadratic Gaussian (LQG) controller together with a Kalman filter estimates in real-time the unknown states, however, suffers from instability. Instability outside predefined domain and discontinuities are major drawbacks of adaptive linear control methods (Liu *et al.*, 2016). Non-linear methods, such as Fuzzy logic control, Neural networks and Lyapunov-based methods argue that they can potentially overcome stability related issues while maintain smooth time-parametrized trajectories (Aguiar and Hespanha, 2003).

2.5 *Topic 5: Human Factors*

In this section the definition of levels of automation (or autonomy; since both terms are used interchangeably) is presented and followed by explanations of the human factors faced by operators introduced to increased automation in their operations.

2.5.1 *Levels of automation (LOA)*

Levels of automation were developed in the 1978. They were used to describe systems and aid the communication in the design phase of automated systems (Sheridan and Verplank, 1978). Multiple versions of LOAs have been issued since then. In the ship industry, LOA proposals exist from multiple sources such as Bureau Veritas, Lloyd's Register, the Norwegian Forum for Autonomous Ships (NFAS), Rolls-Royce, and others. Table 1 shows the LOAs as proposed by NFAS. General agreement exists in the different definitions as they range from human-operated ship (lowest level) to fully autonomous ship (highest level).

Explicitly, all the different variations of LOA classifications, agree that, on the highest level of automation, the machine decides and acts, and requires no communication with the human.

2.5.2 *Increased automation*

Automation is intended to increase safety and efficiency, however, in complex tasks (dynamic environments involving many variables) it changes the nature of the human-role in the task, it affects areas such as workload and cognitive demands. Moreover, the resultant impact of (increased) automation turns out to be more complex than anticipated. The changes are qualitative in context rather than quantitative and uniform (Woods *et al.*, 1996). Main human factors involved in the operator-technology interface are summarized as follows, including responsibility, surprises of automation, management by exception and communication:

1 **Responsibility:** Decisions that the human operator is used to take and implement will be routinely delegated to machines. However, can responsibility be delegated as well? Responsibility perception and calibration of trust between humans and machines are important to safe autonomous operations (Muir, 1987).
Jordan was one of the first to stress out that “we can never assign them (i.e., the machines) any responsibility for getting the task done; responsibility can be assigned to man only” (Jordan, 1963, p. 164). As suggested by Billings, human operators bear ultimate responsibility for operational goals, they must be in command, well involved and well informed about ongoing autonomous activities (Billings, 1991).

Table 1. LOAs as proposed by NFAS (Rødseth and Nordahl, 2017).

Level	LOA name	Description
1	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".
2	Automatic	The ship has more advanced automation systems that can complete certain demanding operations without human interaction, e.g. dynamic positioning or automatic berthing. The operation follows a pre-programmed sequence and will request human intervention if any unexpected events occur or when the operation completes. The shore control centre (SCC) or the bridge crew is always available to intervene and initiate remote or direct control when needed.
3	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. It has defined limits to the options it can use to solve problems, e.g. maximum deviation from planned track or arrival time. It will call on human operators to intervene if the problems cannot be solved within these constraints. The SCC or bridge personnel continuously supervises the operations and will take immediate control when requested to by the system. Otherwise, the system will be expected to operate safely by itself.
4	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.

2 **"Automation surprises":** It could be difficult for the operators to follow up with the autonomous vehicle and understand the grounds for its decisions. When the actions of the "machine" are not similar to what the human operator would do if placed in the same situation then the human would lose track and fail to predict next steps. A simulator experiment to evaluate pilots' mode awareness was carried out that confirmed that "automation surprises" are experienced even by operators with extensive amount of line experience on similar highly autonomous aircrafts. It was shown that in non-normal situations, more problems related to "automation surprises" occurred (Sarter and Woods, 1994). A previous study by Wiener, who conducted a survey of B-757 pilots, resulted that 55% of respondents were still being surprised by the automation after more than one year of line experience on the aircraft (Wiener, 1989). Norman referred to the phenomenon of human operator losing track of machine's behavior as 'breakdown in mode awareness' which has been linked strongly to the following factors: automation surprises, increased error possibilities, new cognitive demands, and failure to intervene appropriately. Increased automation would also cause surprise to the ship designers and owners who experience unexpected consequences because their automated system fails to behave as was intended (Norman, 1988).

3 **Management by exception:** A remote operator, whether monitoring or supervising, is in a double bind dilemma with the machine. A dilemma between trust and takeover. Dekker and Woods explained this phenomenon in their work titled "To intervene or not to intervene: the dilemma of management by exception" (Dekker and Woods, 1999). Supervisory control places the operator in a decision-making situation. A trade-off between intervening too early, before enough evidence is collected about the situation, and intervening too late, after it escalades into an irreversible crisis. The operators, for every moment in time, must assess the criticality of the situation and decide whether to intervene or not. Late decisions are catastrophic. Early decisions are not justified. Decision aids and prediction tools are required, but how much should they be trusted? (Sheridan, 2000).

Human-machine interaction is changing in nature. Increased automation reduces workload in normal-times and increase them dramatically in non-normal times. In non-normal times the 'automation surprises' factor is higher, the 'mode awareness' factor is lower, the attentional demands and the cognitive demands are highly increased. Given the dilemma, this setting is critical in non-normal times as it leads to less situational awareness (SA) and less intervention capabilities. Thus, safety is a big concern if things went wrong in non-normal times. Sarter et al define the term Mode awareness as "the ability of a human operator to track and anticipate the behavior of automated system" (Sarter, Woods and Billings, 1997, p. 6). Situational awareness, according to Endsley, is "the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995, p. 36).

4 **Communication:** For example, the grounding of the Royal Majesty is referred to as a loss of situational awareness problem; a communication problem because of increased automation. Among other factors, the GPS has failed, positioning information were incorrect, autopilot used the faulty information, the ship drifted and that was not apparent to the crew. They believed that the sailing was flawless but in fact, it lead to a grounding (Lützhöft and Dekker, 2002). Researchers emphasized on the value of communication and collaboration with the machine for safer autonomous navigation. Effective communication and coordination

between humans and machines is believed to be key for successful operations (Sarter, Woods and Billings, 1997).

3 RESULTS

This review covers topics concerning the future of autonomous vessels from three perspectives. First from the side of the technology advancements that make such a future possible. Second from the human operator side and the challenges faced while teams are operating highly autonomous systems, remotely. Third from the levels-of-automation side, multiple versions of LOA definitions for the maritime industry that classify human-machine relationship as automation increases. Trying to answer the article's question.

One may argue that the supporting technologies are already available, as there are booming examples of domain-specific advancement, but this review identifies a shortage in the studies that show how well these building blocks work out together, and under uncertainties. Analysis and breakdown of this identified shortage follows:

There is interaction and signal flow among the GNC and hydrodynamics fields, as shown in Figure 1. One publication proposing a novel path planning method would have built-in assumptions regarding (and pre-selections of) ship dynamic models, navigation methods, and control design approaches. For example, Liu, Bucknall and Zhang (2017) proposed a guidance "*fast marching*" method for a USV, and presented their results of full-scale experiments. They used a preselection of navigation methods (Kalman filter), control methods (PID autopilot), and vehicle dynamics model (3-D model) as in (Motwani *et al.*, 2013).

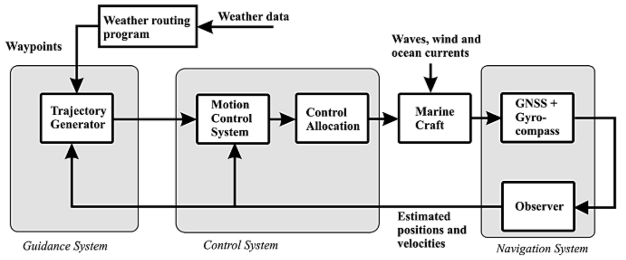

Figure 1. GNC module interaction and signal flow (Fossen, 2011, p. 233)

Given the interrelation, applications of semi-autonomous vessels, both real (full-scale) and virtual (simulators), require a package of GNC and hydrodynamics technologies interacting together. It is widely agreed that the performance of methods is largely altered by uncertainties coming from environmental loads and ship dynamics (LaValle, 2011; Liu *et al.*, 2016; Polvara *et al.*, 2018).

"Automation could increase sources of error". Precautionary perspective is necessary in research and development. Porathe *et al.* (2018) includes a fictive story that predicts a possible future scenario in one of the Norwegian fjords and provides a forecast of the risk picture in the maritime industry.

Human operators face challenges with highly automated systems. In the future, as autonomous ships become reality, advancing through the LOA scale, until eventually, full-autonomous vessels are realized in a safe and efficient manner, remote control will be essential. Safe and efficient remote operations are as important as, or even more important than, no-human-interaction type of control (according to LOA definitions of full autonomy). There is a literature shortage in this multidisciplinary field of "ship remote control". It should cover remote control-centered topics of ship design, GNC systems design, human-machine interaction, navigation functions, interface, and remote control center design.

4 DISCUSSIONS

4.1 *Disagreements*

Viewpoints such as "A ship must follow and adhere to the international regulations for preventing collisions at sea (COLREGS)" are common in GNC technology research. However, these viewpoints oversimplify the problem. They inherently assume that traffic in the sea is well regulated and all players follow the rules. In reality, operators and crew do violate procedures, for different reasons, as shown by a research that collected 1262 questionnaires from tankers and bulk carriers crew (Oltedal, 2011).

Some collision avoidance methods enable manual input of waypoints by a supervisor operator for replanning the path and avoiding approaching obstacle. As Campbell et al describe them: "This is not the most efficient method for avoidance and is subject to operator error" (Campbell, Naeem and Irwin, 2012). This view is common. It promote two points. First, that human operators are subject to more errors than machines. Second, researchers are oriented to develop technologies with high automation level and low human interaction, to avoid human errors. This view conflicts with the status quo of technology, because also machines are subject to error, and it conflicts with human factors research, that having less human interaction with highly automated system introduces the dilemma of management by exception and it can be avoided by having human input and authority over the machines even for highly autonomous systems.

In a recent survey on communication technologies (Zolich *et al.*, 2018) a relation of LOAs with communication requirements was presented. It says, basically, that the higher the LOA is, the lower the amount of data the ship would require to communicate with land. This view conflict with the human operator's requirements for safe and efficient monitoring, supervision and control of the autonomous remote asset.

The definition of full-autonomy, in all the variations of LOA scales, emphasizes on "no human interaction; machine ignores human; no human input". These definitions favor automation over safety and efficiency of the asset because full-autonomous ships need to be remotely controlled, on demand, upon the decision of the supervisor in charge. In such a dynamic multi-objective shipping task, the option of remote control is necessary; the reason for this desire of remote control could be any of the following examples:

- Business and market fluctuation
- Environment regulations and emission related rules
- Cyber-attacks, piracy and hijacking
- Environment loads and extreme weather
- Incidents at ports such as fires or chain-reaction accidents
- Customer relations; cargo health; maintenance issues and etc.

4.2 *Main challenges*

Main challenges from the different perspectives are summed up in this section as follows.

Motion coupling: control advancements consider a simplified ship model, similar to that of a 3-D unicycle model. The effect of motion coupling to stability requires further analysis.

Ship motion in waves: Describing ship motion in harsh weather is a challenge; there is no standard way of doing it. Hydrodynamic research considers that ship motion in calm water is assumed to converge to an underlying true trajectory. The maneuvering committee of the 27th ITTC address this issue as a challenge for both experimental work and numerical modelling (Quadvlieg *et al.*, 2014, sec. 6.4).

Co-simulation of digital models: The development of GNC algorithms has boomed lately. It is challenging to know how they will work together under the influence of stochastic environmental loading and uncertainties. In addition, how will the human (remote) operator experience those advancements?

Remote operator input: How well does these technologies workout together? Research towards enhancing the performance of man-machine systems in dynamic control tasks is crucial in design and operation of future maritime operations. Effects of LOA towards situation awareness and mental workload are researched (Kaber and Endsley, 2004). However, it is challenging to judge automation based on the LOA scale because the whole scale is course; massive variations could be possible within one LOA level. Variations in terms of interface, controllers, inputs, outputs and engagement level are expected for each level.

4.3 *Full Autonomy*

The main challenges of the previous section maps man-machine challenges that are valid for the maritime industry as of today. Worldwide research and development projects will certainly tackle them and innovations will pave the way, gradually, to realizations of higher levels of ship autonomy. The progress will be gradual, evolutionary rather than revolutionary, because of the political, legal and financial inertia involved in such industry.

Systematic bias: Assume that "we are dealing with a transition towards fully autonomous systems" with the main objectives "safety and efficiency". The way the developers perceive the future is key in determining the safety and efficiency of that future. The definitions of LOAs form a huge anchoring bias that weakens the focus on the objectives and strengthens the following views:

1 The ultimate goal is full autonomy
2 Full autonomy is that systems run by themselves with no human interaction
3 Human input is a negative contribution to system objectives

And those views are expanding systematically within and across industries and can be seen popular in technical scientific disciplines and among the youth in societies of most industrial countries. Broek *et al* (2017) mentioned the need of a man-machine "collaboration framework" even for fully autonomous systems.

Towards full-autonomy: As it brings value to other industries, the values of advanced technology must be harvested in the shipping industry as well. We strive for fewer accidents, less social and environmental impact by the utilization of tools such as data analytics, decision support aids, and advanced autopilots. Surprisingly, the GNC literature shows that technology is being developed towards a future with no human interaction. However, I think that the values of full-autonomy cannot be harvested unless the technology becomes developed towards a future with full human interaction.

5 CONCLUSIONS

If the industry's drive is safety and efficiency, then full-autonomy is, at present, not the way to go. Remote control, instead, could facilitate a feasible future, while focused research and development are in need. From the technology side, the literature shows that uncertainties coming from environmental loads and ship dynamics largely affect the performance of GNC technologies in a semi-autonomous vessel. Thus, accurate modeling and prediction of semi-autonomous maneuvering is fragile under uncertainties. From the human side, the literature shows that as automation is increased and interaction is decreased the operators face the *management by exception* dilemma. Operators undertaking safe and efficient ship remote control, even for highly autonomous ships, require high interaction and high authority over the system. Automation is promising because of the possible reduction of cost and risk involved in maritime operations, nevertheless; it could bring in new sources of error, while human operators face serious challenges dealing with highly automated systems. There is a rush of technology-related research but there is a lack of holistic research focusing on "ship remote control". Research that tests the GNC technologies under uncertainties with human-operator in-the-loop is needed. Digital advancements enable virtual experiment environments with human interaction such as simulators. Those safe environments could be the only tools available, for now, to enable us research whether it is full-autonomy the right way to go for exploiting the ocean potentials.

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