DTU Library

Autonomous Surface Vessel with Remote Human on the Loop: System Design for STCW Compliance

Dittmann, Kjeld; Hansen, Nicholas; Papageorgiou, Dimitrios; Jensen, Signe; Lützen, Marie; Blanke, Mogens

Published in:
IFAC-PapersOnLine

Link to article, DOI:
10.1016/j.ifacol.2021.10.097

Publication date:
2021

Document Version
Early version, also known as pre-print

Citation (APA):
Dittmann, K., Hansen, N., Papageorgiou, D., Jensen, S., Lützen, M., & Blanke, M. (2021). Autonomous Surface Vessel with Remote Human on the Loop: System Design for STCW Compliance. *IFAC-PapersOnLine*, *54*(16), 224-231. https://doi.org/10.1016/j.ifacol.2021.10.097

13th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles
Oldenburg, Germany, September 22-24, 2021
IFAC CAMS 2021

Autonomous Surface Vessel with Remote Human on the Loop: System Design for STCW Compliance

Kjeld Dittmann * **Peter Nicholas Hansen** *
Dimitrios Papageorgiou * **Signe Jensen** ** **Marie Lützen** **
Mogens Blanke *

* *Technical University of Denmark, Dept. of Electrical Engineering, Automation and Control Group, DK 2800 Lyngby, Denmark (e-mail: {kjeditt,dimpa,pnh,mb}@elektro.dtu.dk)*
** *University of Southern Denmark, Odense, Denmark (e-mail: {sij, mlut}@sdu.dk)*

Abstract:
Autonomous surface vessels comprise complex automated systems with advanced onboard sensors. These help establish situation awareness and perform many of the complex tasks required for safe navigation. However, situations occur that require assistance by a human proxy. If not physically present on board, information digestion and sharing between human and machine become crucial to maintain safe operation.
This paper addresses the co-design of on-board systems and a Remote Control Centre (RCC). Using the international regulations on watch-keeping (STCW) as a basis, the paper discuss how an autonomous system is designed to meet the STCW requirements. It is discussed how the autonomous system is made aware of the state of the vessel, its surroundings, on-board defects or navigational challenges and shared with the RCC in a collaborating system perspective.

Keywords: Autonomous marine crafts, Safe Navigation, Remote Operation, Autonomous Ship, Regulations.

1. INTRODUCTION

The marine industry is constantly aiming at reducing cost while at the same time enhancing safety and working conditions for officers and crew on board vessels. Temporarily unattended on-board navigation is one of the topics being considered, and another is remote operation for vessels with sufficient levels of autonomy and machine intelligence to handle most situations without human intervention.

Recent technological advancements have resulted in trial experiments with various levels of autonomy, showing the ability to control and move a vessel from the quay in one port and to berth it in another port (Rolls-Royce, 2016), (Kongsberg-Maritime, 2020). Similar trials have been conducted with remote operation of offshore vessels and tugs from a shore-based control centre (Wartsila, 2017). These trials have been performed in assigned test areas under the current regime of rules and regulations, (IMO, 2019),(DNV, 2018), which require a safety manning on-board the vessels during testing. However, development is rapid and some forecasts say that the first generation of autonomous vessels will be in operation by the end of 2021 (BIMCO, 2020). To make this happen, without compromising safety, a fundamental paradigm shift is needed in the design of the on-board system, the shore based support system, the approval process as well as training of crew members on board and on shore.

Introducing autonomy on board ships, (Thieme et al., 2020) pointed to the need for goal-driven design and risk based assessment of the complex cyber-physical system and (Rambøll and CONE, 2018) assessed regulatory barriers. Incident reports have documented that up to two-thirds (EMSA, 2019) of all incidents involving marine surface vessels were caused by human error and only a minor part by direct equipment and component failures. The potential risk associated with marine surface vessels is of continuous concern and effort has been made to improve the issue of human error, with strong system integration being a dominating factor. When adopting an increased level of automation and computer-based solutions, the sources of risk changed towards the software development and validation (Earthy et al., 2001), and to the cyber-physical dimensions (Rokseth et al., 2019), (Vander Maelen et al., 2019), (Thieme, 2018). One of the findings in the literature on human factors was the importance of transparency, i.e. the system must have a predictable behaviour, even in situations of failures or reduced performance (Earthy and Lützhöft, 2018). Another important finding was the necessity to consider the system as an entirety and not sub-system by sub-system. Extending the problem to be a Seafarers Training Certification and Watch-keeping (STCW) compliant co-design process of vessel and remote control is an essential step forward.

This paper addresses how overall STCW requirements are mapped onto the design for autonomous operation. New

Table 1. List of Acronyms

Notation	Description
ACS	Autonomous Coordination Supervisor
AI	Artificial Intelligence
AIS	Automatic Identification System
ANS	Autonomous Navigation Supervisor
APS	Autonomous Platform Supervisor
ATC	Air Traffic Control
DHS	Distress Handling Service
DP	Dynamic Positioning
ENC	Electronic Navigational Chart
IMO	International Maritime Organization
OOW	Officer on Watch
RCC	Remote Control Center
SAS	Situation Awareness Service
SCC	Ship Control Center
SFU	Sensor Fusion
SHP	Short Horizon Planner
STCW	Seafarers Training Certification and Watch-keeping
UNCLOS	UN Convention of Law of the Sea
VCS	Voyage Control System
VTS	Vessel Traffic Service

technology and methodologies are introduced to ensure safe and predictable reactions to both normal and abnormal events. The paper also addresses the case of an autonomous ship, where high-quality decision support is instrumental to obtain a periodically unattended bridge. It is shown how an STCW-compliant unmanned bridge operation is supported and how remote operation is possible, should this be needed.

The remainder of the paper is structured as follows: Section 2 introduces the context and Section 3 summarises the essential STCW regulations. Section 4 shows how complexity is dealt with in a system with human in the loop and local supervision is part of the vessel automation. Section 5 details the mapping of STCW regulations onto functionalities within the autonomous on-board system and extends this to a comprehensive solution of the co-design of vessel and remote operation where vision and machine learning are essential to enhance autonomous and remote situation awareness. Section 6 deals with the remote control centre and Section 7 offers the conclusions.

2. THE AUTONOMOUS SYSTEM IN CONTEXT

Operation of vessels at sea is governed by international legislation. The rules that describe how safe operation is ensured, is part of the International Maritime Organization (IMO) STCW resolution (IMO, 2010). The STCW has historically been the vehicle for design, approval, training, roles and responsibilities; it establishes a regime for safe vessel operation. The code lists the overall international requirements to maintain a ship's safety and security, and ensure protection of the marine environment.

It is foreseen that with autonomous capabilities on-board a marine vessel, there can be periods in which the navigator can leave the bridge for other duties including maintenance, loading planning for next voyage, checking cargo or providing services to passengers. In these periods, the bridge is handled by the autonomous system.

In this paper, the term autonomous vessel does not equal an unmanned vessel and thus the following section will provide a high-level introduction to the autonomous system intended for marine vessels. The current liability regime assumes an on-board statutory crew with well-defined roles and responsibilities. It can be argued that by introducing electronic-based solutions with the aim of replacing parts of the on-board statutory crew, a substitute crew will need to resume responsibility. A Remote Control Center (RCC), often shore-based, is likely to assume that role. In Fig. 1, a simplified block diagram shows the key elements of an autonomous ship. The shore-based crew of an RCC

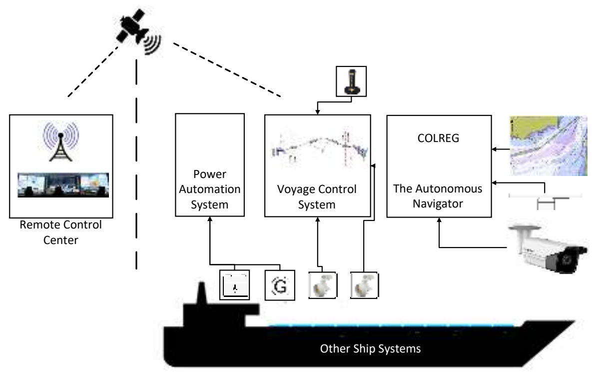

Fig. 1. Key elements of an autonomous ship

is assumed to be master mariners undertaking the role of Master/Captain, Chief Engineering Officer and the Officer of the Watch. The manning of the RCC will need a level of situation awareness as if being on the vessel in order to fulfil that assignment. The derived functional requirement to an RCC and its communication link imposes stringent reliability and capacity requirements, however this is considered outside the scope of this paper.

The pre-departure voyage planning for the autonomous vessel will be performed, as for a conventional vessel, based on optimization criteria e.g., weather, tide as well as required arrival time and it is represented by a series of way-points (IEC, 2016). The transit part of the route is equivalent to the route information used by a track control system (IEC, 2014), but the slow speed track follower and berthing tracks needs to be supplemented with additional specific information like Center of Rotation. In the proposed system, the execution of the planned and amended track is performed by the Voyage Control System (VCS). The VCS has three modes: manual, automatic and remote. In manual mode the vessel is handled by the crew on board, while in automatic mode the autonomous on-board system provides the track to follow, i.e. it is controlling the vessel, and finally in the remote mode the VCS is controlled and handled by the RCC. The autonomous navigator monitors the situation by information from cameras, radar, Automatic Identification System (AIS), own vessel navigational data, i.e. speed, heading, position, wind & depth, and the electronic sea charts. If the autonomous navigator detects any need for a route deviation, caused by COLREGS, it will, depending on the operational mode, either instruct the VCS to follow the newly suggested route or forward the suggestions to a human proxy (either on-board or RCC based).

3. GUIDING DESIGN CRITERIA

Designing and organizing all functionalities of an autonomous ship in an all-embracing architecture is an extensive task and inevitably, this paper will not address all aspects. However numerous contributions has been publish, such as the communication architecture (Rodseth et al., 2013), the reliability and safety aspects (Dittmann et al., 2021), the liability aspects (Chircop, 2018) and the view of a class society (DNV, 2018).

The contribution of this paper is to apply the STCW as a known paradigm in association with the MSC.1/Circ.1455 resolution on alternative and equivalent solutions (IMO, 2013).

3.1 The Human Factors Elements

The human factor aspect is a constant source of concern, i.e. the user interaction with the technology on-board as well as at the RCC is an important element that needs to be addressed (Earthy and Lützhöft, 2018). A significant finding in the literature on human factors is the importance of utilizing a known paradigm or regime, which often results in a significantly improved human-system interaction in comparison to a green field design. Microsoft Windows lay-out and controls is in (Earthy and Lützhöft, 2018) used as an example.

3.2 The Regulatory Regime

The United Nations (UN) has a number of domain agencies with the IMO being the one responsible for the maritime domain. IMO has the mandate and obligation to create a fair and effective regulatory framework. In accordance with the UN Convention of Law of the Sea (UNCLOS), vessels are only granted permission to operate if they comply with international regulation, (UN, 1982). Both UNCLOS and IMO conventions are based on a principle of skilled seafarers who manage the ship and ensure compliance with regulations, representing the flag state and the owner. The rapid development of autonomous systems has challenged IMO and guidelines for conducting trials have been published, (IMO, 2019). Originating from IMO's principle of no favorable treatment, it must therefore be documented that the autonomous system provides the same degree of safety, security and protection of environment as a conventional manned vessel. A standard for what is recognized as appropriate qualifications is provided by the STCW (IMO, 2010). Thus, if a system is to be accepted as periodically taking over the watch, also denoted a periodically unattended bridge, it shall provide the same degree of safety as the watch-keeping personnel it replaces; a requirement which would then also apply for a remote bridge operation from an RCC. The watch-keeping officer is, according to STCW, not allowed to leave the bridge, but the position of the bridge is not defined which is why remote bridge operation may comply with this requirement, however this is still to be further examined. In ch. II of STCW, the competences required to operate as a navigational officer is specified, and what is required by a watch-keeping officer and the principles to be observed is specified in Ch. VIII of STCW (IMO, 2010). The required competences have been divided into three

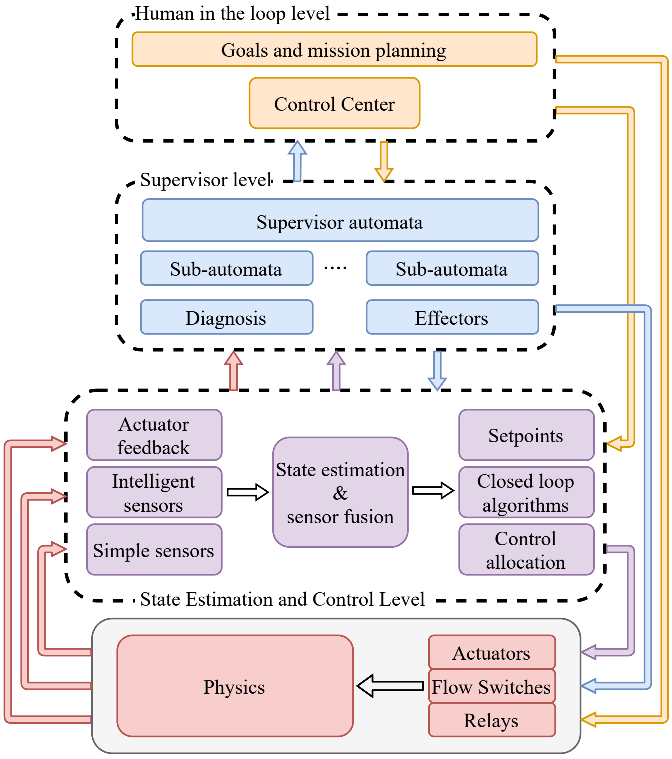

Fig. 2. Generic control hierarchy for a system with supervision. For example in space systems, the operator is in the loop when ground station passage takes place. For agricultural robots, a human can be in the loop from a remote control centre if required. For ships, a human in the loop is the officer on watch present on the bridge.

functions: navigation, cargo handling, and controlling the operation of the ship. Those functions are described for operational level as well as management level. To assume the responsibility as watch-keeping officer, competences required for operational level is sufficient, while the backup system, RCC or Ship Control Center (SCC), will need competences on a management level. The principles on watch-keeping requires that *"watch-keeping personnel shall notify the master/chief engineer officer/officer in charge of watch duties without any hesitation when in any doubt as to what action to take in the interest of safety."* (STCW A-VIII/2-8.9). Therefore, if the Officer on Watch (OOW) is to be replaced by a system, this system shall possess qualifications equal to those described in STCW for operational level, listed in table A-II/I from page 32 and onward of (IMO, 2010).

4. DEALING WITH COMPLEXITY

It is essential to have a commonly agreed-upon structure, often referred to as an architecture or abstraction model, to ensure correct astringent allocation of functions, communication and interoperability. IMO has recognized that the systems installed on vessels are getting increasingly more complex, and that this requires a modular design and certification standards (IMO, 2007). IMO has published a strategy for the implementation of E-Navigation (IMO, 2018a). IMO's definition of E-Navigation covers the electronically provided harmonized exchange, analysis and presentation of information on-board, as well as on-shore for conventional vessels. The current version of the proposal (IMO, 2018) addresses three main topics; the ship, the communication link and the shore side infrastructure. The proposed architecture addresses the direction of the IMO rules and standards framework on a very high level.

Fig. 2 shows an architecture illustrating how to deal with the complexity that follows from operation in both normal and not normal conditions. Effects of abnormal conditions in various parts of an automation system including the plant itself, actuators, sensors and software modules that perform signal conditioning, estimation, control or force allocation. In response to complexity and risks of defects in software implementation and lack of test-ability, architectures for fault-tolerant systems were developed. The architecture has separate layers for control and estimation, and supervision with modules performing diagnosis, others to perform supervision and yet others to execute decisions of a supervisor. The latter were referred to as effectors (Blanke et al., 1997). These principles led to modular, testable and low-complexity software designs that have proved their value in spacecrafts (Bak et al., 1996) and in autonomous robot vehicles (Blanke et al., 2012).

Decomposition and modularity has proven to be an effective way of accommodating abstraction, automated testing and certification. Problems/failures more frequently arise due to poor design and/or high complexity rather than hardware malfunction (Kopetz, 2014), (Obermaisser and Huber, 2009). In addition to reducing the cognitive challenges, a stringent modular design supports the often-incremental certification process. It supports the needed test strategy of module and regression tests.

5. APPLYING THE STCW REGIME

The autonomous system is managed by an autonomous supervisor, which takes over the responsibilities of watch-keeping, navigation, etc. The watch-keeping principle stipulates that the OOW must notify the master without hesitation, if needed. This also applies to the autonomous case. If a situation arises that the autonomous system cannot handle, the autonomous supervisor will notify both the SCC and the RCC and/or request assistance.

5.1 Autonomous Supervision

The fundamental principles of the design of the autonomous supervisor comprise a hierarchically distributed architecture with a main coordination unit at its centre. The motivation for this architecture lies in the fact that there is a need for segregated services which relate to different functionalities e.g., situation assessment & navigation, system status monitoring, etc. The autonomous supervisor comprises three main modules, namely, the Autonomous Coordination Supervisor (ACS), the Autonomous Navigation Supervisor (ANS) and the Autonomous Platform Supervisor (APS). The three modules shown in Fig. 3 are described in the following.

Autonomous Coordinating Supervisor The ACS is the main intelligence of the autonomous system. Its purpose is to ensure that all services on the vessel are available to

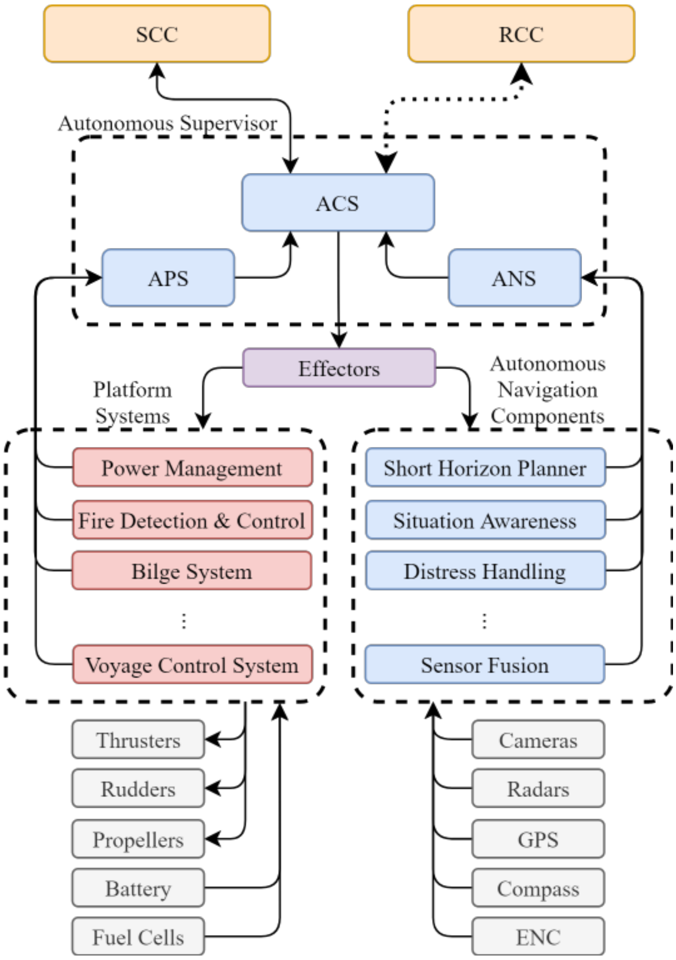

Fig. 3. Simplified Allocation of Functions.

an acceptable (defined by performance specifications and standards) level and if not, to take remedial actions. Such actions can range from informing the human proxy (either RCC and/or SCC) of eminent risks due to functionality deficiencies to changing operating modes and in worst case, system shut down. The ACS has local software agents in each of the system nodes, that are responsible for monitoring node health and system integrity.

Autonomous Platform Supervisor The APS is responsible for assessing the overall system health by gathering information from local diagnostic systems dedicated to each machinery component. The information coming from these local diagnostics are consolidated into status reports of higher abstraction. In this way, the APS provides the ACS with a report indicating the change between nominal and degraded performance of the main vessel functionalities. Such functionalities include propulsion, manoeuvring, power systems, fire detection and bilge systems, communication link to shore, etc.

Autonomous Navigation Supervisor The ANS is responsible for ensuring that all navigation is conducted in a safe manner. The ANS will constantly monitor the surrounding vessels and objects and it will compare the actual events with the anticipated scenarios generated by the Situation Awareness Service (SAS). The SAS is a module that describes the current and future situation

Table 2. Mapping STCW required competences to functionalities in the autonomous system

Task	STCW	Mapping of Autonomy
1a	Plan and conduct a passage	ACS ← ANS ← {SHP,SAS}
1b	Determine ships position, heading and speed (by multiple means)	SFU
2	Maintain a safe navigational watch	ACS ← ANS ← {SAS,SFU}
3	Use of radar and ARPA to maintain safety of navigation	ANS ← SFU
4	Use of ECDIS to maintain safety of navigation	ANS ← {SAS,SFU}
5	Respond to emergencies	ACS ← (SCC ∨ RCC) ← ACS ← APS
6	Respond to distress signal at sea	ACS ← (SCC ∨ RCC) ← ACS ← ANS ← DHS
7	Use the Standard Marine Communication Phrases in English	(SCC ∨ RCC)
8	Transmit and receive information by visual signaling	ACS ← (SCC ∨ RCC) ← ACS ← ANS ← DHS
9	Manoeuver the ship	VCS ← ACS ← ANS ← {SAS,SHP}

based on the interpretation of the collected data from the cameras, radars, etc. (Hansen et al., 2020). Whenever a manoeuvre is needed, the ANS triggers the Short Horizon Planner (SHP), which is the main manoeuvre-planning module (Enevoldsen et al., 2021). Furthermore, the ANS is tasked with detecting navigation anomalies and deviant behaviours of the surrounding vessels. If there are any inconsistencies with the actual unfolding of the events, e.g. give-way vessels that does not give-way or the anticipated path of a vessel is not correct, the ANS will notify the ACS that the current situation differs from the anticipated one.

To put the role of the three basic components of the Autonomous Supervisor into context, one should associate the ANS to the human navigator, the APS to the chief engineer and the ACS to the captain. Fig. 3 shows the allocation of functions in an autonomous ship.

5.2 Mapping the STCW to Autonomous Functionality

In order to comply with the STCW, a mapping of responsibilities has to be made to ensure that the Autonomous system has capabilities to meet responsibilities as required by (IMO, 2010). This mapping is shown in Table 2. The notation in the “Mapping of Autonomy” column of Table 2 is interpreted as follows.:

$$A \leftarrow B : A \text{ receives input from } B$$
$$A \leftarrow \{B, C\} : A \text{ receives input from } B \& C$$

Two examples illustrate the mapping of responsibilities, and explain the notation further:

- Task 2: Maintain a safe navigational watch.
- Task 6: Respond to distress signal at sea.

Task 2: Maintain a safe navigational watch A Sensor Fusion (SFU) module employs data association among radar and camera objects along with a verification against the Electronic Navigational Chart (ENC), when possible. In addition, fault-tolerant SFU capabilities will disregard erroneous information (Blanke, 2005), (Nissov et al., 2021). and meet the STCW requirement that information on correct position, speed and heading are checked by multiple means. Tracking of individual objects (Schöller et al., 2020) and object detection using vision in different parts of the spectrum enhance abilities of the human eye and meets the STCW requirement of outlook.

Situation awareness is obtained by the autonomous system by techniques for reliable object detection and anticipation based on machine learning of historic and current AIS data and ENC information about the area (Schöller et al., 2021). This is achieved by the SAS module, that is constantly monitoring the actual situation using information from the SFU, the ENC, in combination with a COLREGs interpretation of how surrounding vessels should navigate (Hansen et al., 2020). In case an evasive manoeuvre is required, the ANS will request the SHP to calculate relevant deviations from the planned route (Enevoldsen et al., 2021). These are passed on to the ACS for evaluation and possibly sent for approval to a human proxy in SCC and/or RCC.

Task 6: Respond to distress signal at sea A dedicated Distress Handling Service (DHS) module will monitor for incoming distress signals at sea, both from vision (cameras) and radio. In case a distress signal is detected, the DHS will notify the ANS, which in turn will notify the ACS that a distress signal has been detected. The ACS will then request assistance from a human proxy (either through the SCC or the RCC), and re-route any voice communication that the vessel has received to the proxy. The human proxy will either take control over the vessel or instruct the ACS of what to do.

6. REMOTE CONTROL CENTRE

This section will detail how the on-board autonomous functions support and inform the human on the loop with rapidly digestible overview and suggestions to remedial actions when this is required.

6.1 Exchange of Technical Parameters.

The RCC requires information in order to provide the needed situation awareness for the operator, (MUNIN, 2016), (Porathe et al., 2014) and (Earthy and Lützhöft, 2018). Fig. 4 illustrates how information is presented.

(1) Voyage information. On an ENC overlay, way-points, course to steer and allowed cross track corridor are shown (voyage plan - task 1a in Tab. 2).
(2) Navigational information. Position, course, speed, heading. Route related information, e.g. time and distance to next way-point, and weather services (conduct the voyage - task 1b in Tab. 2).
(3) Object detection. Information from the ANS identifying other ships, their anticipated course and speed and any risks (maintain safe navigational watch - task 2 in Table 2).

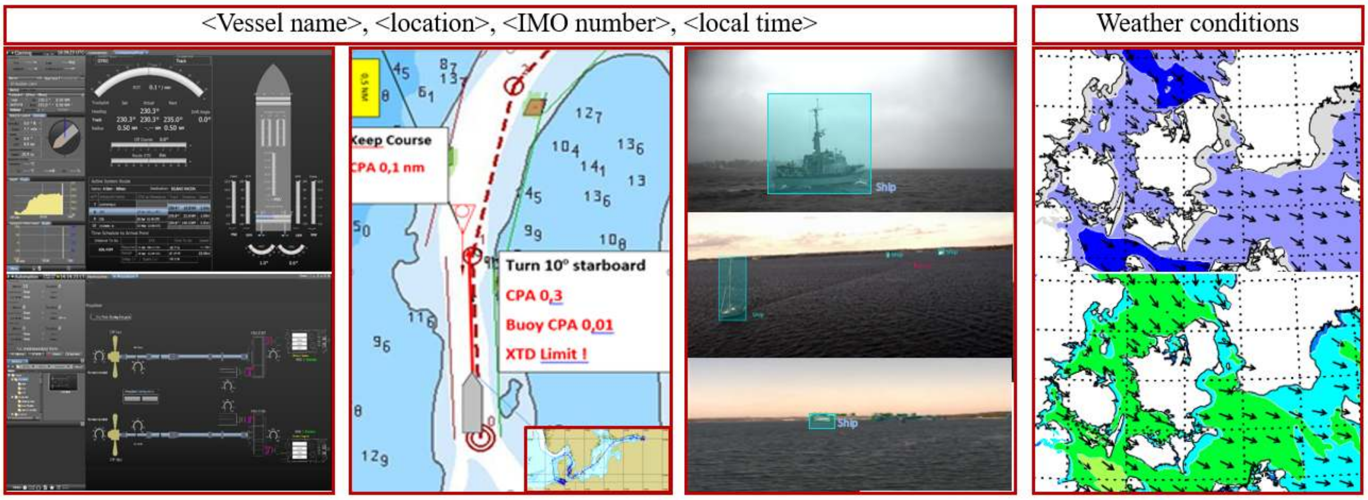

Fig. 4. Sample case of basic screens in RCC room (from left to right): Status of equipment and hardware, navigation pane, camera feed, weather information.

Other parameters that are important information to be transferred from the ship to the RCC are related to the APS:

(1) Dynamic information (ship motions).
(2) Safety and emergency.
(3) Propulsion system status.
(4) Cargo and stability.

The information must be visualized on the ship and at the RCC in the same format. Fig. 4 illustrates an example of how the information could be displayed at the RCC. The information is grouped into four categories: equipment and machinery status, navigational data, environment representation via camera feed and weather conditions.

6.2 Transfer of the command – the roles of ship and shore

The (IMO, 2018b) stipulates that responsibility, authority and interrelationship of all personnel who manage, perform and verify work relating to and affecting safety and pollution prevention must be documented. It accounts for the ship's crew and it should also account for the RCC. The way that the regulation is stipulated, a ship must have a master in charge with an overriding authority. As this issue is related to the liability in case of an accident, it is necessary to determine whether the person denoted and given the authority as a master, is the RCC or an officer on-board.

There must be clear and transparent agreement between the crew on board and RCC on how and who is taking the decisions. Managing a shift of control or how to operate the vessel jointly must be described in detail. Furthermore equal understanding and dual loyalty is very important and must be emphasized. The ship's crew and RCC must constitute a bridge team together and must be aware of the "authority gradient" (Schröder-Hinrichs et al., 2012).

A constant passive monitoring of all the operations on-board increases transparency, however, the crew may feel monitored and watched by "big brother". It is therefore very important that the crew on board knows exactly what is monitored, logged, and shown at the RCC. Attention is drawn by (Earthy and Lützhöft, 2018) to the fact, that the crew may feel devalued if too much responsibility is transferred to the RCC. According to the theory on the authority gradient, this may lead to lack of information flow from the ship's crew to the RCC. It is therefore important to prevent that this will occur (Earthy and Lützhöft, 2018).

The following topics are identified as important when defining the interrelationship between RCC and the ship's crew:

(1) Shared knowledge level; the crew on board must have the feeling that RCC fully understand how a ship is operated (Earthy and Lützhöft, 2018)
(2) Clearly defined hierarchy and responsibilities
(3) Common language (Task 7 in Table 2). All communication must be in the same language; spoken and understood by both the RCC and the ship's crew. The language also includes shared proficient terms.

It can be argued, that the RCC has a similarity to an Air Traffic Control (ATC) or a Vessel Traffic Service (VTS) centre. The ATC direct airplanes with the primary purpose to prevent collisions and organize the flow of air traffic. The ATC team monitor the air-crafts by radars and communicate with the planes by radio. The ATC may issue instructions, that pilots are required to obey, or advisories, that pilots may disregard – however, it is the pilot in command, that is the final authority for the safe operation of the aircraft and the pilot may, in an emergency, deviate from ATC instructions to the extent required to maintain safe operation of the aircraft. The VTS centre is a well-established service in areas with dense and complex traffic. VTS operators are skilled personnel, who provide navigational assistance and in some circumstances are authorized to issue instructions to vessels with regards to navigation. The VTS and the ATC are clearly different from an RCC. Operators at VTS and ATC do not have access to the internal of the craft but rely only on surveillance information from sensors and the crew. The biggest difference is that the RCC team and the ship crew are not foreign units but can be considered as colleagues sharing the same operational information.

6.3 Manning, education and training

A detailed analysis of the manning, education and training is outside the scope of this paper, however for the RCC operator to assume the role of a watch-keeping officer, it will be necessary to possess the competences required by STCW. When introducing a highly automated function, it is important to identify ways to maintain the practical training. Valuable insight can be obtained from the US Federal Aviation Administration, the Flight Deck Automation Working Group (Federal Aviation Authority, 2013). They found that in about 60% of analyzed accidents, pilots had trouble manually flying the planes. In the maritime domain, Dynamic Positioning (DP) operators have expressed concerns with regards to skill degradation when the human operator is reduced to be a passive supervisor during longer periods of time (Øvergaard et al., 2015).

Special attention must be drawn towards situations where the autonomous system must manually be taken over by human navigators, at the SCC or the RCC. Studies by (Øvergaard et al., 2015) showed that decision making in uncertain contexts requires extensive domain specific knowledge and an ability to recognize patterns. With the autonomous system supported by vision and Artificial Intelligence (AI) to provide situation awareness and compute remedial actions, these abilities are heavily supported by the on-board autonomous functionality. The collaboration and communication skills for improving the interrelationship between RCC and ships crew must also be trained and maintained.

7. CONCLUSIONS

This paper addressed the co-design of on-board systems and a Remote Control Centre (RCC). Using the international regulations on watch-keeping (STCW) as a basis, the paper described how an autonomous system can meet the STCW requirements. It was discussed how the autonomous system makes the RCC aware of the state of the vessel and its surroundings. Emphasis was given on how the navigational risks are assessed by the autonomous system and the solutions it provides to the human on the loop.

Finally, It was shown that each of the main requirements of the STCW was mapped to and supported by the autonomous functionalities.

ACKNOWLEDGEMENTS

This research is sponsored by the Danish Maritime Foundation, Orients Fund and Lauritzen Fonden through the ASAN project (grant 2018-056) and by these foundations plus the Danish Innovation Fund through the ShippingLab project (grant 8090-00063B).

REFERENCES

Bak, T., Wisniewski, R., and Blanke, M. (1996). Autonomous attitude determination and control system for the orsted satellite. In *1996 IEEE Aerospace Applications Conference. Proceedings*. IEEE. doi:10.1109/aero.1996.495975.

BIMCO (2020). First ever standard contract for autonomous ship operation underway. URL `https://www.bimco.org/news/contracts-and-clauses/20201106-first-ever-standard-contract-for-autonomous-ship-operation-underway`.

Blanke, M. (2005). Diagnosis and fault-tolerant control for ship station keeping. In *Proc. of the 2005 IEEE Int. Symp. Mediterrean Conference on Control and Automation Intelligent Control, 2005.*, 1385–1390. IEEE Xplore. doi:10.1109/.2005.1467217.

Blanke, M., Blas, M.R., Hansen, S., Andersen, J.C., and Caponetti, F. (2012). *Fault Diagnosis in Robotic and Industrial Systems*, chapter Autonomous Robot Supervision using Fault Diagnosis and Outdoor Semantic Mapping, 1–22. iConceptPress.

Blanke, M., Izadi-Zamanabadi, R., Søren, B., and Lunau, C. (1997). Fault-Tolerant Control Systems - A Holistic View. *Control Engineering Practice*, vol 5, 693–702.

Chircop, A. (2018). Testing International Legal Regimes : The Advent of Automated Commercial Vessels. *The German Yearbook of International Law*, 1–34.

Dittmann, K., Hansen, P.N., Papageorgiou, D., and Blanke, M. (2021). Autonomy for ships: A sovereign agents architecture for reliability and safety by design. In *IEEE Xplore - Proc. IEEE SysTol'2021*. IEEE. Accepted.

DNV (2018). Autonomous and remotely operated vehicle. Technical Report September, DnV. URL `https://rules.dnv.com/docs/pdf/DNV/cg/2018-09/dnvgl-cg-0264.pdf`.

Earthy, J., Jones, B.S., and Bevan, N. (2001). The improvement of human-centred processes - Facing the challenge and reaping the benefit of ISO 13407. *International Journal of Human Computer Studies*, 55(4), 553–585. doi:10.1006/ijhc.2001.0493.

Earthy, J.V. and Lützhöft, M. (2018). Autonomous ships, ICT and safety management. *Managing Maritime Safety*, 141–165. doi:10.4324/9780203712979.

EMSA (2019). Annual Overview of Marine Casualties and Incidents 2014. Technical report, EMSA.

Enevoldsen, T.T., Reinartz, C., and Galeazzi, R. (2021). COLREGs-Informed RRT* for Collision Avoidance of Marine Crafts. In *2021 Int. Conf. on Robotics and Automation (ICRA)*. IEEE. Accepted.

Federal Aviation Authority (2013). Operational use of flight path management systems. URL `https://www.faa.gov/aircraft/air_cert/design_approvals/human_factors/media/OUFPMS_Report.pdf`. D. Nakamura, Chairperson: Report of the PARC/CAST Flight Deck Automation WG.

Hansen, P., Papageorgiou, D., Blanke, M., Galeazzi, R., Lûtzen, M., Mogensen, J., Bennedsen, M., and Hansen, D. (2020). Colregs-based situation awareness for marine vessels - a discrete event systems approach. *IFAC-PapersOnLine*, 53(2), 14501–14508. doi:https://doi.org/10.1016/j.ifacol.2020.12.1453. 21st IFAC World Congress.

IEC (2014). IEC 62065:2014 Track control systems – Operational and performance requirements, methods of testing and required test results. Technical report, IEC.

IEC (2016). IEC 61162-1:2016 Maritime navigation and radio communication equipment and systems - Digital interfaces - Part 1: Single talkers and multiple listeners. Technical report, IEC.

IMO (2010). The Manila Amendments to STCW. Technical Report STCW/CONF.2/34, IMO.

IMO (2013). MSC.1/Circ.1455 Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments. Technical Report MSC 1, IMO, London.

IMO (2018a). E-Navigation Strategy Implementation Plan – Update 1. Technical Report 0, IMO, London.

IMO (2018b). ISM Code - International Safety Management Code. Technical report, IMO.

IMO (2019). Interim Guidelines For MASS Trials. Technical Report MSC.1/Circ.1604, IMO.

Kongsberg-Maritime (2020). Autonomous shipping - Kongsberg Maritime. URL `https://www.kongsberg.com/maritime/support/themes/autonomous-shipping/`.

Kopetz, H. (2014). A Conceptual Model for the Information Transfer in Systems-of-Systems. *Proceedings - IEEE 17th International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing, ISORC 2014*, 17–24. doi:10.1109/ISORC.2014.19.

MUNIN (2016). Maritime Unmanned Navigation through intelligence in networks. Technical report, DnV.

Nissov, M.C., Dagdilelis, D., Galeazzi, R., and Blanke, M. (2021). Analyzing cyber-resiliency of a marine navigation system from behavioral relations. In *Proc. European Control Conference ECC'2021, to appear.*

Obermaisser, R. and Huber, B. (2009). A multi-core platform for integrated modular avionics derived from a cross-domain embedded system architecture. *SAE Technical Papers*. doi:10.4271/2009-01-3262.

Øvergaard, K., Sorensen, L.J., Nazir, S., and Martinsen, T.J. (2015). Critical incidents during dynamic positioning: operators' situation awareness and decision-making in maritime operations. *Theoretical Issues in Ergonomics Science*, 16(4), 366–387. doi:10.1007/s13437-012-0032-3.

Porathe, T., Prison, J., and Man, Y. (2014). Situation awareness in remote control centres for unmanned ships. *Human Factors in Ship Design and Operation*, 27(February), 1–9.

Rambøll and CONE (2018). Analysis of Regulatory Barriers to the use of Autonomous Ships. Technical report, Danish Maritime Authority.

Rodseth, O.J., Kvamstad, B., Porathe, T., and Burmeister, H.C. (2013). Communication architecture for an unmanned merchant ship. *Oceans 2013 Mts/ieee Bergen: the Challenges of the Northern Dimension*. doi:10.1109/OCEANS-Bergen.2013.6608075.

Rokseth, B., Haugen, O.I., and Utne, I.B. (2019). Safety Verification for Autonomous Ships. *MATEC Web of Conferences*, 273, 02002. doi:10.1051/matecconf/201927302002.

Rolls-Royce (2016). Remote and Autonomous Ship – The next steps. Technical report, Rolls-Royce.

Schröder-Hinrichs, J., Hollnagel, E., and Baldauf, M. (2012). From Titanic to Costa Concordia—a century of lessons not learned. *Wmu Journal of Maritime Affairs*, 11(2), 151–167. doi:10.1007/s13437-012-0032-3.

Schöller, F.E.T., Blanke, M., Plenge-Feidenhans'l, M.K., and Nalpantidis, L. (2020). Vision-based object tracking in marine environments using features from neural network detections. *IFAC-PapersOnLine*, 52(2), 14517–14523. doi:10.1016/j.ifacol.2020.12.1455.

Schöller, F.E.T., Enevoldsen, T.T., Becktor, J.B., and Hansen, P.N. (2021). Trajectory prediction for marine vessels using historical ais heatmaps and long short-term memory networks. In *Proc. IFAC CAMS'2021*. IFAC. Submitted.

Thieme, C.A., Mosleh, A., Utne, I.B., and Hegde, J. (2020). Incorporating software failure in risk analysis – Part 1: Software functional failure mode classification. *Reliability Engineering and System Safety*, 197(January), 106803. doi:10.1016/j.ress.2020.106803.

Thieme, C.A. (2018). *Risk Analysis and Modelling of Autonomous Marine Systems*. Ph.D. thesis, Norwegian University of Science and Technology, Trondheim.

UN (1982). United Nations Convention on the Law of the Sea. Technical report, United Nations.

Vander Maelen, S., Buker, M., Kramer, B., Bode, E., Gerwinn, S., Hake, G., and Hahn, A. (2019). An Approach for Safety Assessment of Highly Automated Systems Applied to a Maritime Traffic Alert and Collision Avoidance System. *2019 4th International Conference on System Reliability and Safety, ICSRS 2019*, 494–503. doi:10.1109/ICSRS48664.2019.8987712.

Wartsila (2017). Wartsila-tests-remote-control-vessel-from-8000-km-away. URL `https://www.offshore-energy.biz/wartsila-tests-remote-control-vessel-from-8000-km-away/`.

