Proceedings of the 1st International Conference on Maritime Autonomous Surface Ships

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PREFACE

These proceedings contain selected papers from the first International Conference on Maritime Autonomous Surface Ships (ICMASS), held in Busan, Republic of Korea, on November 8th and 9th, 2018. The first day of the conference had ten invited presentations from the international autonomous ship community, while the second day contained parallel sessions on industrial and academic topics respectively. A total of 20 industrial and 16 academic presentations were given. From the presentations, six full manuscripts are presented in these proceedings after peer review by two Korean and Norwegian experts.

ICMASS is an initiative from the International Network for Autonomous Ships (INAS, see http://www.autonomous-ship.org/index.html), an informal coalition of organizations and persons interested in autonomous ship technology. In 2018 it was organized by KAUS – Korea Autonomous Unmanned Ship Forum. The plan is to make this a yearly event in different places around the world. In 2019 it will take place in Trondheim, arranged by SINTEF Ocean AS and NTNU in cooperation with the Norwegian Forum for Autonomous Ships (NFAS).

The organizing committee would like to thank everyone who has helped with review of manuscripts, all those who helped to promote the conference and all authors who have submitted and presented their contributions.

Kwangil Lee & Ørnulf Jan Rødseth

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MASS TECHNOLOGY DEVELOPMENT BY MEANS OF SHIP HANDLING SIMULATION

Hans-Christoph Burmeister[1], Ah-Ram Lee[2], Johannes Oeffner[3], Srikanth Shetty[4], Laura Walther[5]
[1,3,4,5] Fraunhofer Center for Maritime Logistics and Services, Hamburg, Germany
[2] Daewoo Shipbuilding & Marine Engineering Co., Ltd., Seoul, South Korea

[1] Corresponding author e-mail: hans-christoph.burmeister@cml.fraunhofer.de, Tel: +49 40 42878-6131
[2] Corresponding author e-mail: arlee@dsme.co.kr, Tel: +82 2 2129-7312
[3] Corresponding author e-mail: johannes.oeffner@cml.fraunhofer.de, Tel: +49 40 42878- 4379
[4] Corresponding author e-mail: srikanth.shetty@cml.fraunhofer.de, Tel: +49 40 42878- 4778
[5] Corresponding author e-mail: laura.walther@cml.fraunhofer.de, Tel: +49 40 42878- 4641

Abstract

This paper will stress the importance of Ship Handling Simulation (SHS)-based Maritime Autonomous Surface Ship (MASS) prototype development and aligns it with the IMO Guidelines on Software Quality Assurance and Human-centered Design for e-Navigation. This is demonstrated by means of an implemented semi-autonomous ship concept. This concept envisions a periodically unmanned bridge with an advanced autonomous navigation system taking over in the absence of the officer of the watch. Thus, it is equipped with autonomous monitoring, collision avoidance as well as harsh weather applications embedded within an ECDIS environment, that require sufficient integration and testing. Based on a requirement analyses, the need for SHS-based testing is derived and a technical framework (SMARTframe) enabling connection of MASS prototypes with SHS on the basis of a message-oriented middleware is introduced. Finally, an indication is given how this set-up ensures proper MASS testing and developing for technical as well as Human-centered Design development.

Keywords: *MASS, Periodically Unmanned Bridge, Human-centered Design, Ship handling simulation, Message-oriented Middleware*

1. Introduction

Maritime Autonomous Surface Ships (MASS) are on the horizon. MASS cover a variety of vessel concepts from ships with autonomy assisted bridges, periodically unmanned bridge, periodically unmanned ships to continuous unmanned ships [1]. However, it is misleading that MASS take out the human factor of the safety equation, as the majority of MASS concepts still foresee control by humans in-the-loop or on-the-loop either from ashore as well as from onboard. This is also why focusing on the human element still plays an important role in the ongoing IMO Regulatory scoping exercise [2]. A proper way to include the human element in the design process is described by the IMO Guideline on Software Quality Assurance (SQA) and Human-Centered Design (HCD) for e-Navigation [3]. In parallel, Ship-handling simulation (SHS) is a known tool for assessing navigational safety and appropriately incorporating the human factor into development projects according to the World Association for Waterborne Transport Infrastructure PIANC [4]. Thus, enabling and assessing MASS concepts in SHS is key to enable human factor, operational as well as safety assessments to fully exploit MASS potentials. Though, this requires a proper integration of MASS prototypes into SHS.

In 2015, DSME and Fraunhofer CML started to develop a first prototype for a semi-autonomous ship concept consisting of an Autonomous Navigation System (ANS) and a Shore Control Centre (SCC). In the end, this concept displays a periodically unmanned bridge operation [2]. Based on the ANS developed, this paper will elaborate how MASS technology development and human-centred design (HCD) can be supported by SHS elaborating DSME's and Fraunhofer CML's approach.

2. Software Life Cycle and HCD

In accordance with IMO, the generic life-cycle for software development can be described by the five steps [4]:

1. Concept Development,
2. Planning and analysis,
3. Design,
4. Integration and testing and
5. Operation,

with this paper focusing on the middle three. The first step is excluded in this paper, as the stakeholder and user analyses is based on the MUNIN project. Information about MUNIN's approach towards stakeholder involvement and its derived concepts can be found e.g. in [6], [7] or [8]. The second step Planning and analysis does primarily cover user and system requirement derivation with regards to software quality assurance as well as HCD, which was done in this project based on a literature review, specifically [8] and some user interviews. The Design phase includes the software architecture as well as the design solution development and its implementation, which was done by the Fraunhofer CML via the SMARTframe framework within a SHS environment. The fourth step on Testing and usability evaluation is only briefly touched in this paper.

3. Requirements Activity

3.1 Overall goal

The high level goal of the ANS in this context has been defined as being an on board system capable to take over certain nautical tasks and decisions during deep sea voyage from an officer of the watch (OOW) to enable a periodically unmanned bridge or advanced decision support. Overall, autonomy hereby means a system of at least level 7 of the Sheridan scale [9], that "executes automatically [and] then necessarily informs the human" for all four stages of Parasuman's information processing steps [10], specifically in the field of decision and action selection.

3.2 Needs, expectations and requirements

More detailed analyses of stakeholder's needs and basic requirements have been derived from [8], but down-scaled to the case of a periodically unmanned bridge. Thus, the scope of processes was limited down to:

- Conduct weather routing,
- Follow track and
- Avoid collision.

The core regulations and principles to be included in the first processes is hereby the Revised Guidance to the master for avoiding dangerous situations in adverse weather and sea conditions [11] and for its derived mandatory specifications it is referred to Table 1 and Table 2, splitting this process into its strategic and operational level. For the latter process, the baseline is the Convention on the International Regulations for Preventing Collisions at Sea [12], with its mandatory requirements being outlined in Table 3. The execution of the follow track process can in principle already be performed by any modern track keeping system, which is why its detailed specification requirements are not detailed here. Instead, it is referred to e.g. [13].

Additional expectations from the user-side have been identified to be an electronic navigational chart-based graphical user interface with touchscreen accessibility stating the different activities of the autonomous system, to allow for a smooth interaction of OOW with the ANS.

Table 1: HWC Specification Requirements (per trigger)

The Harsh Weather Controller (HWC) must
be capable to 1. receive own ship's meteorological observation data 2. receive own ship's motions in all six degrees of freedom 3. consider own ship's current course and voyage plan in IEC 61174 standard route exchange format [18]
4. monitor current environmental conditions (sea state, wind, current) 5. identify possible threats due to current environmental conditions (e.g. based on the MSC.1/Circ.1228 [11]) 6. initiate actions, i.e. course and/or speed alterations, if threats related to current environmental conditions are identified 7. provide information on weather routing recommendation to Collision Avoidance Controller
offer OOW the possibility to 8. define the threshold where current environmental conditions pose a threat to the ship by taking into account the ships seakeeping characteristics

Table 2: SWR Specification Requirements (per trigger)

The Strategic Weather Routing (SWR) must
be capable to 9. consider meteorological forecasts (GRIB1-Format) relevant for planned voyage 10. consider meteorological forecast updates while underway (automatically)
11. evaluate meteorological forecasts effects on expected Fuel-Oil-Consumption (FOC) 12. identify critical safety areas based on meteorological forecasts 13. respect safety areas in route planning if threats along the planned route of own ship related to upcoming environmental conditions are identified 14. optimize the number and position of waypoints of the route with regards to FOC in deep-sea 15. optimize the speed profile between waypoints with regards to FOC in deep sea 16. provide the optimized route in IEC 61174 standard route exchange format [18]
offer OOW the possibility to 17. set weather routing safety parameters

Table 3: CAC Specification Requirements (per trigger)

The Collision Avoidance Controller (CAC) must
be capable to 18. receive own ship's visibility range 19. receive traffic ships' data 20. receive weather safety checks from HWC
21. monitor objects in vicinity (i.e. ships, other objects) 22. detect an avoidance manoeuvre of the other ship 23. evaluate upcoming development of traffic situation based on CPA, TCPA, BC and TBC 24. identify possible upcoming close quarters situations based on CPA, TCPA, BC and TBC 25. consider COLREG B while navigating in open sea 26. evaluate which collision avoidance rules COLREG Part B apply under the prevailing visibility conditions if the vessel is not in a narrow channel or a traffic separation scheme 27. identify if own ship is give-way or stand-on ship 28. ascertain possible solutions to avoid upcoming close quarters situations in compliance with COLREGs if a danger of collision is identified 29. initiate action according to COLREG R17 to avoid collision if an imminent collision situation arises 30. perform a steady course and speed if the unmanned ship is the stand-on ship 31. transmit the traffic picture to OOW 32. notify OOW if an imminent collision situation arises 33. notify OOW if a close quarters situation is developing 34. notify OOW if an appropriate collision avoidance manoeuvre has been identified 35. notify OOW if the system requires assistance in finding a valid solution to avoid pending collision 36. notify OOW if an avoidance manoeuvre of the other ship is detected 37. notify OOW if other ship does not act according to COLREGs 38. notify the OOW if the other ship has been passed well clear and the close quarters situation has been resolved
offer OOW the possibility to 39. define parameters 40. access information about upcoming close quarters situations and proposed safe deviation routes 41. to define a specific collision avoidance maneuver, besides the one found by the CAC

4. Software design activity

4.1 *Prototype*

The ANS prototype is comprised of different modules to ensure later scalability and reusability of different elements. Thereby, a principle navigation system (as described in [13]) is augmented by three additional core modules that adapt a layout already proposed in [14] (see also Figure 1):

- A Strategic Weather Routing (SWR) Module, that aims for safe operations by avoiding unfavorable weather conditions
- A Harsh Weather Controller (HWC) Module, that reduces negative impacts of encountered environmental forces, as well as
- A Collision Avoidance Controller (CAC) Module, that ensures sailing in compliance with COLREGs Part B.

Besides their primary focus, all modules are aiming to solve their mission under economic considerations, meaning by reducing voyage length and fuel oil consumption. An important link between those modules is the negotiation part between the HWC and the CAC [14]. While both modules do normally serve different aims, which could result in different decisions, this link ensures, as far as possible, a harmonized solution finding by incorporating the HWC in the CAC where necessary. This has also been identified as one important requirement (requirements number 7 and 20 respectively).

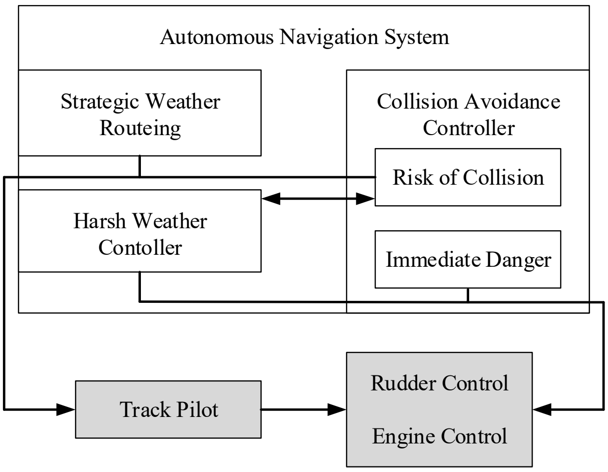

Figure 1. Autonomous Navigation System layout (in dependence on [14]))

4.2 *User Interface and interaction*

In line with [4], the initial user interface has been designed by a mixture of collaborative design as well as creativity methods including direct involvement of nautical offices, but also experts from software engineering. Hereby, first simulator experiences from the previous MUNIN project have also been taken into account, especially with regards to a better monitoring possibility of the autonomous systems [14].

During the initial design, the principle user interface for the OOW has been defined as an electronically nautical chart with ECDIS like features (e.g. other vessels and monitored route). The main interaction is done via the chart itself, with all main functionalities being touch supported by context menus (see mainframe in Figure 2). Within this standard overview, also the status of all three main components Track Pilot, HWC and CAC is permanently shown as follows (see three squares in the upper left corner of the mainframe in Figure 2):

- Green: Active, normal operation
- Green-flashing: Autonomy-intervention ongoing
- Yellow: Minor incident, user intervention aspired
- Red: Deactivated/can't fulfil mission; user intervention needed

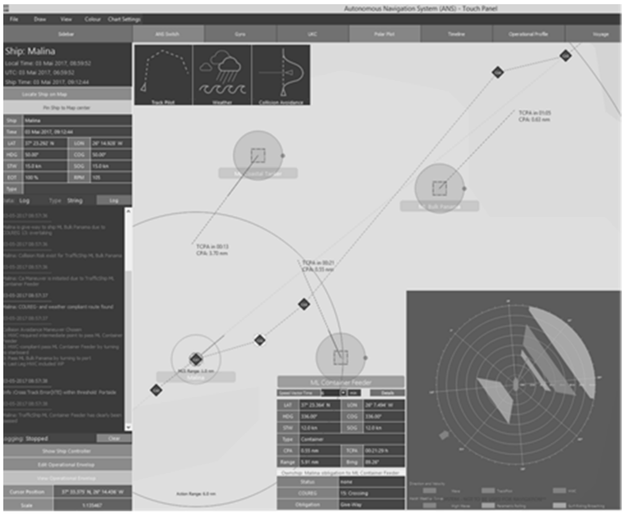

Figure 2. ANS Interface layout

Besides those permanent visible items, a status bar including an ANS log shows the OOW the major own-ship characteristics and informs the OOW about the internal progress and status of the ANS, to fulfil e.g. requirement numbers 32 to 38 (left hand of the mainframe in Figure 2). Further information are purely shown on request on a context basis, like e.g. the data of the traffic ship or the current weather polar plot in the example in Figure 2 (right hand corner on the bottom).

Next to this monitoring interface, the OOW can interact with the ANS by defining its operational envelope, which could be compared to the digital representation of the standing orders. Amongst others, the operational envelope contains the following:

- Monitoring and Action Range: What radius from the vessel shall the ANS monitor and when shall the CAC react;
- Traffic ship handling: which types and to what degree shall traffic ships be respected in the CAC (ignoring, passive monitoring or active evading);
- Ship domains for traffic ships: what are ship-specific safety characteristics with regards to passing distances and preferred sides;
- Maximum cross-track deviation: How far is the ANS allowed to deviate from the original course line;
- HWC vs. CAC priority;

In addition to the standard operational envelope, the OOW can at any time access those values and even make specific exemptions or changes via the touch-screen user interface – before or after the autonomy support. The example in Figure 2 shows e.g. the individual traffic ship domains as circles, which can be directly adjusted by pinch, zoom or pan gestures. The ship-specific adjustment is then taken into account for a rerun of the evasive manoeuvre being determined by the CAC. In a similar way, the OOW can also directly change the CAC's output for the proposed evasive manoeuvre, by e.g. just panning the waypoint to another, preferred position (e.g. for requirement number 41).

4.3 Test-bed

As the proposed prototype as well as its operation is rather complex, a specific test-bed is designed to allow for proper ANS experience, developing as well as user testing. However, as equipping a real vessel directly with a test system is expensive as well as challenging from a legal and liability perspective, an alternative is needed. For harbour channel design studies, which by nature do exclude the use of a real vessel for testing as well, it is e.g. common sense, that nautical experts participating in a SHS exercises is "the only way to ensure that technical ship handling and the important human factors, are sufficiently incorporated" [5]. Thus, incorporating the ANS into a SHS environment is aimed for enabling proper human testing.

4.4 Software Architecture

Modularity, centralisation, scalability, reusability and maintainability are key features for rapid but sustainable software development. With SMARTframe, a specific testbed framework for MASS exists offering high performance in this categories [14]. SMARTframe allows customizing a modular testbed with centralized data exchange unit to fulfil specific user requirements, conceptualizing and developing innovative software solution, integrating simulators, applications or devices into existing testbeds, as well as assessing and validating applications or devices by integrating it into an SHS environment.

Even though the ANS primarily being in an initial prototype development and testing phase, early consideration of reusability and scalability for an efficient development process is aspired. Using SMART-frame's electronic navigational chart application, which is based on a standard ENC Kernel that represent the base chart for ECDIS systems, as the backbone of the ANS development enables easy reusability as well as facilitating possible future certification in this early design phase. Furthermore, SMARTframe also covers standard shipborne interfaces like NMEA or AIS to allow for integration into commercial systems. However, the core of SMARTframe is its Message-Oriented Middleware making it highly modular and scalable, as it allows for a quick implementation of pure data-driven test-beds. [14]

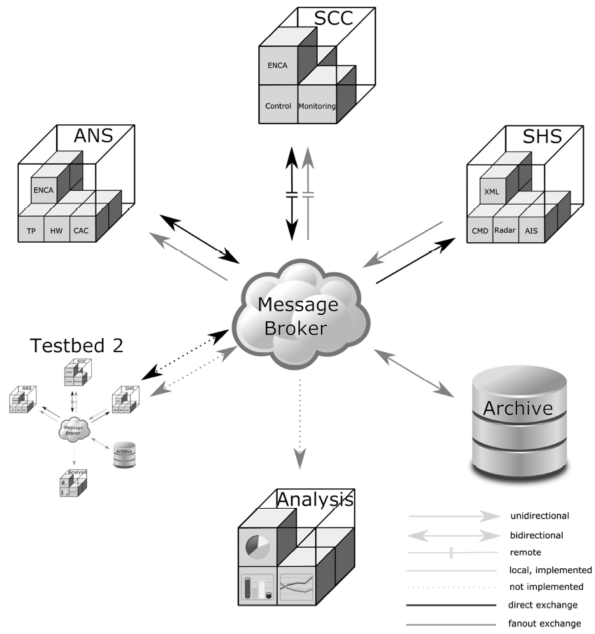

Figure 3. ANS SHS Test-bed sketch (according to [16])

As depicted in Figure 3, a central message broker enables interaction between the SHS, the individual prototypes but also its individual modules. Within SMARTframe, the Advanced Message Queuing Protocol (AMQP) is used, which is an open standard for an interoperable enterprise-scale asynchronous messaging protocol [16]. The concrete broker in this case is RabbitMQ. For details, it is referred to [15]. Thus, the data-driven AMQP design facilitates modular design and enables reusability.

5. Software testing activity

The integration of the implemented ANS prototype took place at a RDE ANS 6000 SHS at Fraunhofer CML as well as at DSME with the SHS of a Korean brand. Concerning the ANS itself, a detailed test against all specification requirements laid out in Table 1 to Table 3 based on pre-defined acceptance criteria as well as by several pre-defined voyage scenarios has been conducted in both environments. Regarding the initial ambition of developing a first operational prototype as demonstrator and test equipment within a SHS environment, the software has been considered reasonable satisfying after several iterations and tests in the SHS fulfilling all pre-defined criteria. Moreover, the ANS technical integration capability could even be tested in 'read-only' mode on board in May 2018 during a six day voyage of the MS HANNAH SCHULTE in the Mediterranean. The easy integration again "demonstrated the capability of the [SMARTframe] to switch from simulated to real-time environment" [15], being also a good indicator for fulfilling the aspired reusability criteria of the IMO Software Guideline [4].

Figure 4. Onboard installation ANS on HANNAH SCHULTE

6. Conclusion

This paper has presented the development process of a periodically unmanned bridge system by DSME and Fraunhofer CML. Thereby, it has highlighted the need for proper user testing methods, like e.g. in a SHS environment, to follow IMO Guidelines requirements and to ensure that user needs and safety is met [4]. Furthermore, the SMARTframe framework for ensuring scalability has been introduced and used during the ANS development. Even so ANS is currently only focusing on a prototype and demonstrator output, SMARTframe ensures software reusability for the next development phases.

According to [3], this next phase would specifically include more detailed user testing including user observation and thinking aloud techniques within the SHS environment to finalize the HCD efforts started and to come up with a periodically unmanned bridge improving ship efficiency and safety in parallel. Besides this concrete case, further MASS technology development by means of SHS testing is even generally aspired as it goes in line with [2] by ensuring that,

- MASS developments are user-driven,
- Safety is not reduced,
- Operability of MASS can be evaluated and
- Human element aspects for MASS are appropriately considered.

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HULL-TO-HULL CONCEPT SUPPORTING AUTONOMOUS NAVIGATION

Svein P. Berge[1*], Marianne Hagaseth[1], Per Erik Kvam[2], Arne Rinnan[2]
[1] SINTEF Ocean AS, Postbox 4762 Torgarden, NO-7465 Trondheim, Norway
[2] Kongsberg Seatex AS, Pirsenteret, Havnegata 9, NO-7010 Trondheim, Norway

* Corresponding author e-mail: svein.berge@sintef.no

Abstract

This paper presents the hull-to-hull (H2H) project where the concept of hull to hull positioning and uncertainty zones are used to assist navigators and operators to perform safe navigation of objects in proximity to each other. Data from position sensors and geometry (2D/3D) data will be shared amongst the H2H objects to calculate for example hull to hull distance to help avoiding physical contact (e.g. steel-to-steel contact). H2H will utilize a variety of positioning sensors, including the European GNSS systems Galileo and EGNOS. The H2H project aims to develop open interfaces such that any H2H compliant equipment provider or user can use the services provided in the planned standard. Data exchange protocols will be based on existing standards as the IHO S-100 standard for geometry and zone descriptions and for describing additional layers needed for ECDIS. Finally, a working methodology describing the needed steps from use case descriptions to implementation of the necessary services is presented.

Keywords: *Autonomous navigation, IHO S-100, Standardization, Interoperability, Digital twins, GNSS, Galileo.*

1. Introduction

Moving from manned to fully autonomous unmanned ship operations requires very accurate and reliable ship navigation systems. Normally, ship navigation is based on several onboard sensors like GNSS, echo-sounder, speed log and navigational radar, as well as electronic chart system (ECDIS) in addition to visual observations by the officer on watch. In manned operation, sensor fusion, situational awareness and control are all done by human in the loop. In absence of human perception and observation, there is a need for additional sensors and new intelligent sensor fusion algorithms applied for autonomous navigation. During maritime proximity operations, like simultaneous operation with several ships, automatic docking and manoeuvring in inland waterways, the relative distances and velocities between the different objects are of major importance.

The H2H (hull-to-hull) concept, initially proposed by Mr. Arne Rinnan at Kongsberg Seatex in a proposal under EU's H2020 program [8], will provide exchange of navigation data supporting both relative positioning and exchange of geometry data between objects using a secure maritime communication solution (e.g. maritime broadband radio system [9]). The H2H solution will be based on existing open standards like the IHO S-100 standard and being prepared to support autonomous navigation. The protocol will preferably be open, such that any H2H compliant system from any vendor can connect and start using the services provided in the standard.

2. The H2H project

The H2H project is funded by the European GNSS Agency under the Horizon 2020 programme. The project is coordinated by Kongsberg Seatex (NO), and participants are SINTEF Ocean (NO), SINTEF Digital (NO), KU Leuven (BE) and Mampaey Offshore Industries (NL). The project started in November 2017 and will run for three years. The project will develop the H2H concept, propose standardization and study safe and secure communication solutions. An H2H pilot will be built and demonstrated in three use cases: simultaneous operation, inland waterways and auto-mooring.

3. The H2H Concept

The core functionality of H2H is to provide hull to hull distance between vessels, and to use the concept of uncertainty zone to visualize the uncertainty of the distance calculation.

To calculate the hull to hull distance it is required to know the location of a vessel's hull relative to the hull of other nearby vessel(s). The basic idea in H2H is to calculate hulls' locations on basis of geometric vessel models in combination with position sensors. The vessel models will be automatically exchanged on digital radio between nearby vessels. Additionally, to provide relative position measurements, sensor data might also be exchanged on the same radio link.

The geometric vessel models will be used to generate digital twins representing the vessels, and then the position sensor data will allow positioning the digital twins relative to each other. Hence, each H2H vessel will be represented by a digital twin implemented in H2H.

In addition to hull to hull distances, the hull to hull velocities are essential navigation information. H2H will therefore also estimate the relative motion between the digital twins, and from this derive hull to hull velocities.

The position sensors can be different types, including systems providing two- and three-dimensional positions (for example GNSS) and systems providing range measurements and angle measurements, as well as inertial systems. In the H2H pilot we will include the European GNSS systems Galileo and EGNOS. Galileo will be used in relative mode providing high accuracy relative positions between vessels, whereas EGNOS will provide an added level of integrity.

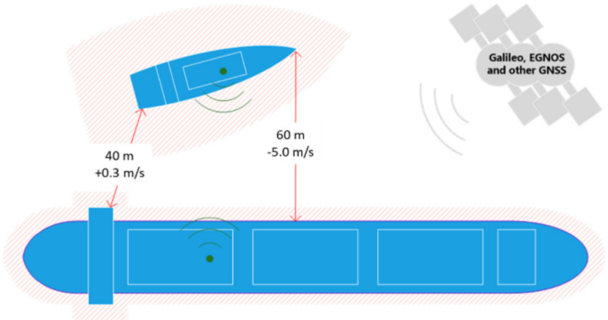

Figure 1. Uncertainty zones surrounding estimated hull location.

As shown in Figure 1, the uncertainty zone will surround the estimated hull location, and hence represent the uncertainty in the calculation of the hull's location. The size of the uncertainty depends upon the accuracy of the estimation of hull location. Therefore, the uncertainty zone will be derived on basis of the accuracy of the positioning sensors and the accuracy of the geometric model.

The concept is extended to not only providing hull to hull distance, but also distance between hull and static objects, for example a quay. Therefore, also the static objects might be represented as digital twins.

As shown in Figure 2, the H2H system has two external interfaces: 1) The H2H Engine User Interface and 2) The H2H Vessel-to-vessel Interface. Both interfaces will be based upon existing standards as far as possible such that different vendors can connect their own proprietary applications and systems following the H2H framework.

3.1 H2H Engine User Interface

The H2H Engine User Interface allows external applications to connect to H2H and obtain navigation information, for example hull to hull distances and velocities and uncertainty zones. Typical output data will be motion measurements, uncertainty zone, relative distances/velocities between different objects and support for ECDIS or other systems.

Real-time motion data for control applications (e.g. auto-docking, auto-mooring) will also be provided in the interface and necessary Quality of Services (QoS) measures (latency, data-rate etc.) will be supported.

3.2 Example of display system – ECDIS

ECDIS provides continuous position and navigational safety information. The system generates audible and/or visual alarms when the vessel is in proximity to navigational hazards. For inland waterway operations there is an own Inland ECDIS Standard [1] based on edition 4.0 for the Product Specification for Inland Electronic Navigation Charts (IENC). For inland waterway operations, the bathymetric data are of special interest. Inland ECDIS provides also the basis for other

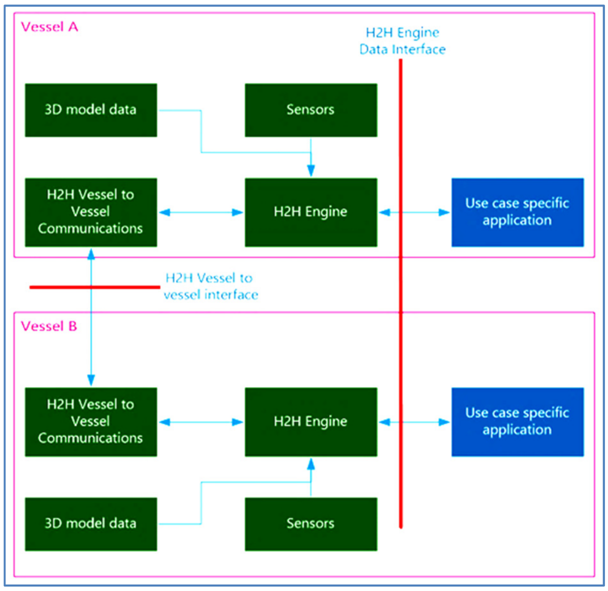

Figure 2. H2H Basic Modules (green boxes) and connection to external applications (blue boxes).

River Information Services (RIS), e.g. Inland AIS. Inland ENC must be produced in accordance to the bathymetric Inland ENC Feature Catalogue and the Inland ENC Encoding Guide. Typical information needed for the Inland ECDIS are;

- Position of own vessel including uncertainty zone
- Bathymetric data
- Navigational hazards (operational zones)
- Inland AIS
    - River Information Services (RIS)
    - NMEA data

Typical standards that are supported in ECDIS systems are;

- **IEC 61174 Ed.4.0** Maritime navigation and radiocommunication equipment and systems – Electronic chart display and information system (ECDIS) – Operational and performance requirements, methods of testing and required test results
- **IMO Resolution A.817 (19)**, Performance Standard for Electronic Chart Display and Information Systems
- **IEC 60945 Ed.4.0** Marine Navigational equipment, General Requirements. Methods of Testing and Required Test Results
- **IEC 61162-450/460** Digital interfaces for navigational equipment within a ship – Multiple talkers and multiple listeners.
- **IEC 61162-1,2,3.** Single talkers and multiple listeners (NMEA 0183, NMEA 2000)
- **IEC 529 Second edition (1989-11)**, Degrees of protection provided by enclosures (IP code)
- **AIS interface** is compatible with ITU-R M.1371 and IEC 61993-2

3.3 Vessel-to-vessel interface

The vessel-to-vessel interface is used for data exchange between H2H objects. The basic types of data to be exchanged is sensor data and geometric models, complemented with other navigation related data. The communication channel could be any wireless system providing required performance (bandwidth, latency, reliability etc.). Different communication solutions will have different bandwidth capacity and latency performance needed to be taken into account in the framework. To avoid cyber-attacks on an open wireless communication protocol, reliable mechanism to reduce cyber risk must also be implemented. IMO has in 2017 initiated the Guidelines on maritime cyber risk management to raise awareness on maritime cyber risk threats and vulnerabilities [2]. Typical, new signature and encryption systems for digital data and use of a public key infrastructure can protect against cyber-attacks on critical safety and operational information. There is currently no functionality or registry in the S-100 standard supporting cyber-security issues. Due to limited bandwidth, data can be serialized with less overhead using for example the **Google Protocol Buffer** to support a variety of programming languages (Java, Python, Objective-C and C++).

3.4 Standardization

As a starting point, we will investigate if the **IHO S-100 standard** could be used for the data exchanges in H2H. The S-100 standard is based on several ISO 19100 Standards covering spatial and temporal schema, imagery and gridded data, profiles, portrayal, encoding and so forth. For the H2H project, additional information about the vessel's geometry data (3D and 2D data), uncertainty zone (position uncertainty) and other operational zones will be proposed as amendments to existing standards.

Exchange of GNSS data supporting relative positioning might be done according to the RTCM standard [6], whereas the NMEA standard [7] is a good candidate for navigation information.

4 Uncertainty Zone

The concept of uncertainty zone was introduced above as a zone around the vessel which represents the uncertainty in the outer boundary of the geometry of vessels or objects of interests, as shown in Figure 1.

The uncertainty zones will be calculated by H2H, based on the accuracy of geometric vessel models and accuracy of the position sensors. The extent of the uncertainty zone from the hull would then represent this accuracy. The integrity requirement for the uncertainty zone will in the baseline application be expressed as the probability that actual position of a point on the hull will be inside the uncertainty zone with a probability of 95%. The probability of 95% has been chosen on basis of common standards for expressing accuracy for safe state in the maritime domain [10], [11]. However, specific applications could select other confidence levels for the uncertainty zone, adapted to their use case.

Uncertainty zone can be modelled as a polygon in either 2D or 3D. A polygon is defined as a plane figure (2D) or volume (3D) that is bounded by a finite chain of straight-line segments closing in a loop to form a closed polygonal chain or circuit. Each corner (edge) is defined by its coordinate including position uncertainty which can be modelled by a parametrized ellipsoid or a sphere.

H2H will be a flexible framework that allows using all available position sensors. The position sensors will be fused into a position and orientation estimator. This will then be used to locate and orientate the vessel model in a chosen coordinate system, for example a geographical grid.

The achievable accuracy, and hence size of the uncertainty zone, depends upon the both the accuracy of the position and orientation estimator, as well as how close the geometric model is in representing the physical hull. Hence, the size of the uncertainty zone, being steered by the accuracy, depends upon the quality of the sensors and the geometric models. A vessel well equipped with high quality sensors, including relative GNSS, and a precisely calibrated geometric model, could achieve uncertainty zones down to meters or even decimeters level.

Finally, it should be noted that the uncertainty zone could be dynamic. In case improved accuracy of a position sensor, for example when there are more GNSS satellites in view, then the uncertainty zone would shrink. Adversely, in case a sensor input disappears, then the uncertainty zone will increase. In case of a fallback to inertial navigation, then the uncertainty zone will grow with time.

Additionally, the uncertainty zone represents the uncertainty of a snapshot of the location of the hull, and does not take into account other constraints, e.g. external forces or vessel maneuverability. Those other constraints will be represented by operational zones, which are discussed in the next section.

5 Operational zone

Operational zones are any other zones than the uncertainty zone which need to be taken into account when navigating. The H2H concept will focus on defining and providing uncertainty zones related to the position accuracy, whilst the use case applications will define and implement operational zones related to different aspects of safe navigation. Hence, the H2H concept includes exchange and display of operational zones, whereas the calculation of the operational zones will be done by external applications that are adapted to specific use cases.

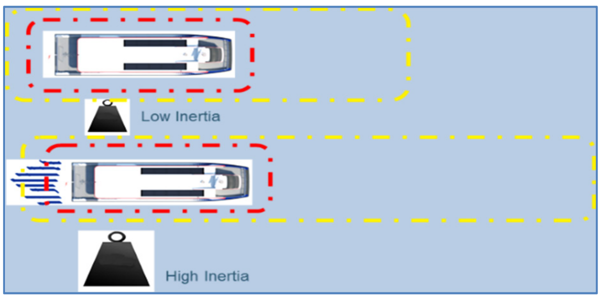

Figure 3. Examples of operational zones for inland waterways.

The uncertainty zone represents the uncertainty of the position of the hull at a given time. However, when it comes to safe distance between vessels and objects, also the vessel's dynamics and manoeuvrability need to be taken into account. Additionally, when navigating relative to a map, the map accuracy must be considered. Further, additional margins might be required to further reduce the risk of accident. As an example, if several H2H vessels are doing simultaneous operations, common safety zones or escape zones need to be transmitted to all interested H2H objects using the same zones for navigation. Safe navigation will also be different, depending upon type of operation and vessels involved, and could include distance, speed, course, maneuverability, etc. This will be included in the operational zones.

Other examples of zones are escape zones for offshore operations and different zones for inland waterways dependent on the vessel's ability to stop completely.

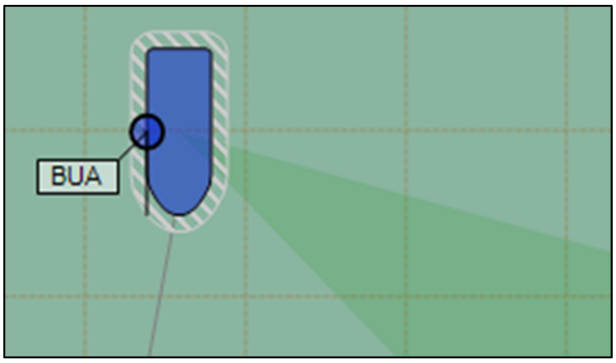

Figure 4. Escape Sector Zone.

Some of those zones are illustrated in Figure 3 and Figure 4. As a part of the next phase in the project, the H2H standardization work will define a format for representing the uncertainty zones and the operational zones.

Each zone can also be related to a specific contextual meaning, e.g. the **colour** is representing level of a warning or an alarm. It can be used to give guidance to the ship master or the control system on which navigational actions to take. Operational zone can be defined on top of a uncertainty zone or in some cases independent of a uncertainty zone. Operational zones are calculated by the Use Case Specific Applications and has specific semantics related to it as defined by the Use Case Specific Applications, for instance:

- **Warnings** to be raised when two zones are over-lapping or are in close contact, or when an object is entering a zone.
- **Recommendations** to specific actions to be taken by autonomous systems related to a zone, for instance for auto-mooring, where a new phase starts when an overlap is identified.
- **Access restrictions** to the zone, also linked to specific time periods, vessel types, vessel sizes and geographical areas. This can be used to indicate locks (including closing/opening times), quays or VTS areas. Another example is to use this zone to indicate fixed obstacles that must be passed on a certain distance, for instance the riverbank or navigation marks.
- **Navigational zones** to ensure that vessel keeps safe distance to other vessels and obstacles during navigation. Examples are the Waypoint Operational Zone defined for inland waterways passages indicating that the vessel should stay within this zone to ensure safe passage and the safe zones defined for two vessels approaching on a passage (collision avoidance).
- **Safe zones** and other zones related to safe operations that are used to indicate safe operations for vessels in close proximity with each other or to a fixed object, or escape zones, no-go zones, stand-by zones and responsibility zones.
- **Communication zones** can be an area of interest/first communication zone defining that a vessel moving into this zone should be made known to the object that has defined this zone and should start communication with this object in the cases where both objects are H2H compliant and able to communicate. This type of operational zone can be used to define what information to be exchanged at what time. This can be defined based on how several operational zones relates to each other or based on an object entering or leaving an operational zone.
- **Regulations**: Operational zone can be defined based on requirements given in maritime regulations for instance related to piloting, tug usage, reporting and VTS areas.

Each operational zone can be defined by a set of parameters that are listed in the following:

- **Shape:** This is the geometrical shape of the operational zone (polygon, circle etc.) and whether it is 2D and 3D. The shape (circle, ellipse, square, polygon) is determined by the Use Case Specific Application. The shape of an operational zone for a certain vessel can change during the different phases of an operation or navigation action. An example is a situation where two vessels are approaching and passing in close distance: When the relative distance between the vessels is large, having a circular or rectangular shape, or just a point, may be enough. When the vessels are moving in closer proximity, the shape of the operational zone may be based on the shape of the hull.
- **Size:** This is the size of the operational zone. The size of the shape must be determined, either by the diameter, length of the sides or by other means.
- **Time:** This is the time period when the operational zone is valid in case of time-varying information, for instance in the case of opening hours for locks and quays, bridge opening hours and mooring gear availability.
- **Information:** This is the information that is related to the OZ and is described by the following dimensions:
- **What information is transferred?** This can be information related to the vessel or fixed object: position data, geometric model, vessel dimensions, intended routes, already calculated uncertainty zones

and operational zones, among other kinds of information needed by the Use Case Specific Applications. It can also be operational information, as for instance warnings, recommendations, information about restricted waters or related to regulatory requirements.

- **When the information is transferred?** For an operational zone, the trigger for exchanging information can be defined to be for instance the time when two operational zones meet or when they intersect. It can also be when an object or vessel enters an operational zone. Further, it can be when a uncertainty zone meets or intersects with an operational zone. The timing of the operational zone information can be defined by the Use Case Specific Application user.

6 Development Methodology

Next phase in the H2H project is to work on the H2H framework defining the needed services for the two interfaces defined in Section 1.

Based on the work in the MUNIN [4] and MiTS project [5], we use the 3 layers model defining the conceptual, logical and technical layer, see Figure 5. Following this methodology, it is possible to break down the use cases into programmable interfaces (APIs) and data models for implementation.

As the modelling tool, we use the Enterprise Architect (EA) software from Sparx Systems. The EA is a visual and design tool based on the OMG UML. Typical work flow is to start defining the use cases where the interaction or activities between different actors and systems are visualized by simple symbols.

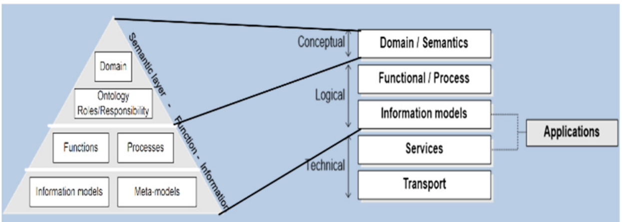

Figure 5. MiTS Architecture [5].

6.1 Use case specifications

Figure 6 presents the activity diagram for the simultaneous operation case in the H2H project. The text boxes show the system boundaries, while the oval shapes define the activities. Each use case has also a textual description based on a template which defines the goal, short summary, different actors, preconditions, triggers and successful scenario.

6.2 Main components

The right part of Figure 5. shows the main components of a proposed architecture as described in [4,5]:

1. **Domain and Semantics**: This is the definition of facts **about** what the architecture covers, including the definition of the area of interest: The domain model. This also includes business models: "Why a function is implemented". This layer is described by a domain model, an ontology and roles and responsibilities.
2. **Functional and process:** This layer describes **what** and **how** functions are implemented. This layer will focus on the minimum and generic aspects of the required functionality. This is described by use case diagrams.
3. **Information models:** This is the definition of the **required information** elements, including an exact definition for each element, its context, meaning and representation.
4. **Services:** Functions are implemented as a **number of services defined** in this layer. It also includes definitions of **information requirements for the services**. These are defined by APIs.
5. **Transport:** One also needs to consider the data transport mechanisms available to the services that needs to be covered by the communication solutions.

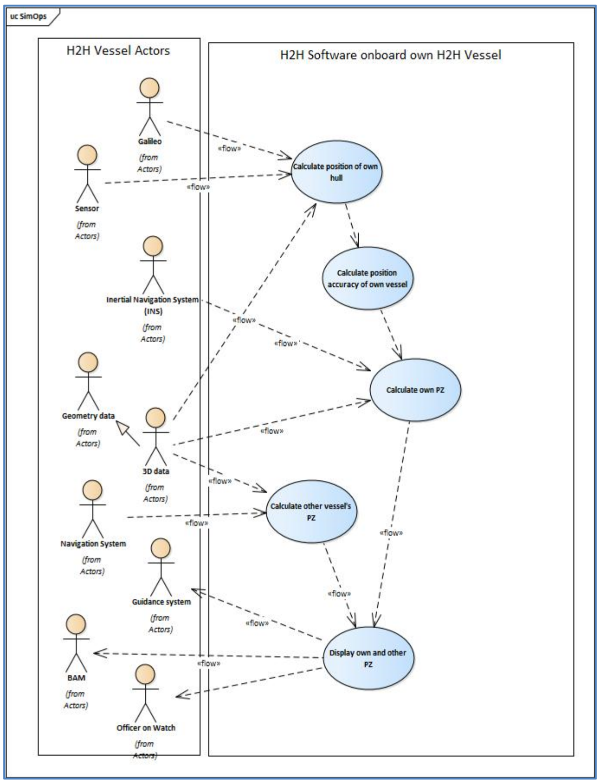

Figure 6. Activity diagram in EA.

7 Conclusion

This paper describes the initial concept of the H2H project defining the uncertainty zone as a measure of monitoring the physical distances between two or more objects, movable or fixed. This concept can be used to assist navigators and later being included into control systems for autonomous navigation. The H2H project supports the process moving from manned to fully unmanned autonomous navigation. The uncertainty zone calculation is based on exchange of 3D/2D models between H2H compatible objects and by use of GNSS Galileo or other positioning sensors if needed.

The operational zones are also defined and will be exchanged during maritime operations to provide necessary and additional information for safe navigation. The H2H project also propose open APIs both for internal communication on the ship itself and external communication from ship to ship using wireless IP network. The open API defines both the public data and services. Data security is obtained using authentication, authorization and encryption mechanism.

Three pilots will be developed within next year and used to demonstrate three different operations from open sea operation (simultaneous operations), inland waterways operations with hard constraints, and auto-mooring (ship-to-shore operation) by use of the H2H concept. Based on the user requirements for these three pilots, we will use the Design Methodology defined in Section 6 to derive the initial API including necessary services for all the three pilots.

As earlier mentioned, **the H2H concept does not yet focus on unmanned operations. Safety and risk are still managed by the operators.** Even if the overall goal of the project is to increase safety of close proximity operations, failures in the H2H system might give undesired consequences and reduced safety. The safety aspect should therefore be the backbone in further development of autonomous navigation when there is no human in the loop. **A safe design rule is to develop new autonomous navigation systems with at least the same level of safety as for the dynamic positioning (DP).** A fully unmanned, autonomous H2H navigation system will require an extensive safety analysis and may be divided into different classes like DP systems with different levels of redundancy in both hardware and software.

Acknowledgements

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DEFINING SHIP AUTONOMY BY CHARACTERISTIC FACTORS

Ørnulf Jan RØDSETH[1*]

[1] SINTEF Ocean AS, Trondheim, Norway
*E-mail: OrnulfJan.Rodseth@sintef.no

Abstract

Several papers have proposed ways to define levels of autonomy (LOA), i.e. how responsibility is shared between an automation system and a human when the automation system to some degree can operate independently of the human. The different LOAs are developed for different purposes and therefore often have different priorities for what parameters to use in the classification. This makes them difficult to compare. The main purpose of this paper is to propose a more general characterization scheme that can be used to clarify the description of the different LOAs and their practical meaning. It is suggested that the characterization should be done in terms of three main factors: Operational complexity; degree of automation; and operator presence. It is also proposed to subdivide operator presence into two parameters: responsibility onboard and responsibility in remote control center. The other objective of the paper is to propose the concept of "constrained autonomy" as one specific degree of automation. This proposal also includes an argument for how constrained autonomy may be able to improve human-automation interfaces and simplify testing of autonomous control functions.

Keywords: *Autonomous ship; Unmanned ship; Autonomy levels, MASS, Constrained autonomy*

1. Introduction

The International Maritime Organization (IMO) use the term MASS (Maritime Autonomous Surface Ship) for ships that fall under provisions of IMO instruments and which exhibit a level of automation that is not recognized under existing instruments. In the following, the term "autonomous ship" is used to mean a merchant ship that has some ability to operate independently of a human operator. This covers the whole specter from automated sensor integration, via decision support to computer-controlled decision making. An "unmanned ship" is a ship without crew that needs a certain degree of autonomy, e.g. when communication with a remote control center is lost. The term "automation" will be used for the abilities of a control system to implement functions that commonly have been done by humans. The term "autonomy" will be used to characterize a ship system (the ship and its support system onboard and on shore) that to some degree can operate independently of human operators. Thus, automation is necessary to implement autonomy, but automation will not in itself lead to autonomy. This distinction is not always used in the literature and when in the following levels of autonomy (LOA) is discussed, this refers to autonomy as defined above. To avoid confusion, the term "degree of automation" (DA) will be used to refer to automation levels.

Definitions of LOAs have received much attention over the years. One survey of the most common taxonomies investigated 14 different classification schemes [1]. This is to be expected as different LOA are developed for different purposes and with varying emphasis on different properties of autonomy or automation. However, this also introduces significant ambiguity in definitions of LOA, which can be exemplified by the preliminary classification levels used in the IMO regulatory scoping exercise for MASS [2].

This paper proposes another and complementary way to characterize ship autonomy. The main purpose is to provide better terminology to discuss and describe ship autonomy. This also includes the means to provide a more unambiguous definition of what different LOAs mean in terms of general ship autonomy [2]. The proposed taxonomy is still evolving. It is based on the original NFAS classification of ship autonomy [3], as updated in [4] and later adjusted in [2].

1.1 Levels of autonomy and human factors

Kaber [5] discusses LOA in the context of human-automation interaction (HAI). The paper particularly looks at the use of LOA as taxonomies to structure and improve analysis of human performance, workload, and situation awareness as well as some of the problems that this may cause.

Supporting systematic analysis of HAI is one important application of LOA. Many LOA are variants of the "pipeline" model of human information processing [6] as illustrated in Figure 1.

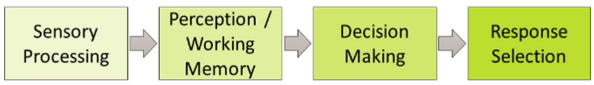

Figure 1. Human information processing pipeline [6]

In this context, higher degrees of automation imply that the human responsibility shifts to the right in the pipeline. This is not necessarily supporting autonomy as it always requires a human to be active or stand-by in the pipeline. Shifts to the right can also be argued to negatively impact situational awareness and cause "out of the loop" problems since it may mentally distance the operator from the physical reality. This can be a problem when the situation rapidly changes. The pipeline principle is also apparent in some LOAs proposed for the maritime sector, e.g. [7] and [8].

One of the points that Kaber makes is that LOA may not always be an accurate tool to predict human behavior or system performance. The introduction of increasing automation changes the way human and machine interact in many ways that may not always be captured by a given LOA classification [5], e.g.:

- *Complacency*: The system operator is satisfied with performance but may lack awareness of other safer or more efficient methods of operation.
- *Satisficing*: This represents an aversion to effort, by accepting a solution that meets minimum requirements, rather than looking for better solutions that are known or suspected to exist.
- *Lack of situational awareness, i.e. out of the loop problems*: Operator does not fully understand the situation and cannot determine the correct actions when human attention is required.

One can again argue that these problems may be related to the pipeline type HAI where humans are supposed to be continuously supervising the system, while most of the work is done by the automation. This paper will not try to fully describe or solve these problems, but section 6 will suggest that constrained autonomy may have the potential to reduce some of these problems.

1.2 One or several definitions of levels of autonomy

LOAs can be used to analyze human and system performance and, thus, support the design of new autonomous systems. There are also other applications of LOA, e.g. for use in safety and risk analysis [13] or as standard terminology in industrial developments [11]. It is not likely that it is possible to define one common LOA, even for one specific type of vehicle, system or application: Different LOAs will be needed for different purposes. However, this may cause confusion among practitioners related to what is meant by the different LOA classifications and how to compare them.

Thus, there is a need to find a more consistent terminology to discuss and compare the different implementation approaches to ship autonomy and scenarios, including definitions of LOA [2]. This may require a reduced focus on the details of HAI and an increased focus on higher-level design options in autonomous ship implementations. This does not mean that the HAI is not essential to safe and efficient operation of autonomous ships and that the classic LOA schemes are less important. Contrarily, it can be argued that a two-level approach to taxonomies can make it easier to apply more detailed and differently targeted LOAs more accurately on the different parts of the autonomous control system, including the human-machine interfaces.

2. Why a special taxonomy for ships?

Regarding autonomy, merchant ships have some special properties that tend to distinguish them from many other autonomous systems. These properties are common to other types of automated vehicles and systems that have been called "*industrial autonomous systems"* [10]. These are systems with high value, high damage potential and absolute requirements to cost-effectiveness. Specifically for autonomous ships, this means:

- Ships are high value assets with a potential for creating dangerous situations for itself or for other ships. *One needs to be conservative in how autonomy is applied.*
- Ship voyages can last for weeks, with long stretches passing by without creating any disturbing events for a remote human operator. However, when situations change, rapid responses may be required. *One needs to be careful in how autonomy is applied*
- Ship operations are very cost sensitive which requires strict cost controls both in capital investments and in operational costs. *One needs to be cost-effective when applying autonomy.*

In addition to these issues, and partly because of them, ships also lend themselves to significant flexibility in how they are operated. At deep sea and in calm weather the ship may be virtually fully autonomous, while in constricted waters and heavy traffic it may have to be fully under direct and remote human control. It is expected that remote control centers will be extensively used to supervise the autonomous ships, which adds flexibility in task assignments between ship and control center. One also has flexibility in how the voyage is planned, e.g. transiting constricted waters may be planned to avoid meeting larger ships. One may also make use of land based infrastructure as it is often better to complement ship sensors with more accurate situation information from shore. Some coastal state authorities are also investigating how to better support autonomous ships. This is in relation to pilotage, vessel traffic services (VTS) and other more general monitoring and control services. This can provide further flexibility in autonomous ship operations.

It is of particular interest to make autonomous ships fully unmanned. This removes living quarters, life support systems and much safety equipment from the ship, saving money, increasing cargo capacity and reducing environmental footprint. Unmanned operation is also of interest if one wants to create a fleet of more frequent and flexible transport systems, where crew costs on multiple ships would otherwise be prohibitively expensive [9].

These features mean that ship autonomy is qualitatively different from autonomy as proposed for, e.g. cars [11]. In cars, it is commonly assumed that one always has a person in the car that can either take part of the control or act as backup in case of failures. Trips are significantly shorter and there is normally not a remote control center.

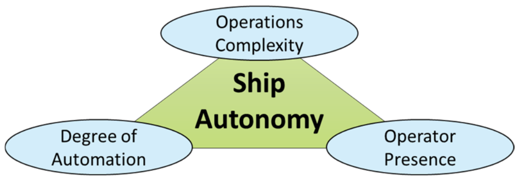

Figure 2. Autonomy as a function of three main factors

To cater for these issues, this paper proposes to define ship autonomy as a function of three main factors as illustrated in Figure 2. This is similar to the ALFUS framework [12], but differs in that "Mission Complexity" and "Environmental Difficulty" are merged into "Operations Complexity" and that "Human Independence" is split into "Degree of Automation" and "Operator Presence". These differences are directly resulting from the special requirements in ship autonomy as discussed above.

"Operations Complexity" and "Degree of Automation" will be defined in terms of "Operational Design Domain" (ODD) and "Dynamic Ship Tasks" (DST) as discussed in sections 3 and 4. "Operator Presence" covers both crews on board and in remote control center as well as sharing of responsibility between the crews. This is discussed in section 5.

3. Operations Complexity

The degree of automation is in principle independent of task complexity. A thermostat is arguably fully autonomous, in the sense that it keeps room temperature constant without needing any human interaction at all. However, its automation is not very complicated. Thus, there is a need to specify operations complexity in addition to the degree of automation.

To capture the complexity of the operations that needs to be performed by a ship, we propose to use the concept of the "Operational Design Domain" (ODD) from the SAE J3016 standard for cars [11]. The operational domain can be seen as multi-dimensional state-space $\boldsymbol{O}$ containing all expected system states s. Each s is normally a vector, but for simplicity, the vector sign is omitted in the following. Note that voyage complexity, level of autonomy and other factors will vary over a ships voyage, i.e. its time t and position p, so the ODD should be defined over the time and positions that are *relevant* for the ship's voyages, i.e. as $\boldsymbol{O}(t, p)$. This was discussed in [3] and [4] and will be returned to later in this section.

In addition to the ODD, one also needs to define a fallback space $\boldsymbol{F}$ that is entered when the ODD is exceeded, as illustrated in Figure 3.

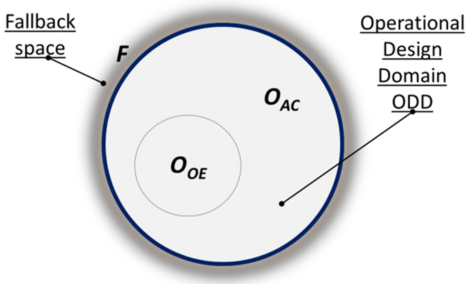

Figure 3. Operations Complexity

The ODD is used to define the operational envelope for the autonomous ship and its support systems. This includes all *anticipated* failures that should be handled by the ship and its systems. The ODD must consider the different ship functions and their constraints, e.g.:

- *G:* Geographic constraints.
- *T:* Other ship and vessel traffic constraints.
- *W:* MetOcean conditions and visibility.
- *V:* Vessel characteristics and capabilities.
- *N:* Navigational infrastructure, aids to navigation, etc.
- *P:* Port facilities and support.
- *C:* Communication system facilities.
- *M:* Mission characteristics.
- *R:* Minimum safety and performance requirements.
- *O:* Other constraints.

The ODD will consist of two sub-spaces, $\boldsymbol{O}_{AC}$, normally controlled by the automation systems, and $\boldsymbol{O}_{OE}$, controlled by the operator exclusively, see Figure 4. Any state that the ship can enter that is not defined in these two spaces will implicitly be in the "fallback space" $\boldsymbol{F}$, which will be discussed later.

$$\boldsymbol{O}(t,p) = \boldsymbol{O}_{AC}(t,p) \cup \boldsymbol{O}_{OE}(t,p) = \{O_G, O_T, O_W, O_V, O_N, O_P, O_C, O_M, O_R, O_O\} \quad (1)$$

In DNVGL class guidelines for autonomous and remotely operated ships [13], the ODD will form part of the CONOPS ("concept of operations"). The other part of the CONOPS will be the "Dynamic Ship Tasks" (DST): The set of tasks that the operator or the automation system must be able to execute to satisfy the ODD. A similar approach was used in the MUNIN project, where Unified Modelling Language (UML) "use cases" described the ODD and DST [14].

Also, the DST concept has been adapted from the SAE J3016 standard [11]. However, DST has been renamed from "Dynamic Driving Tasks" (DDT) to reflect the wider range of ship functions beyond only "driving", including, e.g. energy production, propulsion systems, safety functions and cargo supervision. The word "Dynamic" is used to highlight that these tasks are associated with the execution of a voyage and not the strategic planning or re-planning that takes place before and possibly during the voyage.

The DST is divided into Operator Exclusive tasks (OE-DST), that only a human operator is expected to be able to perform, and Automatic Control tasks (AC-DST) that the automation system is designed to handle, but where an operator, if available, can intervene. This is illustrated in Figure 4.

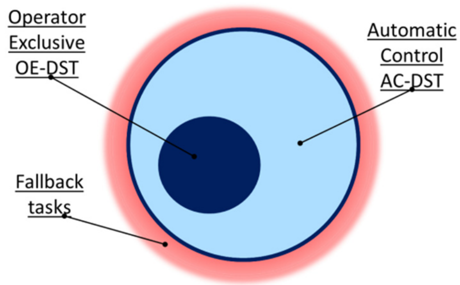

Figure 4. Division of task responsibility

There should be a defined function f in either of the DST function spaces $\boldsymbol{T}_{AC}$ and $\boldsymbol{T}_{OE}$ for each state s that can be entered into in $\boldsymbol{O}$, as shown in equation (2). The function may be to do nothing if the state is safe and sustainable.

$$\forall s \in \boldsymbol{O}(t,p): \exists f(s) \in \{\boldsymbol{T}_{AC} \cup \boldsymbol{T}_{OE}\} \quad (2)$$

DST fallback functions are required to handle reachable states outside the ODD and to bring the ship to an acceptable minimum risk condition (MRC). MRC does not include states related to anticipated failures or problems that are defined to be handled within the ODD. These shall be included in the ODD itself. One may also need more than one fallback strategy and/or MRC to handle different types of problems or situations. DNVGL stipulates that there generally will be two levels of fallback [13]:

- *Minimum Risk Condition (MRC):* Possibly recoverable states where some ship systems remain operational. These may be sustainable only for a limited time.
- *Last Resort MRC (LR):* These shall be sustainable until the ship can receive external assistance but may not be automatically recoverable.

The MRC is similar to what is sometimes called "Fail to Safe", but the MRC makes it explicit that one cannot in general define a completely safe state for a ship and for all external forces or threats that can be applied to it.

Fallback functions and MRC require that all relevant or "reasonably foreseeable" fallback cases can be identified, i.e. all transitions from states in $\boldsymbol{O}$ that can end up outside $\boldsymbol{O}$, as shown in (3). The fallback space $\boldsymbol{F}$ can be divided into $\boldsymbol{F_{LR}}$ for last resort fallbacks and $\boldsymbol{F_{MRC}}$ for normal fallbacks. As for $\boldsymbol{O}$, $\boldsymbol{F}$ will normally also be defined over the relevant time and positions for the ship's voyages.

$$\begin{gathered}\boldsymbol{F}(t,p)=\{\boldsymbol{F}_{MRC}\cup\boldsymbol{F}_{LR}\}=\\ \{\hat{O}_G,\hat{O}_T,\hat{O}_W,\hat{O}_V,\hat{O}_N,\hat{O}_P,\hat{O}_C,\hat{O}_M,\hat{O}_R,\hat{O}_O\}\\ \forall s\in\boldsymbol{O}(t,p),\hat{s}\notin\boldsymbol{O}(t,p),s\rightarrow\hat{s}:\ \hat{s}\in\boldsymbol{F}(t,p)\\ \forall s\in\boldsymbol{F}(t,p):\ \exists f(s)\in\{\boldsymbol{T}_{MRC}\cup\boldsymbol{T}_{LR}\}\end{gathered} \tag{3}$$

As for the DST functions, one should make sure that all states in $\boldsymbol{F}$ that can be entered into, can be mapped to a (possibly empty) fallback function.

The last resort MRC could be defined by creating states s that have the property that all events will still keep the system state in the same state s, see equation (4). The last resort states will normally be general and defined for a wide range of MRC states and events.

$$\forall\ s\in\boldsymbol{F}_{LR}(t,p):\ s\rightarrow s \tag{4}$$

Note that the definition in eq. (4) does not allow the ship to recover from a last resort state automatically. It will need some form of operator intervention to return to the ODD. This may be reasonable, as last resort actions most likely will be very basic, e.g. dropping anchor or shutting down propulsion. However, other last resort definitions may be necessary in some cases.

Figure 5 shows the general transitions between states in the DST and MRC, including the dashed arrow showing return to DST. As this transition often is operator controlled, it can be expected to go to OE-DST before going to AC-DST.

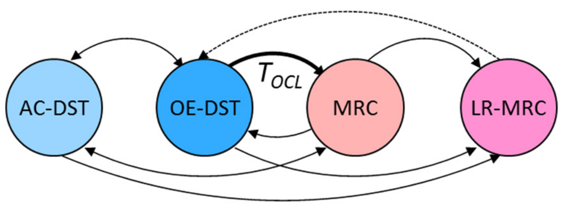

Figure 5. Transition between states in DST and MRC

In general, there will be a maximum time T_{OCL}, the operator command latency (*latency* [2], or *command latency* [13]), between entering the operator exclusive task state and before a fallback action is activated and the system automatically moves to an MRC. T_{OCL} will therefore be the operator's maximum allowed response time and will be discussed in sections 4 and 6.

Thus, the complexity of operation can be qualitatively described by defining the ODD, DST, DST Fallback and MRCs. It is obvious that the complexity rapidly can increase, as there are a high number of interacting components both in the $\boldsymbol{O}$ and $\boldsymbol{F}$ spaces. This has impacts on the testing and approval costs and on establishing acceptance criteria for the safe use of the autonomous ship. Cost-effective development and deployment of autonomous ships requires that the complexity is kept under control. This will be discussed further in section 6.

4. Degree of Automation

Section 1.1 discussed various forms of Human-Automation Interface (HAI) based levels of autonomy. It is clear that these LOA have important applications in various types of human factors research, but for a more general characterization of ship autonomy, they are often too detailed and also to focused on the human interaction issue. While the LOAs could be translated to correspondingly detailed degrees of automation, this paper proposes to limit the degree of automation to five basic cases, where the degrees are defined by the need for a human to be present at the control station, not what type of task the human has, when at the station. This classification was originally suggested in [3], further developed in [4] and updated in [2]. Although the word "autonomous" is used in the names of some of these degrees, this only means that the degree can be used to support system autonomy, not that the system becomes autonomous by the automation degree alone.

- *DA0 – Operator controlled*: Limited automation and decision support is available, as on today's merchant ship. The human is always in charge of operations and need to be present at controls and aware of the situation at all times.
- *DA1 – Automatic*: More advanced automation, e.g. dynamic positioning, automatic crossing or auto-berthing is used. Crew attention is required to handle problems defined in ODD as OE-DST, such as object classification and collision avoidance. The human may use *own judgement* as to how long he or she may be away from the control position. For automated fjord crossing in good weather, little traffic and in sheltered water, the operator may, e.g. be away from the controls for several minutes.
- *DA2 – Partial autonomy*: The degree of automation is higher than for DA1, but there are still limits to the automation system's capabilities. These limits are not defined or constrained (see DA3), so the human operator must still use *his or her judgement* as to the required attention level. However, it is assumed that the need for attention is lower than for DA1.
- *DA3 – Constrained autonomous*: The degree of automation is similar to DA2, but system capabilities are now constrained by programmed or otherwise defined limits. The limits are set to enable the system to detect that limits are exceeded and to alert the operator in time before operator intervention is required. After an alert, the operator has a maximum time of T_{OCL} before he or she needs to be back at controls and take remedial actions.

- *DA4 – Fully autonomous:* The ship automation can handle the full ODD without any intervention from crew. Fallback and MRC can be activated without crew assistance. Crew is not required at any time at control stations.

With respect to the system's ability to operate without human support, DA2 is very similar to DA1, although DA2 is meant to represent a significantly higher degree of automation. As the automation system's limitations in neither degree are known to the operator or the system itself, it cannot be known when operator intervention is necessary, and in both cases the operator may need to intervene on short notice. Section 6 will elaborate on this issue and argue why this degree of automation in most cases should be avoided.

It can also be argued that DA0 and DA1 could be merged into one. With the example of an autopilot in calm weather, little traffic and open sea, one can easily argue that this should fall under category DA1. However, to be able to distinguish between current ship systems and new more advanced systems that still require continuous human presence at controls, it is considered useful to maintain this division.

Thus, the focus of the proposed automation degrees is to indicate to what degree an operator needs to be present at a control position for safe operation of the ship. This is in contrast to some other classifications that put more emphasis on human factor issues and where in the HAI pipeline the automation system and operator meet.

Table I. Sheridan's ten levels versus five degrees (DA0 – 4)

Sheridan's ten LOA / DAn	**0**	**1**	**2**	**3**	**4**
human does the whole job up to the point of turning it over to the computer to implement	■				
computer helps by determining the options	■				
computer helps to determine options and suggests one, which human need not follow	■				
computer selects action and human may or may not do it	■				
computer selects action and implements it if human approves		■	■		
computer selects action, informs human in plenty of time to stop it				■	
computer does whole job and necessarily tells human what it did					■
computer does whole job and tells human what it did only if human explicitly ask					■
computer does whole job and decides what the human should be told					■
computer does the whole job if it decides it should be done, and if so , tells human, if it decides that the human should be told					■

If the proposed five DA are compared with a more traditional LOA scale, e.g. the one proposed by Sheridan [15], a comparison can be set up as in Table I. Dark cells show the correspondence between the two definitions.

DA0 covers the first four levels in the scale and this is caused by different human positions in the decision pipeline, while the human still needs to be continuously available to make the final decision. A similar phenomenon can be seen in the DA4 classification of levels 7 to 10, where the human is not actually needed in any of the cases and can be taken completely out of the control loop if desired. Note also that DA1 and DA2 maps to the same level 5.

5. Operator Presence

Making a ship completely unmanned removes the need for a hotel section, much of the safety equipment and enables completely new ship designs. This has a significantly higher potential for changing and improving maritime transport than just increasing automation onboard [9]. However, unmanned ships will in most cases require some form of remote monitoring and control. Having operator backup on shore is also becoming more common for manned ships, either for maintenance purposes [16] or for general supervision of ship operations [17]. Thus, different combinations of ship and remote control, is a very relevant direction for conventional as well as autonomous ships.

Thus, the third factor that is characterizing ship autonomy is the location and availability of the operators. In the following, crew availability will be designated as *LnRn,* where *L* and *R* means local on ship and remote off ship respectively and *n* specifies the degree of crew availability in each location:

- *0 – None*: There is nobody available to man the control position. The control position may not exist.
- *1 – Backup*: Person(s) are available to operate the control position but are not present. They need to be called and there will be a latency, that generally should be lower than T_{OCL} (see Figure 5), before they can resume full control.
- *2 – Available*: Person(s) are available at the control position but is not actively controlling the ship. In a remote control center, they may control or monitor other ships [18]. The operator can regain full control of the ship at short notice (usually shorter than T_{OCL}).
- *3 – In control*: Person(s) are at the control position, are in charge of and actively controlling the ship.

When two control positions are in use, it is also necessary to define what position is in charge and has the main responsibility for acting when something requires operator attention. The other position will be responsible for fallback responses in case the primary fails to act or acts in a way that put the ship at danger. It will normally be the control position with the highest crew availability that is in charge. In the nomenclature used in this paper, the position in charge will be marked with a star: *L0R2** means that the remote crew is in charge of an unmanned ship; or *L3*R2* means that the ship crew is in charge and directly in control, but have a shore crew actively monitoring operations, without taking control except in exceptional situations. The exception to this is in fully autonomous mode, when no one is in charge and the notation would be just *L0R0.*

For fully unmanned ships, it may also be relevant to have two remote control centers to provide fallback solutions in case the primary center is disabled for some reason. On many of today's ship one will also routinely have a situation where the manned bridge monitors the periodically unmanned engine room (L1R3*). The same classification and considerations can be used also in these cases. Note also that each different shipboard function, e.g. bridge watch, engine control or cargo monitoring may use different control level and operator presence.

Table II. Examples of operator presence and matching DA

Presence	DA	Explanation
L3*R0	DA0	Today's ship bridge
L1*R2	DA0	Periodically unmanned engine
L3*R2	DA0	Supervised operation from shore
L2*R0	DA1	Auto-crossing / berthing
L0R3*	DA0/1	Unmanned, full remote control
L1*R0	DA3	Periodically unmanned bridge
L1R2*	DA3	Supervised, unmanned bridge
L0R2*	DA3	Constrained autonomous
L0R1*	DA4	Monitored, fully autonomous
L0R0	DA4	Fully autonomous

Table II shows some examples of relevant combinations of operator control with degrees of automation (DA). Many other combinations can be envisaged for more specialized operations than those listed here.

The total number of crew, locally or remote, will often be an important cost factor and it is expected that this will be minimized where possible, i.e. one will normally prefer a high degree of automation to reduce crew. DA3 will allow a lower crew number in remote control than DA2 as each crew may monitor more ships.

6. Benefits of constrained autonomy

As pointed out in section 4, the maximum time allowed before a human operator is able to regain control needs to be considered before selecting degree of automation and human presence. From this it follows that partial autonomy (DA2) will not generally give more benefits with regards to manning levels than automatic (DA1). One should in most cases use constrained autonomy (DA3) instead. This section will extend this argument into two specific areas: A potential for avoiding some human factor problems and improved testability when constrained autonomy is used instead of partial.

6.1 Improved human-automation interface

Section 1.1 discusses some problems associated with human-automation interaction (HAI) that causes problems with operators' reduced vigilance and loss of situational awareness. It could be argued that the pipeline model of HAI (Figure 1) may contribute to this in that it increasingly separates the final human decision making from sensory input when degree of automation increases. An alternative model is the hierarchical control model, e.g. as presented by Brooks [19].

Figure 6. Layered control system according to Brooks [19]

This model increases degree of automation by adding new abstraction levels onto the closed loop control system. This relieves the human of tedious and detailed sensory processing and actions and could enable the operator to concentrate more on higher-level monitoring and control functions, without removing him or her from the sensory input. For a ship, this may, e.g. look like Figure 7.

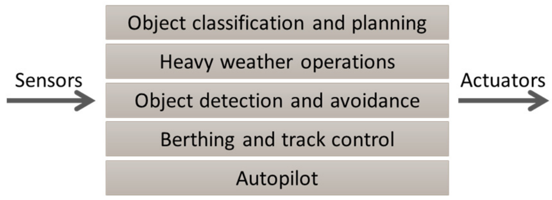

Figure 7. Possible layered control for a ship

For this model, it could be argued that by having humans supervising or acting as backup for higher levels of control, it may offer more deterministic latencies and a better environment for assessing the situation than in the pipeline model. However, checking and verifying this argument is outside the scope of this paper.

As constrained autonomy is defined in this paper, it includes two important principles:

1. The system is able to detect that the ability of the automatic functions will be exceeded; and
2. There is a minimum latency T_{OCL} associated with the automatic transition to MRC, if the operator fails to react to a necessary intervention.

The latter requirements can be expressed in (5), where all possible new states $\hat{s}$ in the Operator Exclusive ODD that can be reached from the current state s in the Automatic Control ODD, need to have a lifetime L greater than T_{OCL}. The lifetime function L estimates how long the new state $\hat{s}$ can safely be maintained without any action from the operator.

$$s \in \boldsymbol{O}_{AC}(t,p), \forall \hat{s} \in \boldsymbol{O}_{OE}, s \rightarrow \hat{s}: \ L(\hat{s}) \geq T_{OCL} \quad (5)$$

This means that, if the system is correctly designed, it is possible to alert the operator when situations escalates beyond the limits of automation and still give the operator enough time to gain a good understanding of the situation and to plan and execute remedial actions.

It is reasonable to believe that this approach should remove or reduce some of the human factor issues discussed in section 1.1. However, it should be noted that neither the author nor his team has examined this effect in any relevant studies.

6.2. Improved testability of functions

Traditionally, ship safety has been approved as shown on the left hand of Figure 8. Equipment and systems have been approved as "safe to operate" by being tested according to performance requirements, e.g. from class societies or the International Maritime Organization (IMO), and corresponding test standards. The crew has been certified to "operate safely", based on training and qualification requirements from IMO and national authorities. Included in the latter part is the assumption that by giving the crew proper training, the operators will be able to understand what actions to take when new situations or variants of trained situations are encountered.

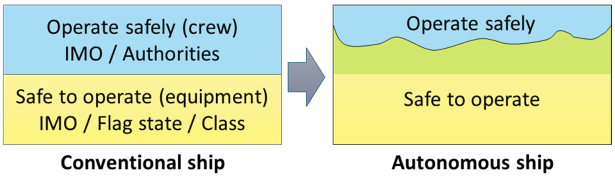

Figure 8. Approving safety of ships

With introduction of automation that takes over all or some of the crew functions, the "safe to operate" approach must now be applied to much more complex problems, where previously one relied on human flexibility and competence to handle variants in dangerous or demanding situations. In addition, one may also find that the limit between operators and automation's responsibilities becomes more blurred.

Traditionally, technical equipment has been tested according to test standards with prescriptive and quantitative test criteria. This will not generally be possible with the new control functions and a more risk based approach will be necessary. This has also been recognized by, e.g. DNV GL [13] and Class NK [21]. However, the agreement is that specific tests and test criteria will still be needed, also for complex functions.

Testing advanced autonomous ship functions poses several problems. The first is to determine the acceptance criteria for the overall functionality of the autonomous ship [20]. DNV GL argues for "equivalent safety" (to manned ships), but this is also problematic, e.g. in that it is not known how many incidents or accidents are *averted* by the crew on today's manned ships as indicated on the right hand side of Figure 9.

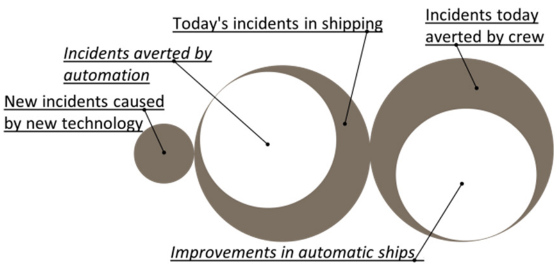

Figure 9. Assumed risk picture for autonomous ships [20]

The next problem is to define exactly what automatic functions are required, i.e. define the AC-DST. Following this, one will need to define performance criteria for all the identified functions.

Finally, one will also need to determine how to test the new functions. All autonomous ship functions are expected to be software intensive and proper procedures for specification and development of the software will obviously be required. However, it is unlikely that critical functions like object detection and classification ("lookout") and collision avoidance can be approved by other than test-oriented procedures that are able to verify the functions' capabilities in simulated or real scenarios.

Testing automated functions with complex behavior will obviously be difficult. As discussed in section 3 and shown in equations (1) and (2), the combinatorial complexity of the operational spaces $\boldsymbol{O}$ and $\boldsymbol{F}$ are normally very high, and this will make it very difficult to design test cases with sufficient functional coverage. In addition, one can assume that there are many rare combinations, particularly in anti-collision cases. To address this, one may use stochastic simulations, but it will still be a challenge to get statistically significant test results for rare cases that may never have been encountered before. Combining constrained autonomy with human assistance for the rare cases may help to solve this problem. Constraints may be defined to move the rarest and possibly unforeseeable cases out from the test space of the automated functions and leave them to the human operator.

Another problem is the use of, e.g. deep learning or similar techniques to train object classification or anti-collision algorithms. Deep learning implicitly makes it impossible to define a priori what the limits of the functions' capabilities are. This makes it difficult or even impossible to device good test-procedures when the test space is virtually unlimited. Constrained autonomy may again be used to define operational limits and by that enable test procedures with sufficient coverage for a more limited operational space.

However, it is not yet clear how easy it is to identify and implement the operational limits required by constrained autonomy. Object detection and classification limits may be relatively easy to quantify, e.g. by defining specific weather and environmental limits for reliable identification of objects of given sizes and types. Anti-collision capabilities may similarly be constrained by overall situational parameters, e.g. number of and distance to other ships as well as navigational complexity due to geographic restrictions.

Given the testability problems discussed above, it may be necessary to introduce constrained autonomy to get sufficiently well tested automated systems for partly or periodically unmanned ships. It will not solve the testing problem for fully autonomous functions, but it can certainly contribute to increased experience and knowledge about testing autonomous functionalities.

7. Summary and conclusions

Classification schemes for autonomous vehicles and ships in particular, are an area in constant development. As the autonomous ship is a relatively new concept, mostly dating back to the MUNIN project from 2012 [22], it is also natural that classifications evolve.

The usefulness of the different classifications of autonomy depends on their intended application. Developing classification schemes for human factors in teleoperations is different from classifications related to testing and approval of industrial autonomous systems like ships. The characterization scheme proposed in this paper is not a replacement for existing or other emerging classifications but is intended as a means to give a better and more formalized description of what the different types of classification actually means in terms of automation of a ship. The three factors used in the characterization, complexity, degree of automation and operator presence is thought to be sufficient and necessary to describe what is meant with an autonomous ship on a high level.

Limiting the degrees of automation to five is also thought to be sufficient for high-level descriptions of autonomous ships. The focus on the operator's need to be present is also suggested as a better metric than, e.g. metrics involving the location in the human information processing pipeline.

Furthermore, the concept of constrained autonomy may be necessary to develop fully or periodically unmanned ships. It can be argued that both human factor issues and testability problems can be significantly reduced by restricting the automation to functions that allows the system to alert operators sufficiently long before they need to take control of the ship. This may be an important step towards reliable and safe semi-autonomous ships and a contribution also to development of fully autonomous ships.

The ideas presented here are still being developed and it is hoped that this paper can be a small contribution to the ongoing discussions and future work.

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Outlook for Navigation - Comparing Human Performance with a Robotic Solution

M. Blanke[1], **S. Hansen**[1], **J. D. Stets**[2], **T. Koester**[3], **J. E. Brøsted**[3], **A. Llopart Maurin**[1], **N. Nykvist**[1], **J. Bang**[4]
[1] Technical Univ. of Denmark, Dept. of Electrical Engineering, {mb,sh,addlo}@elektro.dtu.dk
[2] Technical Univ. of Denmark, Dept. of Applied Mathematics and Computer Science, stet@dtu.dk
[3] Force Technology, {tsk,jebs}@force.dk
[4] Danish Maritime Authority, cjb@dma.dk

Corresponding author e-mail: mb@elektro.dtu.dk

Abstract

Considering whether a temporarily unattended bridge could be allowed, Maritime Authorities wish to investigate whether sensor technology is available that, when seconded by sophisticated computer algorithms, is able to provide outlook with the same reliability and safety as that of the average human outlook. This paper reports findings from a comparative study of human versus electronic outlook. Assessment of navigator's outlook is based on measurements with a wearable eye-tracker and areas of their visual attention are recorded on video. Simultaneously, a set of electro-optical sensors provides image-data as input to computer algorithms that detect and classify objects at sea within visual range. The paper presents the methodology used to deduct, from the observations of fixations, when the navigator turned his attention to a particular object and compares this with the Electronic Outlook. On the technology side, the paper details on how machine learning is used for object detection and classification, an discusses quality attributes, including efficiency and robustness of detection and classification, expressed through statistical measures.

Keywords: Outlook for navigation, autonomous vessels, electronic outlook, human outlook.

1. Introduction

Look-out for navigation is the task of observing various objects which can have an impact on a ships planned route and maneuvering capabilities, for example other vessels, buoys and land. If the outlook is a separate person on the bridge, observations are reported to the officer in charge who decide any remedial actions. The look-out is made using sight and aided by available technology such as RADAR, AIS and ECDIS systems. Development within camera technology and computer vision algorithms has provided an additional possible source for look-out. This study investigates the quality of this "electronic outlook" and compares with human look-out.

A survey of maritime object detection and tracking methods was published in the survey by [21], who emphasized that RADAR, which is required by IMO on merchant vessels, is sensitive to the meteorological condition and the shape, size, and material of the targets. They emphasize that RADAR data need to be supplemented by other situational awareness sensors to obtain safe navigation and collision avoidance. Electro-optical sensors were available in this study for several spectral ranges: visual (450-800 nm), near infrared, (NIR 800-950 nm) and long wave infrared (LWIR 8-14 μm). Outlook was based on eye-tracking by glasses that monitor the Navigator's areas of attention, judged by observed *fixations*. The eye-tracking glasses were limited to determine fixations on outside bridge objects in daylight conditions, and this defined the scope of comparison in this paper.

The paper first summarizes the task of watch keeping/lookout for navigation in Section 2, and 3 explains how human outlook is observed through measurements where a navigator wears eye-tracking glasses. Section 4 outlines the use of electro-optical and other sensors to provide electronic means to replicate the human observation of surroundings. Section 5 introduces present technology for object detection and classification at sea, showing the features obtainable with image processing and machine learning techniques, while Section 6 provides details on data and training. Section 7 presents results on object detection performance for the network chosen. Section 8 presents findings from ferries in near-coastal and shallow water navigation and Section 9 discusses limitations and perspectives of results. Finally, conclusions and future directions are offered in 10.

2. Outlook for navigation

A. Human outlook

The analysis of manual lookout/watch-keeping is based on a combination of observations on board several vessels in Danish waters. Electronic observations and Eye tracking measurements were conducted during the summer of 2018 on ferries in Northern Øresund and South Funen archipelago.

Further, but outside the scope of this study, generic observations were made on board a large number of vessels during the period 2000-2018. The generic experience also includes observations from ship simulator exercises at FORCE Technology in Lyngby, general knowledge on human factors as well as literature, see [25] and [27].

B. Endogenous and exogenous driven visual attention

The look-out task involves both endogenous- and exogenous-driven activities. Endogenous activities are visual attention controlled by the navigator himself on his own initiative and based on relevant knowledge and experience, such as observing navigational markings, sighting of land and watching out for other vessels. Exogenous activities are caused by an external (and in principle unforeseeable) event catching the attention of the navigator. For instance, the sight of a vessel which the navigator has not been looking for or some light or sound signals. Everyday scenarios will typically be a combination of endogenous and exogenous look-out activities.

It is important to be aware that the outlook is just one among several tasks of the navigator on the bridge. Other tasks include observation of the condition of engines and systems, communication and passenger and safety related tasks.

When it comes to performing an outlook, it makes sense to distinguish between pure observations not requiring action and observations requiring action, e.g. to prevent a collision. An action is often seen as a combination of several elements including signalling, steering and engine manoeuvres, but the decision to act could not be covered by the present analysis.

1) Recognition of objects: The navigator's recognition of objects is based on both the visual appearance and on the behaviour of objects.

This study has not employed means to disclose how the navigator interprets what he sees. The eye tracking glasses can determine where the navigator has had visual focus. The detailed recognition of objects and their behaviour are therefore not in the scope of this investigation.

3. Eye-tracking

In the maritime context, the use of eye tracking as means to examine the visual attention of ship navigators is nothing new. At least not when it comes to the use of eye tracking in simulation environments. [3] investigated the operators' foci of attention during simulated dynamic position operation. [2] examined the difference in attention-allocation comparing novice and expert navigators during use of the Conning Officer Virtual Environment, a simulation system developed to train ship handling. [2] concluded a clear link between the experts' superior ship-handling performance and a "tight Attention-allocation pattern that focused only on the relevant areas of interest. Novices' Attention-allocation patterns were highly scattered and irregular" (p. xviii). [19] and [23] focused on evaluating and improving the training of navigators using eye tracking data and [20] suggested using (stationary) eye tracking to determine or monitor the level of fatigue in the boat driver with the purpose of enhancing situation awareness. [11] used eye tracking data examination to suggest improvement of usability design on the ships' bridge layout and in the software's graphical user interface on a maritime navigation display. [12] also investigated eye tracking data in the pursuit of a recommendable optimal *visual scan pattern* for navigators aiming to mitigate the mental workload needed to monitor the increasing amount of technology used at ship's bridge.

A somewhat rare example of an investigation using eye tracking during actual, real life navigation was presented in [8]. They investigated gaze behavior data from 16 experienced and novice boat drivers during high speed navigation and concluded that novices looked more at

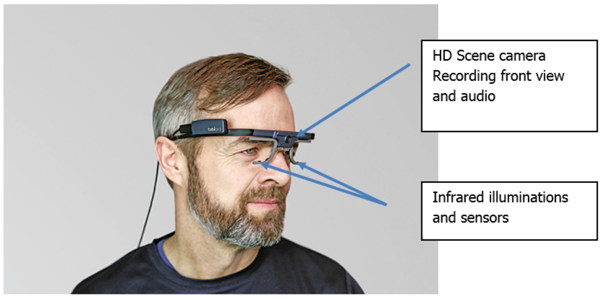

Fig. 1. Tobii® eye tracking glasses. (*photograph courtesy of FORCE Technology*)

objects closer to the boat while experts looked more at things far from the boat. Also, novice boat drivers were more focused on electronic displays, while the experts focused mostly outside the boat and used the paper-based sea chart to a larger extent than novice drivers.

The methodology of using eye tracking devices in real life maritime situations is not often seen, and is considered a feature of this study.

A. Eye tracking technology applied in this investigation

The eye tracking data was collected using Tobii® Pro Glasses 2 ([1]), which is a lightweight wearable technology illustrated in Figure 1

The head unit has a scene camera recording the wearer's front view (including audio) and the frame has infrared illuminators and sensors installed thereby using the eye tracking technique Corneal reflection (dark pupil). The belt clip unit holds a SD card for recording data, operates on rechargeable batteries and is Wi-Fi controlled through PC-based software (in this case iMotions®). This setup makes it very easy for the person wearing the eye trackers to freely move around on the ship and due to the non-invasive design, most subjects easily forget they are even wearing them while performing their job. Additional specifications are shown in the table below, adapted from the Tobii Pro Glasses 2 User's Manual (2018, p. 40). Based on the recording from the scene camera and the associated eye tracking data, the iMotions software (version 7.1) produces a video showing what was in the wearer's field of view during the recording (a 1st person perspective replay), including a graphical overlay. A yellow dot indicates where the person was looking at any given time, within the field of view. The software was set to illustrate fixations by increasing the size of the yellow dot. A fixation is defined as a period (100 ms or more) in which the person's eyes are focused on a specific object (or location) in the field of view. Fixations are excellent measures of visual attention [14], [19].

The image in Figure 2, shows a single frame from replay of an eye tracking recording. The yellow dot is the location of the navigator's fixation and the yellow line illustrates eye movements faster than 100 ms (ie. saccades).

B. Limitation in scope due to equipment

The eye-tracking technology was challenged by the high contrast between outdoor and inside bridge, and eye-

Fig. 2. Eye tracking example in dense traffic and confined from South Funen archipelago.

tracking could not reveal which objects on the Radar screen or on the ECDIS caught the attention of the navigator. Eye tracking could not be used in low-light conditions during dusk and evening. The electronic to human outlook investigation was therefore restricted to compare performance in daylight conditions.

4. Electronic outlook

The electronic outlook system in this comparison consist of 5 cameras, an FMCW RADAR and an AIS receiver for reference. The vision system is composed of 2 colour cameras (JAI GO-5000C 2560×2048, 12 bit), 2 monochrome cameras (JAI GO-5000M, 2560×2048, 12 bit) with longpass filters for the NIR range and 1 LWIR camera (Teledyne Dalsa Calibir 640, 640×480, 14 bit). The sensors are mounted on a forward facing stand on board, see Figures 3 and 4.

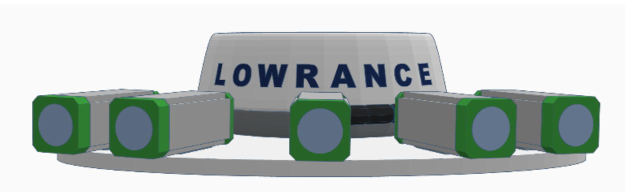

Fig. 3. Sketch of the sensor platform. The five camera houses are looking forward. Camera units, CW-FM RADAR and GPS receiver are mounted on the test platform. The combined horizontal field of view of two daylight cameras is 110 deg.

5. Object detection and classification

We wish to identify what objects are present on the water within a given distance from our vessel. Information about stationary objects such as buoys, rocks, bridge pillars and islands, and moving objects such as boats, ferries, etc. are important for positioning, navigation and collision avoidance.

A. Image-based Object Detection

We use image-based object detection and classification to determine what is present in the environment in which we navigate. Our electronic outlook system is continuously

Fig. 4. Southern Funen archipelago. Sensor platform mounted beyond wheelhouse / ship's bridge.

sampling images at a fixed rate, and we wish to know what objects are present in the images and where. This is valuable information that can later be used to determine the objects approximate position relative to our vessel.

For this task we use instance segmentation, which is a pixel-wise classification of the image. Using instance segmentation, we not only get classifications of the objects present but a segmentation mask of each of the instances in the image i.e. if more objects of the same class are present in the image, each of them are assigned a unique label. That enables us to potentially track individual objects from the same class.

Recently, data-driven solutions, such as deep neural networks, have proved to give robust and accurate results but these require large sets of annotated training data. Annotations often have to be done manually, and especially pixel-wise annotations for semantic and instance segmentation requires accurate annotations which can be cumbersome. Techniques that require less or no prior data also exist but tend to be less generalizable than a learning-based approach. Since our system is operating near the coast, many types and sizes of boats and ships can appear in the images. Additionally, we can have both land and water as background. The following provides an outline of some challenges for a maritime environment along with related prior work.

B. Related work

Several previous works address object detection, classification and tracking in a maritime environment. Challenges include waves that can cause a rapid change in the frame of reference [7], sudden change of illumination and unwanted reflections from the water [4], and the possibility of poor weather conditions that reduce the range of sight. As mentioned in the survey papers [21], [18] there exist a range of methods concerning detection and classification in images of the maritime environment, and horizon line detection and background subtraction seems to be effective for object detection [28], [26]. Methods include to utilize infrared and visible light images [21], but also thermal imaging alone has the ability to provide information about objects on the water [16]. With recent progress in deep learning based segmentation and classification methods, visible light images is an obvious choice for object detection since much training data, such as e.g. ImageNet [6], already exists and can provide a good base for training. Specifically for maritime environments, [15] and [5] show that deep learning methods are effective, and annotated data from the maritime environment exists [21]. This project has used training data collected from observations on-board ferries in Danish coastal waters.

C. Mask-RCNN detection and classification

Objects that are within visual range of the cameras are detected and classified using a Convolutional Neural Network (CNN), also referred to as deep learning technology. The network architecture employed in this project to detect different objects in the maritime environment is Mask-RCNN [13], which has the novelty of not only being able to recognize and detect (bounding box) of several classes, but is also able to segment all instances of each one and create the corresponding binary mask at a pixel level. Mask-RCNN is an architectural model that started with a Region-Based Convolutional Neural Network (RCNN) [10], followed by Fast-RCNN [9] and then Faster-RCNN [22].

6. Dataset and Training

We found that existing maritime image datasets are not sufficient to cover the scenarios we encounter in our recordings. Consequently, a subset of images is hand-annotated and used for both network refinement and to test the performance of the detection algorithm. The subset is labelled for instance segmentation so that pixels belonging to each object in the image is labelled separately with a polygon shape. Manually labelling of images for instance segmentation is a time consuming and to ease the process we use a free web-based annotation tool *LabelMe* [24] to create polygons. Each object is assigned to a class and Figure 5 shows how polygons are drawn for each object in a picture. The process of manual labelling an image with a few objects takes from 1-5 minutes depending on the complexity of the silhouettes.

The images annotated were captured with the on board RGB camera setup and additional images were acquired with a DSLR camera on separate trips. Images from internet sources are also added to the training data. All images were manually annotated using the above mentioned technique. In summary, the annotated images for the data-set consists of:

Data source	Number of images
On-board RGB camera setup	330
On-board DSLR	179
Internet source	8
In total	517

The 517 images are annotated with two classes: buoy and ship. A total of 600 buoys and 639 ship instances are annotated across the data-set.

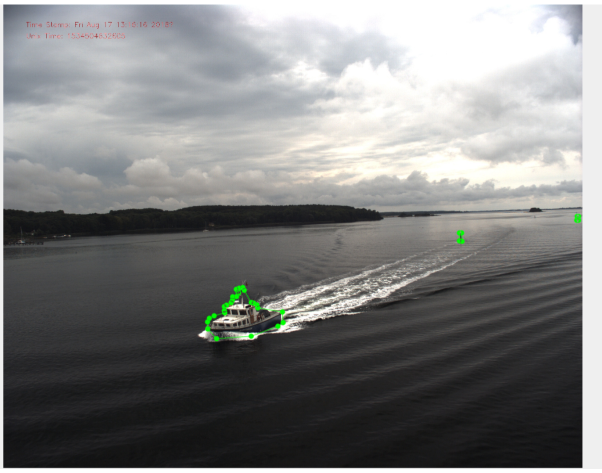

Fig. 5. Green polygons show the boundaries for one boat and two buoys that are present in this image.

A. Training

The on-board RGB images are split so that 406 images are used for training and 111 are used for validation. The validation set consists of images from the on-board RGB camera setup, as we wish to evaluate the performance of the object detection on the on-board camera system. To produce additional training data, data augmentation was used on each of the on-board RGB training images as follows: random rotation within a $\pm 25\,\mathrm{deg}$ range, flip image horizontally (mirroring), combine flipping and rotation, replace an image pixel with a chosen colour for every 50 pixels.

The augmentation increases the data-set with an additional 5×406 images. The images are cropped into 16 regions in a 4×4 grid. After this operation, the total increase of the data-set is $16 \times 5 \times 406$ images, resulting in $16 \times 5 \times 406 + 406 \times 5 = 34510$ images.

The Mask-RCNN uses the pre-trained weights obtained from the COCO dataset [17] and we fine-tune the network to detect the two classes provided in our training data: buoy and ship. The network was trained for 40 epochs on the first 4 layers (classificatory), then another 60 epochs for the rest of the layers and finally 80 epochs for the whole network. The learning rate was set to 0.0003 and the momentum was 0.9. The total training time took around 24 hours on a GeForce GTX 1080 GPU.

7. Performance

This section evaluates the performance of the network used through validation of images from the on-board RGB camera system. With the above-mentioned training procedure, we obtain a mean average precision (mAP) of 62.74%. The 0.5-mAP is used which means that intersections of regions less than 50% are not included in the calculation.

Object detection is done in two stages. First, detect and classify a relevant object in the image. Second, determine how accurately it is segmented. To discuss the results with the aim of supporting navigation, the mean average precision (mAP) is not very useful as a measure of quality. The reason is that safe navigation requires that

Reference			Detected & Classified			
			Buoy	Ship	$\sim$ Buoy	$\sim$ Ship
	near	Buoy	47	0	0	
		Ship	0	83		0
	far	Buoy	27	1	54	
		Ship	0	51		0
	none	$\sim$ Buoy	6			
		$\sim$ Ship		34		

TABLE I. Performance of the object classification. Detected objects are compared to objects that were labelled in the validation set. The number of detections is noted for two categories of objects: buoy and ship. The distance to objects are divided into near and far. The symbol $\sim$ denotes negation.

all objects are detected, which might present a risk to safe navigation. We therefore employ the standard terminology from statistics for quality assessment of object detection and classification:

True positive Object is present in a frame and is detected.

False positive Object is not present but a detection occurs.

True negative Object not present in the frame and no detection occurs.

False negative Object present in the frame but is not detected.

For our application, we need a good overall localization of the object in the image, but not necessarily a precise segmentation border around the object. We conclude that segmentation of the objects are acceptable in most cases where a true positive detection occurs, using visual inspection.

We also wish to investigate to what extent the network is detecting the objects it is supposed to find, the occurrence of false positives i.e. false classifications. To do this we note down the comparison of the reference (ground truth) annotations with the predictions provided by the network. The precision of the segmentation mask is omitted here, so it is only the object classification which is reflected in this part of the results. Note that our validation set consists of annotated images with one or more objects, but also images without objects are included in the set. Table I shows the results of the object detections and classifications. We consider the two object classes buoy and ship and divide the detections as near and far. The separation near versus far was determined by the estimated distance to an object in the frames.

The results in Table I show data for the validation set. Classification of nearby objects is very satisfactory. 100% of buoys and 100% of ships are found, and none are misclassified. With objects farther away numbers drop to 33% correct classification of buoys and 66% of ships. One buoy is detected but is misclassified as a ship. No ships are mistaken for buoys. False positives occur at far distance, a total of 6 buoys and 34 ships were detected without being present.

The numbers in Table I are valid for single frame recordings in the validation data set. Since the relative distance to objects are reduced as they approach, they are eventually detected and classified. The essence is that objects are detected and classified in time to plan a path for safe navigation and collision avoidance. Whether detection and classification of far away objects is critical therefore depends on time to encounter.

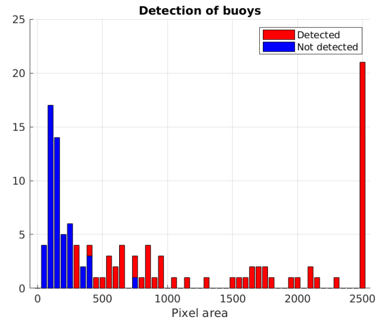

Fig. 6. Histogram of pixel area versus buoy detections.

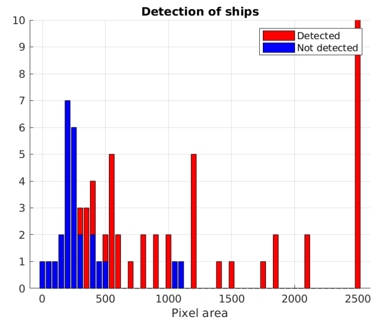

Fig. 7. Histogram of pixel area versus ship detections.

The false positives are often detections on the water where a piece of land far away is detected as a ship or in the region above the horizon line, where clouds are detected as ships. While it is not entirely straightforward task, we argue that a number of false positives in the cloud region could be removed by detecting the horizon in the image, as part of a robustification of the classification.

Classification performance is further scrutinized in Figures 6 and 7, which show missed detections in blue and correct detections in red colour as a function of pixel area. The Figure reveals that probability of detection raises sharply when object size in the image is above 450 pixels. All objects larger than 2500 pixels are detected but are not shown in these histograms.

Object classes were limited to *buoy* and *ship* to take advantage of the more than 3000 images of the class *ships* from the COCO data-set. For assessment of properties of the objects met at sea, it would be an advantage to add more classes to cover navigation and manoeuvering capabilities of nearby objects.

It is noted that the above statistics are based on inspection in the visual range only. Additional sensors such as near infrared and thermal imaging provide additional valuable information, but have not yet been included in the classification pipeline in this stage of the study.

8. Results

This study compares the human outlook by assessing the fixations determined by the eye-tracking system with object classifications made by the electronic outlook. Eye-tracking glasses were unable to determine areas in focus on RADAR or on the electronic chart display (ECDIS) screen on the bridge.

Comparison between the capabilities of electronic outlook and the human counterpart are therefore done looking at the instant of first observations of a given object. The eye-tracking software gives an indication of fixation on an object when the human lookout has been gazing at it for $100ms$. This time is compared to the time-stamp that the Mask-RCNN indicates its first detection and classification of the object. Figure 8 shows a snapshot of eye-tracking. The right part shows what the lookout is focusing on. The yellow line on this shows that the eye focus wander around, which is normal. Fixation is indicated by the red circle. The Electronic Outlook is illustrated in Figure 9.

A. Temporal Comparison

This section presents an analysis of the time-wise differences between the electronic lookout system and the human counterpart. This is achieved by time-stamping detection of objects observed by the electronic lookout and comparing them with fixations captured by the eye-tracking system. A comparison is done by examining the difference

$$\Delta t_{obs} = t_{HO} - t_{EO} \tag{1}$$

where t_{HO} is the time that the eye-tracking system indicates the first fixation on an object, and t_{EO} is the time that the electronic outlook first detects and classifies the same object. Figure 10 shows a histogram of Δt_{obs}. Figure 11 shows the time difference Δt_{obs} histogram for ships and buoys separately. A positive value of time difference means that electronic outlook classifies an object earlier than the navigator has a fixation on it.

The time elapsed between the instant of detection of an object and the instant when this object passes behind the RGB camera's field of view is defined as the time to react. Two time differences are defined to analyze this characteristic,

$$\Delta t_{HO} = t_{pass} - t_{HO} \tag{2}$$

$$\Delta t_{EO} = t_{pass} - t_{EO} \tag{3}$$

where t_{pass} is defined as the time instant when the object passes behind the RGB cameras' field of view.

Figure 12 shows Δt_{HO} vs Δt_{EO}. The range is $0-200$ s before passing own vessel. In average, electronic outlook allows more time to react.

9. Discussion

Since the ship has a RADAR and AIS sensors on board, the detection of objects that are visible to RADAR or have AIS transmitters, could be done quite accurately. However, several objects are not visible on RADAR, such as leisure surf borders and sea kayaks, boats without RADAR reflector and AIS transmitter, and even containers that accidentally dropped over board. Electronic outlook with object classification is therefore essential for the ship to act in a safe manner.

Object detection performance of the Mask-RCNN network showed a satisfactory detection probability for objects larger than 400-500 pixels in an image, a quantification that is useful for camera system design for electronic outlook. However, a few outliers exist in the form of some false detections and very few missed detections. Missed detections can be critical and are believed to be a consequence of lack of training of the network. Sufficient coverage in the training of a neural network, and robustness of detection, are challenges that need be further addressed. A combination of neural net classification with more classical image analysis methods, addition of object tracking, and fusion with other sensor information could be ways to obtain robust classification.

A combination of object positions from these sensors and the Mask-RCNN architecture could increase the performance and the results. Examples include object tracking from camera information and using detected objects positions, by vision sensors and by Radar, as possible region proposals in the network.

Further results will, therefore, fuse on-board RADAR and AIS information with visual information in different spectral ranges. This will include calibration that enables RADAR and AIS data to be projected into e.g. the pixel-coordinates of the input images to the CNN. This data could be used for region proposal in the network and be particularly useful in situations with reduced visibility of the cameras.

A. Coverage of this analysis

Some of the elements of look-out are not captured by only observing the fixtures with eye tracking glasses, but would require further interpretation. This includes: general visual observation of nothing in particular, but often focused on the direction of the vessel and abeam/passed objects in relation to progression of the navigation; exogenous-oriented attention – something turns up - can include comparison or verification with information from Radar and AIS; endogenous-driven observation of objects from other sources – sea charts, Radar or AIS .

Such interpretation of the situation was not part of this study.

B. Electronic outlook as a fifth sense supplement for the navigator

Look-out is just one among several tasks of the navigator on the bridge. Other tasks include: observation of the condition of engines and systems; handling of cargo and passengers; safety-related routines; communication internally on board the vessel and with external parties; management of staff and other administrative tasks; QA and documentation tasks; handling of safety-critical situations on board.

With several other tasks to care for, which might sometimes distract the navigator, it is believed that electronic

Fig. 8. Eye-tracking of the manual look-outs fixations. Left: Forward facing camera used as reference in the analysis. Right: Eye-tracking result. The yellow spot surrounded by a thin red line indicates fixation on an object.

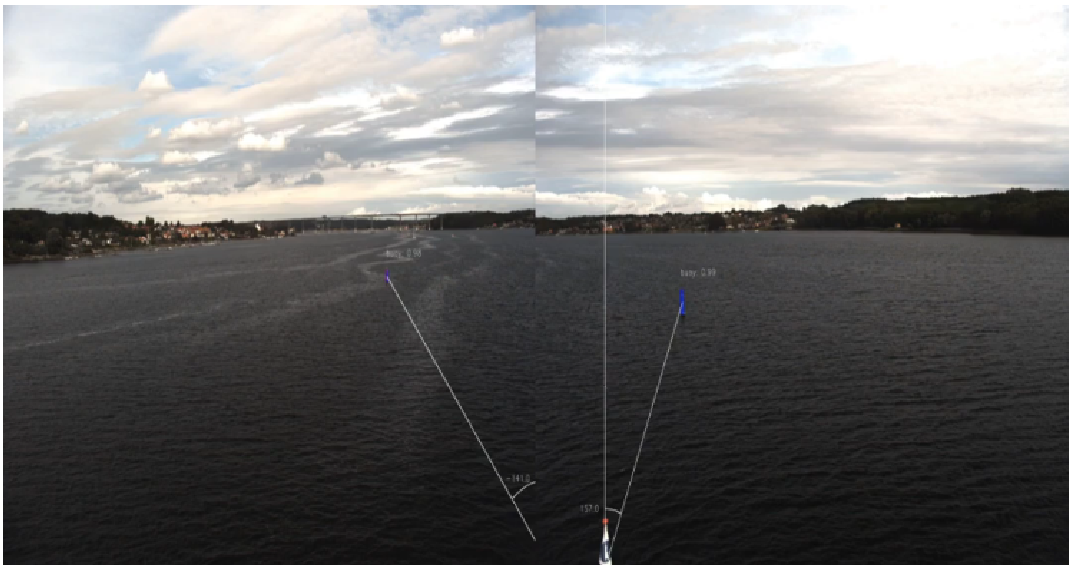

Fig. 9. Object detection and classification on two RGB images are shown by highlighting the detected object in green colour and showing the bearing to detected objects.

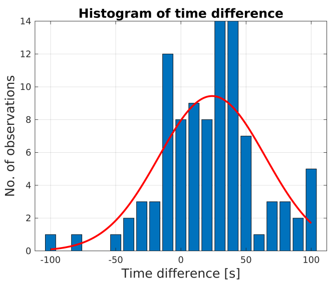

Fig. 10. Histogram of time differences between observations done by the human and electronic lookout (calculated by (1)). The imposed normal distribution has the following parameters: $\mu = 23.9$ s and $\sigma = 41.0$ s. Electronic outlook classifies objects earlier than the human eye fixation by $24s$ in average.

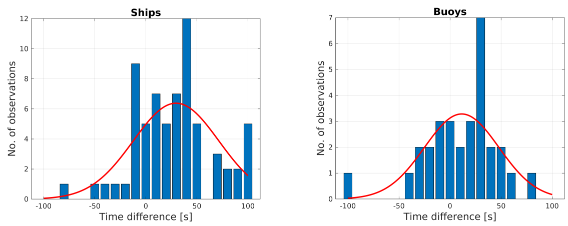

Fig. 11. Histogram of time differences between observations done by the human lookout and the electronic lookout (calculated by (1)). In mean, the electronic outlook detects and classifies objects 30 s faster for ships and 11 s for buoys, compared to human eye fixations. Negative outliers should be avoided by improving robustness.

outlook could serve as a *fifth sense* for the navigator and perhaps pave the way for temporally unmanned bridge in conditions with little other traffic.

10. Conclusions

This study compared human outlook with electronic. Using instance of fixation of eye-tracking glasses with instance of electronic outlook by cameras and mask-RCNN classification, the study provided statistics for a comparison on one of the essential parameters. The performance of the Mask-RCNN was evaluated on the validation set of annotated RGB images. Object detection performance showed a satisfactory detection probability for objects larger than 400-500 pixels in an image, a quantification that is useful for camera system design for electronic outlook. Some outliers were found to exist in

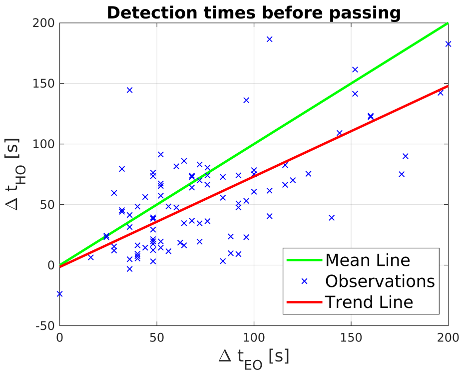

Fig. 12. Scatter diagram of time to react. The plot shows the range $0 - 200$ s. The trend line shows that time to react is longer with electronic outlook than time after a fixation.

form of false detections. A single instance of missed detection was also found in the validation data. Robustification of the classifiers will be needed to obtain the required dependability of electronic outlook and is a topic of further research.

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HUMAN FACTORS ISSUES IN MARITIME AUTONOMOUS SURFACE SHIP SYSTEMS DEVELOPMENT

Hannu Karvonen[1*], **Jussi Martio**[1]
[1] VTT Technical Research Centre of Finland Ltd, Espoo, Finland

* Corresponding author e-mail: hannu.karvonen@vtt.fi

Abstract

The human side of highly automated maritime systems can often be neglected in their development. Paradoxically, history and scientific studies have shown that with highly automated systems, there is still a crucial need for humans to monitor the automated operations. Humans also need to intervene to and control the automated operations particularly in exceptional situations and maintenance operations. Therefore, especially human factors engineering is in a key role when developing maritime autonomous surface ship (MASS) systems. This paper discusses some of the related issues, like automation awareness, cognitive workload, trust in automation and technology acceptance that should be considered in detail when developing MASS solutions. A case study is presented on the development of a ship-handling simulator with an autonomous ship collision avoidance system and it is discussed how to apply the simulator to human factors-oriented studies of MASS systems design and evaluation. The design implications for MASS development on a more general level are also presented. By taking the human aspects of MASS systems as a central focus point in the development, it is possible to create safe and successful maritime innovations for the future.

Keywords: *Human factors, Maritime autonomous surface ships, Collision avoidance, Systems development*

1. Introduction

In developing autonomous maritime systems, the technical efficiency, liability issues, and the reduced operational costs have drawn much of the attention. Consequently, the human elements of the operations seem often to be forgotten from the development. The reason for this phenomenon may be, for example, that with autonomous systems it can be thought that humans are no longer needed and their role in the final environment does not need much consideration.

Quite paradoxically, many previous human factors studies (e.g., [1-3]) have shown that typically with highly automated systems, there is still a crucial need for humans to monitor the automated operations. Therefore, system autonomy does not directly mean completely unmonitored operations. Hence, if the human's role in the development of autonomous systems is not considered on a sufficient level, shortcomings related to both safety and human well-being may arise.

Typically, humans still need to supervise and analyze the operations done by the autonomous systems. Humans also have to intervene and control the systems particularly in exception situations either on the spot or remotely. For example, humans are needed in conducting maintenance operations on-site if some mechanical or hardware fault happens with the used technology.

In this paper, we wish to address some of the relevant human factors issues in the development of maritime autonomous surface ship (MASS) systems. We also present a case study about the development of an autonomous ship collision avoidance system, discuss how to apply it to human factors-oriented research studies, and draw implications for the design of successful autonomous maritime solutions.

2. Background

To account for the human side of (semi-)autonomous systems already several approaches, methods, topics and fields of science exist that may be considered in systems development. First of all, the human factors and human-computer interaction (HCI) with these systems should to be taken into account in their design.

Second, considering the human aspects in the development of autonomous systems can include the study of ethical or moral issues of a certain automation system that brings about changes to work tasks and ***also*** possible reductions in workforce. Third, topics such as how to make autonomous systems more acceptable in the eyes of the users or the wider public are relevant.

Fourth, it is essential to assess what are the organizational, cultural, political and societal impacts of higher degrees of automation, and how to support the changes brought by the systems. Fifth, the utilization of different user-centered design approaches in the systems development is crucial in increasing the probability of success of the systems. Finally, possible privacy and security-related problems for humans may need addressing.

Out of these different human aspects of automated systems, the focus of this paper shall mostly be on the general-level human factors issues of remotely operated and highly automated maritime systems.

3. Some Relevant Human Factors Issues and Approaches in MASS Development

In this section, we first discuss some of the relevant human factors issues and challenges of autonomous systems in general. Second, we go through some analysis and design-oriented human-machine interaction approaches that can answer to these issues and challenges.

3.1 Human Factors Issues and Challenges

Some relevant human factors challenges of remotely operated and automated systems include issues like 1) situation and automation awareness, 2) division of tasks between the human and the automation, 3) level of user experience (UX) and usability of the solutions, 4) appropriate trust in automation, and 5) the provided user interfaces and data visualization techniques. Each of these will be discussed shortly next in more detail, one topic per paragraph.

With MASS, it is essential to think that how the remote human operators monitoring the autonomous systems can achieve and maintain an adequate situation and automation awareness. Situation awareness refers to "the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status" [4]. Additionally, in highly automated environments, also automation awareness becomes relevant. Automation awareness has been defined as "a continuous process that comprises of perceiving the status of the automation, comprehending this status and its meaning to the system behavior, as well as projecting its future status and meaning" [5]. In highly automated remote-operation settings with complex situations, the development and maintenance of both situation and automation awareness becomes often very challenging task.

It is also important to consider the division of the tasks between humans and the automation in order for the humans to not have too much cognitive workload or, on the other hand, too boring tasks in MASS operations. Here, for example, psychological knowledge about the limitations of human cognition and activity is needed. Optimal division of tasks guarantees not only safe operations, but also the well-being of the human operators working with the automated system for long periods.

In addition, the level of user experience [6] and usability of the automated solutions that humans are interacting with is crucial. If the systems are hard to understand and use, the users cannot comprehend what is the current situation and act accordingly. This can result in human out-of-the-loop performance problems (e.g., [7]), which can be detrimental in safety-critical operations.

Likewise, the building of appropriate human operator trust in automation, for example, by means of design is important. Here, trust can be defined as "the attitude that an agent will help to achieve an individual's goals in a situation characterized by uncertainty and vulnerability" [8]. The agent in this context is the (semi-)autonomous system that is working with the human to achieve the task objectives. Appropriate trust, on the other hand, is well-calibrated trust in automation that matches the capabilities of the automation (see Fig. 1). In contrast to appropriate trust, overtrust or distrust in the system may occur, which can result in safety- or performance-related problems.

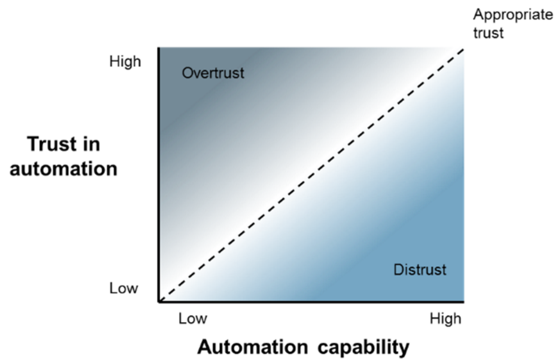

Figure 1. A simplified model of appropriate trust in automation. Figure adapted from and modified based on [8].

Finally, the human-machine or user interfaces, including their data visualizations and interaction techniques, need to be designed and utilized from the users' perspective. Specifically, the data visualizations in the user interfaces used to monitor the autonomous systems need to be simple and understandable for the users. In addition, modern user interface output techniques, like virtual and augmented reality, may be utilized in operations, for example, to highlight or visualize relevant issues from the object environment. In the input interface techniques side, for instance, novel speech and touch control approaches are becoming popular in many environments. However, from the human factors point of view, it should not be forgotten that it can often be much easier and more reliable to conduct routine tasks with a normal keyboard and a mouse compared to some flamboyant new interaction technique that becomes cumbersome in the long run.

Some of the above-mentioned and also some other MASS-related human factors challenges have already been discussed in the previous literature, for example, in [9]. For the purposes of this paper, we do not go into details of many of the other relevant issues and challenges here.

3.2 Human Factors Approaches

To consider more specifically the human factors and HCI issues in systems development, many human-machine interaction analysis and design approaches have been developed. In the analysis side, typically used data gathering methods include user interviews, questionnaires, and observations. The data gained with these methods can be analyzed later on from voice and video recordings, screen tracking videos and system usage logs. In the analysis phase, this data can be used, for example, to conduct task analyses, assess the user experience/usability of the used tools, or in evaluating the level of users' situation awareness and mental workload in different situations.

In addition, based on the analyzed data and gained results, it is often possible to give design recommendations and suggest concept design solutions. To further facilitate the concept design phase, there are several approaches, like focus groups, scenario stories, storyboards, and lo-fi sketches/prototypes that can help the users to understand what the designers have planned, give design feedback, and even possibly ideate new solutions. In an iterative manner, a Concept of Operations (ConOps, [10]) for the final system can ultimately be developed in the early phases of design.

When the final concept is chosen and the actual system development work starts on a more full scale, human factors engineering (HFE, [11]) approach should be systematically and holistically utilized. This can also include elements from conducting core-task design [12] and setting UX goals [13,14]. In addition, for the design of user interfaces in more detail, there are several approaches, like Ecological Interface Design (EID, [15]) or Information Rich display Design (IRD, [16]), to help the human-machine interface designs to be more intuitive from the users' perspective.

Shortly put, there are a lot of different methods and approaches available, but behind these various labels, there are a lot of similar aims and thinking. Typically, the basic idea in them is to put the human or user into the center of the design and evaluation work in order to produce systems that are successful and accepted by the stakeholders.

Next, we present a reference case study where we have utilized some of these approaches and methods mentioned above and elaborate on how they could be used in further studies.

4. Case Study: Autonomous Ship Collision Avoidance System Development

VTT's background in previous human factors-oriented studies has allowed the development of a ship-handling simulator system (see Fig. 2) based on the user needs, work demands and also the environmental constraints of different vessels. In addition to basic interview and observational studies of professional seafarers conducting navigational tasks in the simulator, we have conducted a core-task analysis [17] of the command bridge work done in several different ship types, such as tugs, container ships and platform supply vessels [18, 19]. In addition, the autopilot of the simulator has been programmed to work based on the decisions made by expert seafarers in earlier studies with the simulator. The ConOps of the ship-handling simulator is a result of years of iterative development work. As many parts of the simulator are self-developed by VTT and the whole system is aimed to be a research simulator (in contrast to a training simulator bought directly from a supplier), it is a very flexible tool that allows the modification of its different parts very fast and easily.

Figure 2. VTT's ship-handling simulator.

Recently, at VTT we have been developing a research tool that aims to be flexible enough also for the different needs of the development of MASS systems. This tool is an autonomous ship collision avoidance system that is implemented on our ship-handling simulator. The research objectives that the system allows to be investigated include, but are not limited to, the fulfilment of navigational regulations (e.g., COLREGs, The International Regulations for Preventing Collisions at Sea), simulations of realistic data connectivity errors and delays, functioning of the AI algorithms in different situations, and human factors issues of MASS systems.

Generally, an autonomous ship collision avoidance system includes three subsystems: Situation Awareness (SA), Decision-making and Autopilot systems (see Figure 3). Firstly, the SA system creates an assessment of the current surrounding traffic situation and environmental conditions by using different cameras and sensors, their sensor fusion and analysis algorithms. Secondly, the Decision-making system utilizes the evaluation of the current situation provided by the SA system and makes decisions based on the implemented rules (e.g., COLREGs). Finally, the Decision-making system commands the Autopilot (or a Dynamic Positioning [DP]) system to steer the vessel to the desired location. VTT's Autopilot includes three modes: track, heading and docking mode that are utilized for different navigational purposes. So far, the research and development of VTT's MASS collision avoidance system has been focused especially on the Decision-making and Autopilot modules, but future plans include to extend them to SA system aspects as well.

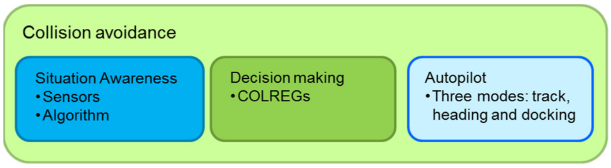

Figure 3. Subsystems of a Collision Avoidance System.

Together with the developed collision avoidance system, VTT's ship handling simulator offers a flexible platform for the verification and validation (V&V) of autonomous navigation systems. An autonomous navigation system can be integrated to the simulator similarly as it would be installed to a real ship. With the simulator, different scenarios can be conducted in specific regions applying the desired environmental conditions easily. As a supervisor of the operations, an experienced seafarer is used. From the human factors perspective, the supervisor can also self-evaluate, for example, the level of her situation and automation awareness during different situations where the autonomous system conducts operations, the appropriateness of her trust in the system, and the experienced workload in supervising the various operations.

Method-wise, VTT has a long history of conducting similar human factors V&V studies in the control room simulators of nuclear power plants [20,21]. In addition, VTT has recently been looking at how to conduct safety qualification related especially to autonomous ships [22,23]. Naturally, conducting studies in simulated environments offers a much more cost-effective and safe way of validating different safety-critical scenarios compared to real-world scenarios. However, the ecological validity of the simulator is crucial. Therefore, we aim to offer as realistic vessel models and operations as possible.

In general, we see that the developed collision avoidance system and the ship-handling simulator can be used for the design and evaluation of autonomous ship systems both in virtual and mixed (virtual and real-world) settings. More specifically, we suggest the following application areas for the system: 1) development of autonomous navigation systems, 2) human factors studies with potential users, 3) verification and validation activities, 4) scenario tests before real implementations on actual autonomous vessels and 5) mixed tests by combining simulation-based and real-world environment testing. Out of these application areas, the last one is particularly novel and innovative approach, to which also human factors studies should be conducted in more detail.

5. Implications for the Design of MASS Systems

Based on our previous contemplations and the presented case simulator environment, in this chapter, we suggest some preliminary implications for the design of MASS systems from the HFE point of view and discuss a few design process implications.

5.1 Human Factors Engineering Implications to be Taken into Account in the Design of MASS

Often, in highly automated environments maintaining operator vigilance may become problematic as the users of autonomous systems do mostly monitoring tasks through their displays. This phenomenon can have a root-cause in the lacking of a proper HFE process and a suboptimal task division between the automation and the human in the system's original development. As a result, the tasks left for the human are monotonous and boring [24,25]. This problem is highlighted by the fact that most of the time in supervisory control work, nothing interesting really happens. However, when something critical happens, it can be very surprising for the operators. In this kind of a situation, the operators should still be ready to act promptly and in a safe manner. The challenge therefore is that how the operators can keep their vigilance level up, notice an exception situation, and act accordingly in a proper manner. To mitigate this challenge, we suggest, for example, meaningful secondary tasks with training-related and technology-supported activities to be provided for the operators during primary tasks' idle time.

In addition, cognitive overload may occur when information about the automated environment is condensed into one place, such as an individual display. This may result in a "keyhole effect" where users focus in on only a small portion of the display space and are unaware of important changes in the object environment's status that are indicated in other parts of the display space where they are not looking [26]. This problem may be exacerbated during alarm situations where the operator can receive a vast amount of information to one's display at once [27].

Both the vigilance and cognitive overload issues contribute to maintaining situation and automation awareness, which were discussed earlier. If these are not taken into account on a sufficient level in the design, it may be very difficult for the operators to stay in the loop of what is happening currently both in the object environment and also with the automation system.

Consequently, the loss of good situation and automation awareness may result in suboptimal level of trust in the system. If the operator does not understand what is going on, it is often too easy for her to trust the automated system too much in situations with which the system has not originally been designed to cope with and therefore where it should not be trusted. Hence, both system design and operator training should aim for appropriate trust instead of maximum trust. If the operator's trust is at an appropriate level, also the operator's decisions and actions from the performance perspective of the joint cognitive system [28] formed by the human and automation are optimal.

5.2 Design Process Implications of MASS from the Human Factors Point of View

Firstly, before starting the design work, there should be human factors-oriented analysis studies of the existing non-automated work setting. In this way, it is possible to understand the users and their work's demands on a deep enough level. Also, benchmarking similar autonomous systems environments may help here. This understanding on the other hand allows the designers to better comprehend how the division of tasks between the human and the automation should be done. This division should take into account that in which tasks the human operator is really needed and which can be automated. Also, the workers' tasks should not be too monotonous or boring so that they can keep their vigilance level up in every situation [29,30].

Secondly, in the co-design phase, relevant stakeholders should participate to the design work through workshops conducted with different co-creation and innovation methods. This allows bringing in not only the voice of the users more clearly to the design phase, but also other relevant groups, such as the system buyers or maintenance personnel perspectives.

Thirdly, to account for good user experience, UX goals [13,14] can be utilized. The UX goals should work like guiding stars throughout the design process to steer the development towards the right direction from the UX perspective [31]. A detailed case study of the utilization of UX goals in a highly automated remote operation setting of container cranes is available in [32-34].

Fourthly, early prototyping should be preferred with different types of visualizations and mock-ups. Prototypes of different maturity levels work well when iteratively evaluating the suggested designs with real users towards the final solution.

Finally, human factors-oriented verification and validation activities form the basis of a safe socio-technical system. The results of these systems engineering activities also provide evidence about the system safety, for example, for authorities regulating the systems. In addition, the operators monitoring and using the systems should be integrated to this process. Without systematic V&V activities, the end-result may cause accidents that ultimately affect the progress of the entire MASS industry.

6. Conclusions

By taking the human aspects of MASS systems as a focus point in the development, it is possible to create safe and successful maritime innovations for the future. In this paper, we have discussed only a fraction of the relevant human factors issues in developing highly automated systems, such as MASS systems. In addition, we have presented a short case study in how human factors has been taken into account in our simulator development.

Theory-wise, future work should focus on identifying more relevant challenges and solutions from the human perspective. We have given some suggestions on these relevant human aspects in this paper.

Further practical work should include different HFE-oriented simulator-based studies. Consequently, we see that a good balance in simulator and real-world-based studies is crucial in the development of safe MASS applications in the future.

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INTERACTION BETWEEN MANNED AND AUTONOMOUS SHIPS: AUTOMATION TRANSPARENCY

Thomas Porathe
Norwegian University of Science and Technology, Trondheim, Norway

Corresponding author e-mail: thomas.porathe@ntnu.no

Abstract

Maritime Autonomous Surface Ships (MASS) is on the research agenda of several countries. In Norway a 120 TEU autonomous container feeder is currently being built. Hopes are attached to safety as well as costs and efficiency benefits. The explicit assumption is that with no humans on the bridge “human error” will go away. However, great challenges will be found in the interaction between MASS and humans on the bridges of other SOLAS and non-SOLAS vessels. An unanswered question is whether a MASS should transmit that she is in autonomous mode or if she should remain anonymous, just as any other ship? This discussion paper argues for the first alternative. Arguments are also given for “automation transparency,” methods allowing other seafarers to “look into the mind” of the autonomous ship, to see if they themselves are detected and what is the present intentions of the MASS.

Keywords: *MASS, autonomous ships, automation transparency, route exchange*

Figure 1**.** The Photomontage of the planned *YARA Birkeland* autonomous container vessel passing the Brevik sound in southern Norway. To the right is the tower of Brevik VTS. (Image by the author.)

1. Introduction

Large autonomous merchant vessels are still not for real. However, they are on the drawing board in several places and in Norway the building contract is already signed for YARA Birkeland, the first Maritime Autonomous, Surface Ship (MASS) container feeder, planned to start tests runs in 2020 [1]. In the absence of international regulations from the IMO, prototype testing will have to commence in national waters, which in the Norwegian case means inshore archipelago navigation with narrow channels in a busy industrial area with gas carriers and vessels with other hazardous cargo and, summertime, with large numbers of small leisure crafts. The area is covered by the Brevik VTS which in 2015 made 623 interventions [2]. The challenge will be to detect, identify and in some cases decide or negotiate a change of action for all these targets.

The project is ambitious, the 80 meters long, unmanned, autonomous vessel, taking 120 containers with a fully electric propulsion system, will replace some 40,000 truck-journeys every year. Thus moving heavy traffic from road to sea, from fossil fuel to hydro generated electricity. The plan is currently that she will start tests in 2020. First with a manned bridge onboard, then with the same bridge lifted off to the quay side remotely controlling the vessel, before finally attempting to go autonomously in 2022 [1].

The technological challenge is of course a major driver for a project like this (subsidized by the Norwegian government) but the environmental benefits (offloading heavy traffic from narrow roads, and switching fossil fuel for electric) are also important, and maybe the most important in the long run. With just one ship planned and in this limited setting the savings on personal (switching lorry drivers for service personal ashore) will be limited, if any.

The safety case, often referred to as the major driver, exchanging “human error” for safe automation, remains to be proven. So far in history, ship automation has shown great safety benefits, for instance reducing the global number of total hull losses from 225 in the year 1980, to 150 in 1996 and 33 in 2016 (ships over 500 gross tons, total losses as reported in Lloyds List) [3]. However, moving from todays supervised automation to the automation levels of tomorrow will be a major paradigm shift.

2. Unmanned, automatic and autonomous

Ships today are already transiting automatically. With an autopilot in track-following mode, set so that the ship can execute turns with a preset radius without acknowledgment from the officer of the watch, the ship can transit from A to B without support - given that the route planning is correct - because the ship is only following a pre-planned route. What is needed to remove the operator from the bridge is different sensors that can detect moving and uncharted obstacles in the sea and anti-collision algorithms based on the International Regulations for Preventing Collisions at Sea (COLREG's) [4].

However, as long as this system does not involve higher degrees of machine learning it will need to be pre-programmed and "black swans" are bound to appear. ("Black swans," unforeseen situations which the programmers have not anticipated, "unknown unknowns".)

Furthermore, an automatic ship does not have to be unmanned. It can have a partly manned bridge ("constrained autonomy" in IMO terms). As the level of automation increases, it might allow the Officer of the Watch (OOW) to take a short power nap during an uneventful crossing, handing over the watch to the automation, relying on that the automation will wake the OOW up in case of anything happens. The watch can also be handed over to a Shore Control Centre that can access the ships sensors and communication, ready to wake up the OOW if something unexpected happens. In this case the ship is still in manual mode, however, remotely monitored). The next step would be to grant the shore centre access to the autopilot, in which case the ship will be remote controlled. It is reasonable to think that this will be a gradual evolution towards higher and higher levels of automation. At a time, we might imagine ships with the captain onboard but the officer of the watch on the bridge is an AI system. However, the captain is there to supervise and intervene – once he has climbed from his cabin to the bridge. Is this an autonomous ship?

It can also be useful to consider the concept "Operational Design Domain" (ODD) used by the self-driving car industry [5]. In the maritime domain, it would mean that there will be certain shipping lanes and fairways were the automation has been specifically trained and which have been specifically prepared, maybe with designated lanes, or by specific technical infrastructure. In these areas, a ship may navigate automatically, while the ship in other areas must navigate manually with a manned bridge or remote controlled from the shore.

For the discussion here the level of autonomy or staffing might not be so interesting as whether the ship is in "autonomous mode" or not. If automation is navigating and taking decisions or if humans are, regardless of whether the captain is in his cabin onboard or in a remote centre ashore. Or does it matter? Maybe the only crucial point is whether the ship follows the COLREGs or not?

A ship would be in "autonomous mode" if the automation "has the con," navigating and doing collision avoidance automatically, wherever there are navigators onboard or not.

3. The COLREG's

There is a difference between humans and machines: machines do as they are programmed; with humans you never really know. They might even have gone to bed. In many maritime accidents, the wheelhouse was found empty, as in two stranding's in Sweden the summer 2018 [6, 7]. It could then be comforting to know that autonomous ships are always awake and vigilant and that they always follow the COLREG's.

However, COLREG's can be ambiguous. Just to give an example the required actions are different for two ships in a crossing situation in fog (rule 19) and in good visibility (rule 15), as it also is in an overtaking situation (rule 19 vs. rule 13). The tricky part is to determine when the visibility is restricted [8]. Discussing the potential ambiguities of the COLREG's is out of the scope of this paper. However, humans interpret rules differently, as there is an abundancy of examples of in accident reports. The question is if MASS will do better. The question is if humans on other vessels will trust the automation – and how the automation will behave when humans do not follow the rules. This is when automation transparency might show to be crucial.

4. Automation transparency

Every one of us that are struggling with the complexity of digital tools know that they do not always do what we want or assume they will do. They "think" different from us. An innate tendency of human psychology is to attribute human traits, emotions, or intentions to non-human entities. This is called anthropomorphism. We do so because it gives us a simple (but faulty) method to understand machines. It is likely that this will also be applicable to MASS. We will assume that they will behave as if they had human on the bridge.

The assumption is that if MASS follow COLREGs its behavior will be a 100 % predictive. However, this is given that the spectrometers onboard interpret the visibility the same way you and I do, and that the intentions of other manned or unmanned ships are interpreted rightly by the AI. An old accident in the English Channel can serve as an example of COLREG's and misinterpreted intentions.

A foggy night in 1979 the French ferry *St Germain*, collided with the bulk carrier Adarte in the English Channel. *St Germain* was coming from Dunkirk in France, destined across the Channel to Dover in the UK. As she was approaching the Dover Strait Traffic Separation Scheme (TTS), she started to turn slowly to port, away from the strait course to Dover, intending to run SW in the inshore traffic zone, down the outside of the TTS in order to find a clearer place to cross the TSS at a right angle (according to rule 10). At the same time the *Adarte* was heading NE, n the NE bound lane of the

TSS. The pilot onboard saw the radar target of *St Germain* and assumed, quite wrongly, that she would cross ahead of him. The pilot made a series of small course alternations to starboard to allow her to cross ahead (giving way for a ship from the starboard side according to rule 15, but not following rule 16 which talks about taking "substantial action"). But instead of continuing her strait course *St Germain* continued her port turn and the two ships collided. *St Germain* sank killing a number of passengers [9].

This accident is retold to illustrate the need to understand intentions. The officers on the bridge of *Adarte* did not understand that the intentions of *St Germain* was not to cross the TTS just yet. The officers on the bridge of *St Germain*, following an accustomed behavior, did not see that their maneuver could be misunderstood from the *Adarte*. The problem would remain if one or both of the ships were autonomous.

Intention sharing among traditional ships, route exchange, has been investigated within the realms of the IMO concept e-Navigation for several years and we will not go deeper into that here apart from how this can be used for MASS.

Automation can share information about its working, its situation awareness and its intentions. Answers to questions like: What is the intention of the MASS? What does the automation know about its surroundings? What other vessels that has been observed by its sensors? could be answered e.g. by a live chart screen accessible on-line through a web portal by other vessels, VTS, coastguard etc. An example of such shared situation awareness screen is showed in Figure 2.

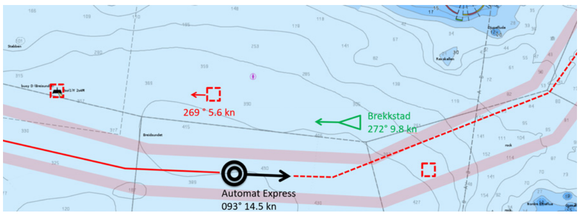

Figure 2. An on-line chart showing the situation awareness of the autonomous ship, where it think it is, what other ships and objects it has observed, and what intentions it has for the close future.

Based on the situation awareness provided by chart and sensors the automation will make decisions on how to interprets the COLREG's. It would then be a safety benefit if these decisions could be communicated to other ships, as argued in [10]. However, there is a difference between the equipment of large SOLAS ships and smaller non-SOLAS vessels when it comes to the ability to receive such communications.

4.1 SOLAS ships

Large ships obey under IMO's SOLAS convention. A SOLAS ship (as defined in Maritime Rule Part 21) is any ship to which the International Convention for the Safety of Life at Sea 1974 applies; namely: any passenger ship engaged on an international voyage, or a non-passenger ship of 500 tons gross tonnage or more engaged on an international voyage [11].

SOLAS ships must transmit their position and some other information using AIS (Automatic Identification System). In addition, SOLAS ships are usually big and make good radar targets, which will provide a second source of information. Furthermore, all SOLAS ship must make a voyage plan from port to port. As mentioned several passed and ongoing projects aim at collecting route plans and coordinating ship traffic for reasons of safety and efficiency (e.g. EfficienSea, ACCSEAS, MONALISA, SMART navigation, SESAME, and the STM Validation projects). These attempts in route exchange would make it possible for SOLAS ships – also MASS - to coordinate their voyages and show intentions well ahead of time to avoid entering into a close-quarters situation where the COLREGs will apply.

Route exchange would for instance allow each ship to send a number of waypoints ahead of the ships present position though AIS to all ships within radio range. All ships can then see other ships intended route. In the ACCSEAS project 2014 a simulator study was made with 11 professional British, Swedish and Danish bridge officers, harbor masters, pilots and VTS operators with experience from complex traffic in the test area which was the Humber Estuary. The feedback from the participants on the benefits of showing intentions were overall positive [10]. Figure 3 shows a screen shot of the test ECDIS.

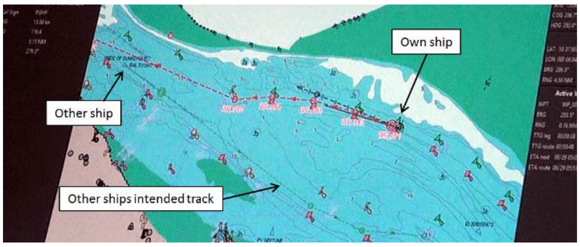

Figure 3. A screen shot from the test ECDIS showing the own inbound ship to the right. Another, outbound ship is to the far left and the question is whether this ship will take the northern or the southern route. By clicking on the ship the intended route (the southern fairway) is shown and problem solved [10].

However, for small, Non-SOLAS vessels, the situation is different.

4.2 Non-SOLAS vessels

The challenge will be greater when we look on smaller, non-SOLAS vessels: small fishing boats, leisure crafts, sailing yachts, motor boats all the way down to kayaks. For these craft there is no mandatory carriage requirement of sophisticated electronic communication equipment. In Scandinavian waters, this kind of vessels often stay close to the coast or inside the archipelago, and will therefore stay out of the way of commercial deep-water traffic. But in the case of the short sea shipping, they will be of real concern.

First, there is the question of detection. Non-SOLAS vessels are not required to have AIS. It is the sensors of the MASS that must detect, identify any small craft.

The human lookout on a manned vessel will on the MASS be replaced by different sensor systems, both daylight and heat sensitive infrared night vision cameras. Then, computer vision algorithms will be used to extract information from these images to try to isolate single objects like boats and buoys. These algorithms will be supported by radar, and maybe LIDAR on short distances up to 100 meters. The challenge here will still be to detect small objects and infer their course and speed. Low visibility in fog, snow, rain and high waves will add to the difficulty. And here we have the problem of automation transparency. Maybe the person in a small fishing boat, leisure craft or kayak, do not trust the MASS with the sole responsibility for detection and avoidance manoeuvre. Maybe he or she will want to know whether or not the autonomous ship observed him or her. How could a MASS communicate intentions to a small craft not equipped will the technology of larger SOLAS ships?

4.3 Some examples of automation transparency for non-SOLAS vessels

As a pedestrian or bicyclist, crossing a street in front of a car that has stopped, you need to make sure that the driver has seen you. You do that by seeking eye contact. If the driver is looking at you, you might assume that an understanding has been negotiated and you can safely cross. (This is a problem that remains to be solved for autonomous car industry.) The situation is more complicated at sea. One solution would be if you got a positive signal when looking at a ship, indicating that that ship has detected you. For instance, a green light meaning that you have been spotted. But of course then that light should only be visible for you and nobody else, which might raise some technical challenges as there might be many boats in the area and each one would need to see s similar green light. If you were not detected the signal would show red (as illustrated in Figure 4).

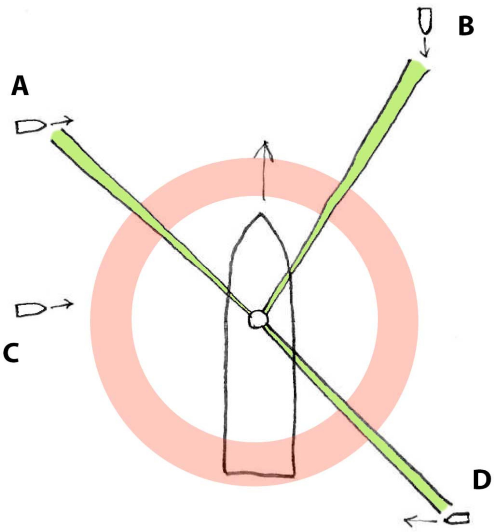

Figure 4. Example of automation transparency: A simplified illustration of an app for autonomous ship communication. Left the image shows the crosshairs of the camera view. Aim at the oncoming ship and press "Acquire". Middle, the answer is received: you are "present" on the chart of the autonomous vessel (and can connect a phone call to the remote control centre). Right, you are not "present" on the chart of the autonomous vessel, but can report you name, position, course and speed.

A good thing with such a solution is that it would not require any equipment on the side of the small craft.

Another, maybe technically simpler solution, would be using smartphones already available in the pocket of most people. All smartphones have a satellite based navigation (GNSS) receiver, which with relatively good accuracy can provide a position. Assuming GSM coverage in an archipelago, this position can be sent to an approaching vessel.

Let us imagine the following scenario: You are fishing in, or crossing, a large fairway in the archipelago. Far off a MASS is approaching. You can see it is in autonomous mode because of its MASS signal (this could e.g. be a purple flashing light/flag – purple is an unused color in COLRE's). You may also see on your navigational chart that you are in an area with MASS traffic. Should you continue crossing the fairway or wait? Or, if you are fishing, should you stay or move out of the way? Has the MASS even seen you?

In this hypothetical scenario your first step would be to take up your smartphone and start the Autonomous Ship Communication App. The interface show the camera view with crosshairs in the middle and the prompt "Aim at the ship" (see Figure 5).

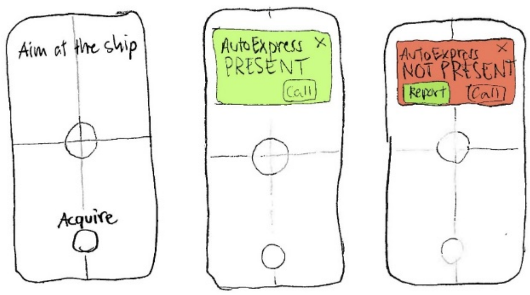

Figure 5. Example of automation transparency: A simplified illustration of an app for autonomous ship communication. Left the image shows the crosshairs of the camera view. Aim at the oncoming ship and press "Acquire". Middle, the answer is received: you are "present" on the chart of the autonomous vessel (and can connect a phone call to the remote control centre). Right, you are not "present" on the chart of the autonomous vessel, but can report you name, position, course and speed.

You then aim the crosshairs at the oncoming ship and click "Acquire". An image of the ship appears with the prompt "Do you want to ask if the Autonomous Express has seen you?" and an OK button.

You click the OK button and wait for an answer.

A few seconds later the answer arrives: "Yes, S/Y Matilde, I have observed you and you are present on my chart. Current course and speed is OK" Or maybe "Thank you for identifying yourself, S/Y Matilde, I have added you to my chart. Please wait until I have passed." (see Figure 5).

4.4 What is your intention?

The short-term intentions of the autonomous ship could be shown on a chart view in a web portal or in the app, as mentioned above, but it could also be shown in a signaling mast together with the sign mentioned above. Such a mast could for instance consist of three vertical lights as shown in Figure 6, left.

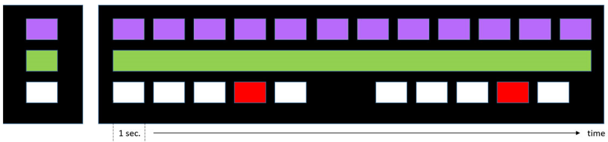

Figure 6. Example of automation transparency: Left, the three self-driving mode signals. One over the other. Right, a time diagram of the flash sequences described in detail in the text.

4.4.1. The top light

The top light should a purple identification light for vessels navigation in autonomous mode. The light must be easy to spot and unique. Some other designated color or character could be used instead.

4.4.2. The middle light

The middle light would be the green or red "your-presence-is-spotted" light mentioned above. It would then show green for vessels known to the automation, and red for "unknown" vessels. In Fig. 6, left, the middle signal show green because my boat has been observed from the ship. The light is static because my course and speed is OK and is not inflicting with the navigation of the autonomous ship. If I need to give way, the green light could be blinking.

4.4.3. The bottom light.

The bottom light could be a signal showing the intentions of the MASS for the next 5 minutes. The light could consist of e.g. 5 flashes, one for each minute into the future. A white flash would mean "I will continue my course straight ahead". A red flash "I am turning port" and a green flash "I am turning starboard". In the sequence illustrated in the temporal diagram in Fig. 6, right, the bottom light shows 3 white flashes "I will continue my course straight ahead for the next 3 minutes". Then followed by a red flash, meaning, "in the 4th minute I will make a port turn", and finally a 5th, white flash, meaning, "I will then continue on this new course during the 5th minute". Of course a port or starboard turn could be of different sizes and take different long times to execute, and maybe one could find more detailed codes for this, or just keep the signal simple and general.

A daylight version of the signals could follow the same pattern using very strong light or LCD boards facing all four directions.

The benefit of such a signaling scheme would be that there is no need for any technological communication equipment to read the intentions of the MASS, or for a kayaker to bring up a smartphone at the same time as he is paddling and balancing his kayak. On the other hand, the signals described above are quite complex (apart from the technical challenge in the "I-have-spotted-you light) and might be difficult for laymen to learn, as indeed are the many light character of common lighthouses.

5. Conclusions

I have in this discussion paper pointed at some communication challenges regarding the interaction between autonomous, unmanned ships and manned ships and crafts of different sizes.

I have also pointed to some possible solutions based on automation transparency, meaning that the automation of the MASSs transparently shares their situation awareness and decision-making with other vessels and authorities like VTS and coastguard.

I have also given some concrete examples of what such automation transparency can look like. Many other solutions are also possible. And nothing prevents the same communication techniques to be used also in the interaction between manned SOLAS vessels and small non-SOLAS vessels.

Acknowledgements

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ICMASS 2018

PROCEEDINGS OF THE 1ST INTERNATIONAL CONFERENCE ON MARITIME AUTONOMOUS SURFACE SHIPS

These proceedings contain selected papers from the first International Conference on Maritime Autonomous Surface Ships (ICMASS), held in Busan, Republic of Korea, on November 8th and 9th, 2018.

ICMASS is an initiative from the International Network for Autonomous Ships (INAS), an informal coalition of organizations and persons interested in autonomous ship technology. In 2018 it was organized by KAUS – Korea Autonomous Unmanned Ship Forum. The plan is to make this a yearly event in different places around the world.

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