From Sensors to MASS: Digital Representation of the Perceived Environment enabling Ship Navigation

H-C Burmeister\textsuperscript{1}; M Constapel\textsuperscript{1}, C Ugé\textsuperscript{1}, C Jahn\textsuperscript{1}

\textsuperscript{1}Fraunhofer Center for Maritime Logistics and Service, Am Schwarzenberg-Campus 4, 21073, Hamburg, Germany
E-Mail: hans-christoph.burmeister@cml.fraunhofer.de

Abstract. Maritime Autonomous Surface Ships (MASS) do require shifting from human information processing to automation functions. While supporting the sensory processing of human navigation by automated information acquisition from different sensors is already established (and even in many cases mandatory) technology with a set of framing standards and information exchanges, defining a common data set for a perceived environment model is currently neglected which hinders modularization of MASS technology development. Beginning with an introduction into the navigational process as well as information processing, this paper subsequently proposes an initial minimum data set for different aspects of ship navigation.

1. Introduction
Already today, automation is present in maritime navigation, especially in the area of information acquisition. Despite human sight and hearing, a variety of sensor equipment is nowadays (mandatory) state of the art on ships, like e.g. Radar, Global Navigation Satellite Systems as well as the Automated Identification Systems. They all perform automated information acquisition functions for the officer of the watch, meaning the sensing and registration of (raw) input data relevant for the navigation process. Existing standardization even allows the exchange and integration of this raw data between different systems, e.g. by the common NMEA format IEC 61162 [1].

In contrast, information analyses on board do still mainly rely on human perception and are less supported by automated information analyses functions, meaning prediction and integration of the (raw) data sets, as stand-alone ECDIS or radar system do primarily only allow overlaying and displaying of raw (NMEA) data sets, as well as some low-level predictions like CPA calculations. Recent Integrated Navigational Systems (INS) provide some more capabilities, as they should monitor the availability, validity, and integrity of connected sensors [2]. However, even in the case of an INS, the system’s intention is to hand over its information to a human for decision-making, resulting primarily in visual output.

Digitalization and further automation are ongoing developments on the way to Smart or even Maritime Autonomous Surface Ships (MASS). MASS are vessels, that can «operate to a varying degree independently of human interaction» up to the stage, where «the operating system of the ship is able to make decisions and determine actions by itself» [3].
Recent MASS feasibility studies as well as published class guidelines on MASS have in common, that MASS with the highest degree of autonomy does conceptually require an Automated Sensor System (information analyses function - also often referred to as ‘situational awareness systems’) as well as an Autonomous Navigation System (decision and action selection function) on board as proxies for the human lookout and officer of the watch\(^1\) \([4]\) \([5]\) \([6]\) \([7]\). Nevertheless, what is lacking is the definition of a specific information transfer between these two systems. While practical function developments for the Automated Sensor System can at least still easily link by the existing sensor standards, no common definition exists regarding the digital description of the perceived environment of a vessel. However, a precise definition of this perceived environment and its related data elements is crucial for further MASS development, as it first enables modular development and connectivity within MASS technology.

Based on an introduction into maritime information processing in the following and MASS sensor system concepts in the subsequent chapter, chapter 4 proposes a minimum data set to be delivered by any to information analyses to allow for a proper maritime decision-making within MASS.

2. Information Processing on board

2.1. Information Processing Theory

Human and automation information processing can be described by a four-stage model, which is also used in some of the recent MASS guidelines \([6]\) \([7]\). On a conceptual level, this model distinguished four stages of human information processing \([8]\):

(i) sensor processing,
(ii) perception,
(iii) decision-making, and
(iv) response selection.

In an automation context, these must be replaced by corresponding automation functions:

(i) information acquisition,
(ii) information analyses,
(iii) decision and action selection, and
(iv) action implementation.\(^2\)

While information acquisition is limited to "sensing and registration of input data", information analyses include predictions based on the raw data "augmenting human operator perception and cognition" up to a level to "provide context-dependent summaries" \([8]\).

2.2. Maritime Information Acquisition

Today’s ships are obliged to fulfill the carriage requirements for navigational equipment according to SOLAS Regulation 19 and 20 \([9]\). These include (besides others) depending on ship size and sailing area the following sensory equipment:

- Magnetic Compass
- GNSS receiver
- Echo sounder

\(^1\) a shore-side unit is normally also foreseen during information processing of MASS, but as long as no direct remote control is executed, this unit does normally act in a ‘supervising’ function for the on board system, which is why it is not further investigated in this paper, as in principle an operation independent from a direct shore connection is aspired for the highest degree of autonomy

\(^2\) called condition detection, condition analyses, action planning and action control in \([6]\)
While this sensory equipment is available from a variety of manufacturers, common maritime standards are in place ensuring connectivity with third-party equipment, like e.g. the established NMEA-standard for most sensor data [1], common de- and encoding for AIS data [10] and newer developments like the Asterix-Format for radar data [11]. Thus, for automation in the information acquisition context, a technical framework, that MASS can build upon, is existing, even though further sensory equipment might be necessary.

2.3. Maritime Information Analyses

This sensory equipment normally provides their data to further mandatory navigational equipment for further information analyses [9]:

- Bridge Navigational watch alarm system (BNWAS)
- Automatics Radar Plotting Aid (ARPA)
- Electronic Chart Display Information System (ECDIS)
- Voyage Data Recorders (VDR)

However, in the context of maritime traffic, information processing with regards to navigation is the officer of the watch’s (OW) responsibility on an operational level, which includes tasks like e.g. to plan and conduct the voyage and to maintain a safe navigational watch. Hereby, the OOW can be supported by a lookout who reports e.g. sound and light signals as well as detected other objects as well as relative bearings [12]. Even though, the OOW is already supported by the aforementioned systems, those serve primarily as a data display during the information analyses stage as they only conduct data integration or prediction on a very low level of automation.

![Figure 1. Level of automation for different functions of maritime navigation (own drawing based on [8]).](image-url)
As indicated in figure 1, several nautical sub-tasks are supported by automated information acquisition, as e.g. the task of collision avoidance, which is automatically getting object information by Radar as well as the Automated Identification System (AIS) and not only by sight and hearing. Thereby, high automation means, that the system decides and executes automatically with or even without information to the human [8]. For the remaining information processing stages, automation is however comparatively low besides some CPA calculations, even within modern INS, meaning that only limited assistance or decision alternatives are provided. Thus, creating the full navigational situation picture by using all available information and check it for plausibility as required by COLREG [13] is still a primarily non-automated task. Also, for further nautical sub-tasks like e.g. anti-grounding or harsh weather operation, a modern INS might get a very limited set of environmental data as sensory inputs, but predicting based on this data as well as all further decision steps rely solely on the OOW. In terms of marine navigation, the only exception with regards to state-of-the-art bridge system is track control, where fully automated systems are available [14].

2.4. Maritime Decision-Making
With the exception of the aforementioned track control systems, decision-making on the bridge is fully up to the OOW. Besides alarms, no concrete recommendations for e.g. collision avoidance, anti-grounding, or harsh weather are normally given. As the OOW fulfills a double function as an information analyst and decision-making unit, no clear data set definition exists, describing the perceived environment which an OOW is using to base its decisions upon, as this is normally hidden within the nautical officer’s mental model.

3. MASS Situational awareness
On a MASS with the highest degree of autonomy, this still human-centered functions of the lookout and the OOW are going to be replaced by automation. Thus, the relevant artifacts of the Maritime Perceived Environment (e.g. own ship’s state, approaching vessels, navigational aids) need to be collected and represented internally through a sensor platform. Generically, this sensor platform relies on integrated onboard sensors (e.g. radar and AIS) and additional inertial and short-range sensors (e.g. cameras and radars in the millimeter frequency range). A sufficient perception of the maritime environment from this sensor system is needed to carry out safe nautical decision-making by any navigation system during transit on a given route mainly for collision avoidance and grounding avoidance over a longer period of time and under consideration of existing regulatory, internal and environmental restrictions.

As seen in figure 2, the sensor system captures sensory input via the Sensor Data Access and processes (i.e. filters, smoothes, associates, estimates and transforms) the gathered sensor data via its core component: Multi Sensor Data Fusion. Subsequently, it transfers the transformed and associated measurements and estimates (i.e. High Level Features, which yield pieces of information with navigational importance or relevance) from the sensor fusion component via three logical interfaces (Objects, Environment, Body) to the navigation system. These interfaces serve the information needs of the navigation system concerning the perceived objects, the environmental parameters, and the own ship’s state. The sensor system decides how often High Level Features are created since the information content is dependent on the quality, amount, and update rate of measurements. Nevertheless, the navigation system may request the creation and submission of High Level Features for a given point in time as they are required for the establishment of situation awareness and as a basis for nautical decision making.

However, a common generic description of the maritime perceived environment regarding the three logical interfaces is necessary to enable independent development and implementation of Situational Awareness and Autonomous Navigation Systems.
Figure 2. Generic overview about sensors, perception, and decision-making on MASS

4. Maritime Perceived Environment Proposal
The idea of the digital representation of the maritime perceived environment is to define a (minimum) data set to be provided by any sensor system enabling the decision-making capabilities of the MASS’ navigation system. Thus, it is necessary to stress that this perceived environment is sensor-independent, as it shall not define how this data shall be gathered, but solely which data points are necessary to allow for connectivity between different MASS modules. Conceptually, the Maritime Perceived Environment is established and refined over time through the High Level Features created by the sensor system. Any High Level Feature is temporarily aligned corresponding to the position of the own ship at a given timestamp since locations are always represented relative to the own ship’s position. This scheme applies also to spatial and temporal context data, e.g. tide, or chart related data. Ideally, an update frequency of 1 Hertz is assumed to be sufficient for time-dependent navigational data.

4.1. Objects
The perceived environment data set must consist of the detected objects in the vicinity of the own ship recording at least (1) system timestamp, (2) unique object identifier, (3) the classification or type of the object°, (4) relative bearing*, and (5) distance* corresponding to the position of the own ship at the system’s timestamp. Relevant object types to be distinguished shall be vessels, aids to navigation, small unlit boats, floating logs, oil drums, containers, buoys, or ice [6].

Moreover, the data set contains additional information for an object and thus further augment the record with information for (1) speed over ground*, (2) course over ground*, (3) heading*, (4) dimensions* (length and width), and in case of vessels (5) navigational status°. For larger objects (i.e. length greater than 20 m), that augmentation is considered mandatory.

In case multiple sensors are used by the sensor system to define one data set, interval values shall be given for discrete values (marked with *) and the number of sensor confirmations...
compared with the number of available sensors types for type assignments (marked with °).\textsuperscript{3} It shall be noted, that the authors assume, that information analyses in the context of collision avoidance does not include determining COLREG statuses and obligations, which rely not just on the object itself but on the given traffic situation. COLREG assessments are indeed considered to be a decision and thus part of the next step of information processing, which is why it shall not be part of the perceived environment description.

4.2. Environment
Ambient data of the own ship’s surroundings is subdivided into disjoint records describing either the wind state, sea state, or visual state.

4.2.1. Wind state A record for the wind comprises at least (1) timestamp, (2) wind force, and (3) wind direction. Again, in case multiple sensors interval values shall be given.

4.2.2. Sea state A record describing the sea state has to have at least (1) timestamp, (2) wave height and, (3) wave direction. Optionally, (4) swell height, (5) swell period, and (6) swell direction can be added to the record. Again, in case multiple sensors interval values shall be given.

4.2.3. Visual state A record on visibility conditions needs to be composed of (1) timestamp, (2) visibility (i.e. range), and (3) an occurring sector designated by two relative bearings.

4.3. Body
The data of the own ship’s state are stored in a record with at least (1) timestamp, (2) actual position in a global reference frame, (3) position accuracy, (4) speed over ground, (5) course over ground, (6) heading, (7) speed through water.\textsuperscript{4} Additional information about the own ship’s state may extend the record: (1) torsion forces, momenta, and force vectors attached to the hull, (2) rotational motion, (3) attitude (i.e. pose).

5. Conclusion
This paper is proposing an approach for a maritime perceived environment data set as an interface from any Situational Awareness to any Autonomous Navigation System, which is decoupled from the specific sensor set-up. Such a harmonization or even a standard is a necessary prerequisite, to improve parallel development of MASS algorithms and technologies for information analyses and decision making, respectively. Besides the data definition, a common, specified, and non-proprietary exchange format would be a necessary future work to ensure modular design and thus flexibility for MASS bridge equipment.

Acknowledgment
The B ZERO project has received funding by the German Federal Ministry of Economic Affairs and Energy under support code 03SX500A.

\textsuperscript{3} if a sensor system is e.g. capable to detect the navigational status by image recognition of lights and shapes, but also uses AIS information, it shall indicate if the current type value is determined by only one or both possible inputs.

\textsuperscript{4} besides the navigational status of the MASS itself being important, it shall not be part of the perceived environment data definition, as it is presumably an input, like e.g. the voyage plan, and nothing that will be given from a sensor system
References
[1] IEC 2016 IEC 61162: Digital interfaces for navigational equipment within a ship (IEC)
[2] IEC 2012 IEC 61924-2: Maritime navigation and radiocommunication equipment and systems - Integrated navigation systems - Part 2: Modular structure for INS - Operational and performance requirements, methods of testing and required test results (IEC)
[3] IMO 2018 MSC 99 Report on the Maritime Safety Committee on its ninety-ninth session (London: IMO)
[4] Burmeister H C, Bruhn W, Rodseth nd Porathe T 2014 International Journal of E-Navigation and Maritime Economy 1 1–13
[5] Poikonen J, Hyvönen M, Kolu A, Jokela T and Paasio A UNaawa position paper URL https://www.rolls-royce.com/ /media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/aawa-whitepaper-210616.pdf
[6] GL D Class guideline: Autonomous and remotely operated ships (dnvgl-cg-0264) URL https://rules.dnvgl.com/docs/pdf/DNVGL/CG/2018-09/DNVGL-CG-0264.pdf
[7] Veritas B Guidelines for autonomous shipping (ni641) URL https://marine-offshore.bureauveritas.com/ni641-guidelines-autonomous-shipping
[8] Parasuraman R, Sheridan T B and Wickens C B 2000 IEEE Transactions on Systems Man and Cybernetics - Part A Systems and Humans 30 286–297
[9] IMO 2019 SOLAS - Safety of Life at sea and Amendments in 2020 (London: IMO)
[10] ITU Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band URL https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1371-5-201402-I!!PDF-E.pdf
[11] EUROCONTROL Specification for surveillance data exchange - part 1 all purpose structured eurocontrol surveillance information exchange (as-terix) URL https://www.eurocontrol.int/sites/default/files/2019-06/part1-eurocontrolpecificationsterixpec_149,ds.4.pdf
[12] IMO 2011 STCW Convention and STCW Code including 2010 Manila Amendments (London: IMO)
[13] IMO 2019 COLREG - Collision Regulations 1972 (London: IMO)
[14] Burmeister H C, Bruhn W and Walther L 2015 TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 9 31–40