MARINER 4.0: INTEGRATING SEAFARERS INTO A MARITIME 4.0 ENVIRONMENT

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SUMMARY

Digitalisation of systems and processes in the maritime industry are spurring *Maritime 4.0*, a digital transformation promising enormous gains, including improved design processes and reduced operational costs. Gleaning inter-disciplinary proficiency from Operator 4.0 in manufacturing, the present work seeks to introduce the *Mariner 4.0* – a seafaring passenger or crew member with technologically augmented skills. This research aims to realise Mariner 4.0 through a human digital twin solution – a virtual representation of the state and behaviour of a unique individual over time – for seafarers on South Africa's polar research and supply vessel, the SA Agulhas II. This paper presents human-related challenges identified on seafaring vessels, the expected value of human digital twin solutions for the maritime industry, the development of a human digital twin solution to integrate seafarers into a Maritime 4.0 environment (i.e. the development of Mariner 4.0), and an illustrative use case focussing on human comfort monitoring and management.

1. INTRODUCTION

Operator 4.0 is defined as a human worker that uses technology to augment their skills and abilities to perform work activities more efficiently, creating a smart and skilled worker in the manufacturing industry (Romero *et al.*, 2016a). With inspiration from Operator 4.0, the present work seeks to introduce *Mariner 4.0* – a seafaring passenger or crew member with technologically augmented skills, forming smart, skilled passengers and crew operating in digitalised maritime environments. Mariner 4.0 aims to embody human factors in digital systems and enable interfacing seafarers with machines and digital systems. Mariner 4.0 strives to represent a human-centric development within Maritime 4.0 by recognising the value of passengers and crew on seafaring vessels and endeavouring to facilitate the inclusion of seafarers in digital developments.

Maritime 4.0 can be defined as an integrated system of systems concept in which the implementation of digital processes and technologies is exploited to realise digitalisation throughout the value chain of the maritime industry (Sullivan *et al.,* 2020). The objective of Maritime 4.0 is to deliver high quality, optimised and reliable systems that leverage state-of-the-art technologies to maximise customer value (Sullivan *et al.,* 2020). The current phase of digitalisation in the maritime industry could be coined Maritime 4.0, as it focusses on revolutionising the industry through adopting the use of digital technologies and concepts – the definition of a *digital transformation* (Heilig *et al.*, 2017).

Maritime 4.0 is influenced by *Industry 4.0*, aimed at developing industrial production systems (Rojko, 2017). The Industry 4.0 concept is realised by creating smart cyber-physical systems (CPSs) and applying internet of things (IoT) to industrial production systems. The Industry 4.0 initiative focusses primarily on connecting systems and machines in order to quickly adapt to meet global and fast-changing demands.

Integrating people within the Industry 4.0 vision is seen as an important focus (Sparrow *et al.,* 2018). Likewise, integrating seafarers into CPS development in the maritime industry to create *human cyber-physical systems* (HCPSs) endeavours to foster human competencies and enable human-system integration in Maritime 4.0 (Romero *et al.*, 2016a). A HCPS is a system created to:

- Improve human abilities to interact and communicate with machines through human-machine interfaces, in both the cyber and physical realms. It is important that these human-machine interfaces are suited to unique human capabilities.
- Augment human capabilities by using technology, for example by using wearable devices.

It is vital to note here that by facilitating human-system integration, technology serves to augment human skills and abilities to better perform work activities (Tzafestas, 2006). Technology, in this case, is not intended to replace the skills and abilities of humans.

Beside the benefits, the technological developments in Maritime 4.0 influence the working and living environments for seafarers and can be considered socio-economic and technological disruptions providing challenges, such as rapid changes in skill requirements and employment patterns (Cicek, 2019). Future workforce skill sets may be vastly different and demand abilities that humans cannot develop (Lützhöft *et al.*, 2019). A conventional view for driving ship autonomy included removing people on board to reduce human error, but an ethnography of maritime autonomy explains that there seems to be a greater desire to keep people on board and use automation to augment seafarer abilities in order to reduce the workload of crew (Lützhöft *et al.*, 2019). The ethnography recognised that humans are likely preventing several accidents that automated systems may not be capable of.

At this stage, people are critical to many seafaring vessel operations and, for example, on cruise vessels human experiences are central to business success. It is important to consider the integration of people within *Maritime 4.0 environments*, which the authors define as an environment influenced by Maritime 4.0. The proposed Mariner 4.0 shall live or work in a Maritime 4.0 environment and, as such an environment is likely realised through creating CPSs, there remains the need to develop human-centric maritime HCPSs. A potential solution to facilitate human-machine interfaces in a Maritime 4.0 environment, and augment the human ability, is digital twin technology.

A *digital twin* is a virtual representation that renders the state and behaviour of a physical asset, based on sensor observations within its operational context, in close to real-time (Erikstad, 2017). In the present work, a seafarer (crew member or passenger on board a seafaring vessel) is considered as the physical asset with an associated *human digital twin* that is a virtual representation of the unique individual, which dynamically reflects the state and behaviour of the individual over time (Bruynseels *et al.*, 2018). Developing such a human digital twin for seafarers on South Africa's polar research and supply vessel, the SA Agulhas II, is the main objective of the present work.

Owned by the South African Department of Forestry, Fisheries and the Environment, the SA Agulhas II was built a polar class 5 vessel in Rauma shipyard by STX Finland. She accommodates up to 50 crew members and 100 passengers on annual research and resupply voyages to the Southern Ocean and Antarctic research bases. Since her commissioning in 2012, Stellenbosch University and Aalto University have led a full-scale measurement and research campaign, studying human factors, vessel structural dynamics and environmental conditions during research voyages (Bekker *et al.*, 2018).

This paper will present human-related challenges identified within seafaring vessels in the maritime industry, the expected value of human digital twin solutions associated with the identified challenges, the development of a human digital twin solution for integrating seafarers into a Maritime 4.0 environment and an illustrative use case focussing on human comfort monitoring and management.

2. HUMAN-RELATED CHALLENGES ON SEAFARING VESSELS

Human-centric challenges that may be experienced on seafaring vessels were identified in literature. These challenges are presented in this section.

2.1 UNCERTAINTY DURING EMERGENCY EVENTS AND DANGEROUS ACTIVITIES

Uncertainty and high levels of stress, often experienced during emergency events, may influence the safety of seafarers on board. This may especially be the case if safety depends on the ability of significantly dense crowds in confined spaces reaching designated safe mustering areas in a timely and secure manner (Casareale *et al.*, 2017). During emergency evacuation procedures, knowing the location of all seafarers on board could be critical for efficient mustering (Casareale *et al.*, 2017). Counting passengers during mustering events can be an impossible task using traditional lists and calling names out; especially when up to several thousand passengers are on board, panicked and there is a time pressure (Elnabawybahriz & Hassan, 2016). It is not uncommon that multi-national crew and passengers are aboard seafaring vessels, which may introduce language and cultural barriers that are especially challenging during emergency events (Elnabawybahriz & Hassan, 2016).

If seafarers go missing during emergency events, being able to find them as a matter of urgency can be challenging; particularly in the case of fire or severe flooding (Elnabawybahriz & Hassan, 2016). Using technology to locate seafarers could allow for quicker mustering and efficient searching for missing seafarers (Kwee-Meier *et al.*, 2016). Efforts have already been made to supplement rescue services with passenger and crew location, such as the Scandinavian Reach service called ConnectPOB (ScanReach, 2021). A similar indoor movement tracking system called inFORCE by InnerSpace, that can offer the last known location of individuals, has also been launched (Swedberg, 2020).

Maritime work may entail dangerous activities, such as underwater welding, which relies on unique knowledge and experience to accomplish. An example scenario, in which uncertainty of surroundings provides unprecedented challenges, is an ice pilot charting routes through relatively uncharted environments (Ligthelm, 2019). In this scenario, existing satellite technology may only provide access to satellite imagery of the ice environment 12 hours retarded. That means today's ice condition "forecast" will only be available tomorrow. The result is that an ice pilot only has yesterday's satellite ice condition information and specialised experience from previous ice piloting to chart through today's continuously changing ice environment, weather anomalies and areas with uncharted bathymetry.

2.2 CONNECTIVITY OF SEAFARERS AND STAKEHOLDERS

Networked connections, such as satellite connectivity, are developing to such an extent that it is possible for offshore vessels to have connectivity for all on board to reach people onshore (Nautilus International, 2017; Lim, 2019). This increased access to Internet offshore also introduces social challenges, for example, more seafarers isolate themselves to communicate with family and friends onshore (Hand, 2018). Connectivity is, however, in some cases still limited in reliability, speed and bandwidth, due to availability of satellites en route (Christos, 2018), or imposed restrictions, such as no video calling, and high costs (Nautilus International, 2017). Communication between vessels in low-coverage areas and onshore remains a challenge (Christos, 2018). Radio communication works well within line-of-sight, but ship-to-shore is not always within range for direct radio communication (Lázaro *et al.*, 2018).

2.3 DATA-DRIVEN CHALLENGES

In the maritime industry, the digital transformation has been practically enabled through the development of sensor and data-driven technologies. The development of such technologies has also facilitated increased and easier access to sensors and IoT devices. The maritime industry has seen the implementation of several sensor networks and systems that were opportunity-driven, rather than needs-driven (Erikstad, 2019). This has resulted in bulk data capturing without the appropriate data handling methods to extract actionable information and insight, such as design and operational decision support. In many situations, sensors have been placed in suboptimal locations and record large quantities of data that have potentially poor accuracy and fidelity, and at arbitrary frequencies (Erikstad, 2019).

2.4 LACK OF HUMAN-CENTRIC DIGITAL PLATFORM DESIGN

Digital services use digital technologies to enhance situational insight and support decision-making for improved operations (Erikstad, 2019). It seems evident from literature that the maritime digital transformation has focussed on development of digital service portfolios for smart asset management (Nowak & Stakkeland, 2019), which result in greater development of the digital presence of inanimate assets than the development of human digital representation. Though platforms or systems exist to monitor vessel performance or structural health, to date there is no recorded human-centric digital platform for monitoring the well-being of seafarers. For example, the automatic identification system (AIS) is primarily focussed on communicating vessel position, course and speed as a safety measure (Lázaro *et al.*, 2018). Nowadays, AIS is used for more than only a safety measure, such as for fleet monitoring, but AIS data does not include seafarer state or well-being. Safety and wellness of seafarers should be a driver for creating human-centric digital platforms that connect vessels, structures and stakeholders within the maritime industry (Christos, 2018).

2.5 FUTURE SKILLS REQUIREMENTS FOR THE MARITIME WORKFORCE

The maritime workforce can be expected to perform laborious tasks with ever-changing schedules and long working hours (Özsever & Tavacioğlu, 2018; Lützhöft *et al.*, 2019). The technological developments in Maritime 4.0 will require more technical knowledge and expertise from the future seafaring workforce (European Community Shipowner's Associations, 2018). These developments will also change the employment patterns in the maritime industry, such as decreasing crew numbers due to increased automation. These potential changes introduce challenges, like the global shortage of skilled seafarers and predicting the future skill requirements of seafarers with the technological advances. These challenges will require continued investment in training to respond to new skills requirements resulting from the technological progress.

Cicek *et al*. (2019) analysed future skills requirements for the maritime workforce with the integration of new technologies in the maritime industry. Important capabilities with regards to four competency categories were found, altogether containing thirty three competencies, including:

- Technological competencies – information and data processing and programming proficiencies.
- Social competencies – ability to transfer knowledge.
- Methodological competencies – information technology and technology affinity, cognitive and learning ability.
- Personal competencies – environmental and safety awareness, flexibility, motivation to learn.

The future maritime workforce may even require abilities that humans cannot develop (Lützhöft *et al.*, 2019). Or a dependency on systems could evolve as more human tasks are delegated to systems, which may result in loss of human training and skills (Pacaux-Lemoine & Trentesaux, 2019). This further motivates human-centric technological development to facilitate human-system integration within Maritime 4.0.

3. THE HUMAN DIGITAL TWIN

The development of a human digital twin concept for integrating seafarers into a Maritime 4.0 environment, which contributes to the development of the Mariner 4.0 vision, is presented in this section. The interdisciplinary proficiency gleaned from Operator 4.0 is also discussed.

3.1 DEFINITION OF THE HUMAN DIGITAL TWIN

A *human digital twin* is a virtual representation of a person, which dynamically reflects the state and behaviour of the unique individual over time (Bruynseels *et al.*, 2018). A digital twin should not be confused with a *digital model* or *shadow* (Kritzinger *et al.*, 2018). A *digital model* is a static digital representation of a physical object. A *digital shadow* is an automatically updated digital representation of a physical object that mirrors the physical object's behaviour. In terms of data flow, a digital model could be considered the lowest level of integration between the physical and digital realms (no automated data flow), surpassed by the digital shadow. The highest level of integration is a *digital twin* that enables automated bidirectional data flow between the virtual and physical objects. The digital twin can offer informational feedback from the cyber world to the real world or, for example with remote commissioning of systems, drive the physical twin.

With reference to the different levels of integration by Kritzinger *et al.* (2018), if a human digital representation only captures the unique attributes of a person, the result may be likened to a *human digital model*. A human digital representation that is a human digital model *and* mimics the state and behaviour of a person may then be a *human digital shadow*. In the context of a *human digital twin*, the digital representation should capture suitable attributes of a unique person and dynamically reflect their state and behaviour over time in such a way to deliver value (Bruynseels *et al.*, 2018), and provide feedback from the cyber world to the person that augments their ability to work, such as helpful instructions. The human digital twin concept discussed further could be accordingly implemented at the level of human digital *model, shadow* or *twin,* depending on the level of integration required for a specific application.

A generic human digital twin implementation for seafarers on board the SA Agulhas II is shown in Figure 1. Relating the definitions of a digital twin by Erikstad (2017) and Kritzinger *et al.* (2018) to the present work, in Figure 1 it can be seen that:

- a seafarer is considered as the "physical asset",
- that lives and works on the SA Agulhas II, which is the "operating context",
- virtually mimics the desired state and behaviour of the seafarer, and
- bidirectional communication between the physical and cyber worlds exists.

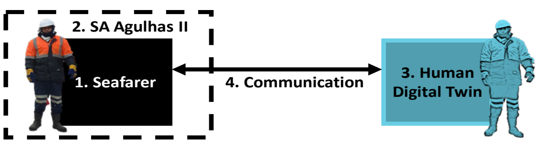

Figure 1. A Generic Human Digital Twin Solution on the SA Agulhas II

The lifecycle of each human digital twin can vary depending on the responsibilities of the seafarer. For a crew member, it may be birthed at the start of training in service, move with them between jobs and eventually retire with them, potentially providing valuable experience for training new seafarers. For passengers, the existence of the human digital twin may only last for one cruise or contribute towards a passenger loyalty service.

3.2 THE HUMAN DIGITAL MODEL

The Operator 4.0 vision considers *human-in-the-loop control* where human behaviour models are incorporated into feedback control of systems (Munir *et al.*, 2013; Romero *et al.*, 2016a). A significant challenge is modelling human behaviours due to the complexity of human behavioural aspects (Munir *et al.*, 2013). Creating technological systems that are human-centred, such as HCPSs, is possible using human factors concepts and techniques (Tzafestas, 2006). *Human factors* is the field in which the relationships and interactions between humans and the equipment, processes and products they use is studied. Various human interactions, such as physical, cognitive and thinking factors, are considered and behavioural sciences is used in the design of machines and human-machine systems (Tzafestas, 2006).

3.3 DEVELOPMENT OF OPERATOR 4.0 IN MANUFACTURING

The shop floor worker evolved into Operator 4.0 during the fourth industrial revolution. *Operator 4.0* is a smart and skilled worker who works aided by machines when so required (Romero *et al.*, 2016a). The generation of Operator 4.0 represents human-centric design and engineering, where automation is considered augmentation of the human's physical, sensorial and cognitive capabilities through creating HCPSs.

The Operator 4.0 vision focusses on augmenting human performance through enhancing human-machine interactions and developing physical-cyber interfaces. Romero *et al.* (2016b) define Operator 4.0 typologies that capture different means through which technologies can assist workers, such as the *Virtual Operator* that uses virtual reality to aid work. Operator 4.0 provides methods of interacting *with* digital systems, but not yet representing the human in the cyber realm *through* a digital presence. Creating a digital presence for a person *through* a human digital twin was recently reported (Sparrow *et al.*, 2021; Sparrow, 2021).

4. EXPECTED VALUE OF HUMAN DIGITAL TWIN SOLUTIONS

Human digital twins are expected to provide the maritime industry with value through data-enriched decision support, human-system integration and more discussed in this section. Support human digital twins may offer for challenges on vessels is also presented.

4.1 DECISION SUPPORT

A significant purpose of a human digital twin solution is to support decision-making. In the functional decomposition, presented in Section 5, most functions are dedicated to decision support and following through with the decisions made. A human digital twin solution aims to facilitate communication among seafarers on board to augment the capability of seafarers in both making decisions and acting on them. Digital twins in general also provide automated integration of real data into decision-making (Sullivan *et al.,* 2020).

4.2 HUMAN-SYSTEM INTEGRATION

A Maritime 4.0 environment is realised through the adoption and implementation of connected technologies throughout the lifecycle of assets (Sullivan *et al.,* 2020). This is likely achieved through the design and production of new, smart assets or retrofitting legacy assets with new, smart technology. The working and living environments of seafarers on vessels are undergoing technical transformations as a result of increasing connections between digital and physical systems. Providing seafarers with a digital presence in the largely machine- and system-dominated digital development through human digital twins can facilitate collaboration between digital systems and humans, and machines and humans, which enable them to benefit from digital twin technology in their respective roles on board.

4.3 HUMAN-CENTRIC DATA ACQUISITION

Human digital twin solutions strive to capture unique, relevant information about each seafarer. As an example, human comfort information can be captured through a comfort response (the person submitting a subjective comfort value ranging between 0 and 10, where 0 is comfortable and 10 is severely uncomfortable) during different sea states. This unique information repository can potentially be used in developing personalised models and comfort thresholds for unique individuals. The personalised models developed could be used to shift human comfort monitoring based on past or real-time sensor observations to predicting human comfort for future charters and routes based on sea state forecasts.

Human comfort predictions may facilitate decision-making with regards to planning operations and routes. The most suited crew could be selected based on previous experience and personal responses in conditions similar to forecast sea states, or for training new crew inexperienced in predicted sea states. In more immediate cases, the captain could determine which seafarer may have the most suitable experience in unexpected situations, like finding a doctor among passengers. Furthermore, it should be possible to determine if forecasted sea states are fit for safe human-related operations using personalised models to plan routes. This can motivate the requirement for autonomous or unmanned vessel operations in dangerous areas or avoid creating work schedules in conditions where workers would not be able to be productive. The cruise industry could identify the most comfortable routes for passengers along which lower comfort scores are predicted.

4.4 INFLUENCE ON VESSEL DESIGN

Though there is motivation to keep seafarers on board, automation can enable reduced crew sizes (Lützhöft *et al.*, 2019; Kooij & Hekkenberg, 2020). Reduced numbers on board call for increased maintenance of seafarer well-being for task performance (Kurt *et al.,* 2016). In the cruise industry, seafarer well-being is an important factor for customer satisfaction. Seaborne tourism is increasing significantly in remote environments, such as the Antarctic and Arctic, which offer challenging charting environments for cruise vessels (Kurt *et al.,* 2016; NOEP, 2021; IAATO, 2021). Especially in these icy environments, seafarer well-being and safety is an important consideration. Human comfort, performance and safety during vessel operation is particularly addressed at vessel design stages (Kurt *et al.,* 2016). Human digital twins could be used to facilitate the communication of human-centric information and feedback throughout the lifecycle of a vessel. Live feedback captured from passengers during voyages and models developed through human digital twins could enable understanding of motion limits for vessels in various shipping applications (e.g. fishing, cruises) which can contribute to supporting decisions at vessel design.

4.5 POTENTIAL HUMAN DIGITAL TWIN SOLUTIONS TO IDENTIFIED CHALLENGES

In Section 2, human-related challenges on vessels were reported. Possible solutions that human digital twins can offer to these challenges are presented next.

4.5(a) Seafarer Location Monitoring during Dangerous Activities

Human digital twins can facilitate near real-time location monitoring of seafarers and made accessible to relevant stakeholders. Immediate access to the last known location of seafarers can be available during execution of dangerous activities, or to crew and rescue services in emergency events, for example to identify and find possible missing parties. The known location can also be used as a method for controlling unauthorised access.

4.5(b) Limited Unique and Specialised Knowledge and Experience

The human digital twin of a uniquely knowledgeable and experienced crew member may be able to capture important and critical decisions, as well as tendencies, which could be used in training or augmenting the capabilities of less experienced crew members. Digitising knowledge could potentially be used in development of autonomous vessels.

4.5(c) Lack of Human-centric Digital Platform Design

Human digital twin solutions are inherently human-centric. A type of digital platform is integral to the realisation of human digital twins and facilitates links between the cyber and real world. Implementation of multiple human digital twin instances can provide a digital platform that facilitates monitoring the comfort of seafarers on board and augment seafarers' skills and abilities to plan and perform work activities. The platform may be used, for example, to store the most-updated vessel information, such as itinerary and schedule, which all seafarers could access through personal interfaces, such as a tablet or smart watch.

Introducing new technologies, such as wearables, can raise concerns with seafarers that need to use them. Aspects like acceptability and trust in new systems may need to be addressed, for which a participatory design approach could be helpful (Flemisch *et al*., 2008). Seafarers should be included throughout the human digital twin development process, which is intended to be customisable for specific applications. It is important to tailor the digital twin functionality to the unique requirements of seafarers so that they are supported in their work tasks and can operate well in the environment they work in, encouraging human-centric design. Incorporating seafarer feedback during system trials and testing is also critical. Bridging gaps between seafarers as users through inclusive development has proven informative for understanding expectations and trust of systems designed for seafarers (Man *et al.*, 2018).

4.5(d) Limited Ship-to-shore Connectivity

The bulk of the data collection and analytics for a digital twin solution could be customised to onboard edge analytics and fog computing, before sharing information about the seafarers directly onshore or to a Cloud platform accessible to stakeholders worldwide. The information could be customised to be only critical or relevant and in compact formats for easier transmission during times ship-to-shore connectivity is available.

4.5(e) Inefficient Data Management

Need-driven design procedures for implementing human digital twins strive to move from opportunity-driven sensor implementations. The human digital twins could facilitate appropriate and efficient data handling methods to extract actionable information and insight, and store organised data.

5. CONCEPTUAL DESIGN OF A HUMAN DIGITAL TWIN

The conceptual development of a human digital twin for seafarers on board the SA Agulhas II, i.e. the development of Mariner 4.0, will be discussed. A systems engineering approach was used, wherein the design process progresses from a broad scope, considering the system as a whole, before being refined into subsystems with specific requirements.

5.1 NEED IDENTIFICATION

Generic human digital twin needs, much like client needs in a standard engineering design process, were determined. Table 1 presents these needs, many of which were inferred from digital twin needs identified in maritime literature (Taylor *et al.*, 2020).

Table 1: Human Digital Twin Needs.

Human Digital Twin Need	Need ID
Facilitate insight provision and decision support, at different levels and temporal scales, with regards to seafarer well-being from real operational data. This need further implies automated integration of operational data into decision-making.	N_1
Integration of complex individuals and various sources of data into the digital realm.	N_2
Remote inspection of the well-being, or state, of seafarers and assistance to improving, or managing, their well-being.	N_3
Remote monitoring of seafarer state through controlled access and up-to-date information.	N_4
Platform for reliable bulk data analytics relating to seafarer state on large volumes of data measured from sensors.	N_5
Express the unique identity of the seafarer. This is to capture the unique personal and job-related characteristics of the person, such as gender, height, susceptibility to seasickness, job description or seafaring experience. This implies a one-to-one digital twin-to-person relationship.	N_6
Facilitate digital twin-to-digital twin communication.	N_7
Perform safety checks or alerts when unsafe conditions are a reality, for example in the case of man overboard.	N_8
Augment the ability of the seafarer to perform activities, for example by providing instructions on how to do something, where fellow seafarers are or directions on where to go.	N_9
Present relevant information to the seafarer in a practical manner and facilitate interaction, such as responses to an instruction or indication of task progress, from the seafarer to the digital twin.	N_10
Capture the relevant state and behaviour relating to each person on board in close to real-time.	N_11
Store data and information in a sustainable and organised manner.	N_12
Facilitate capturing and managing future events and planned activities, such as a schedule, for the seafarer's personal and public use.	N_13

5.2 FUNCTIONAL FLOW DECOMPOSITION

A functional analysis was completed as a method of examining what actions a human digital twin solution would be required to perform as a system. The highest level of functional flow considered, the system-level, is shown in Figure 2. These functions can be used to break the system into subsystems with specific requirements to fulfil, however, this is often achieved for a context-specific application. The functional flow discussion will be directed towards a human digital twin for monitoring and managing human comfort, relevant to the use case described in Section 6.

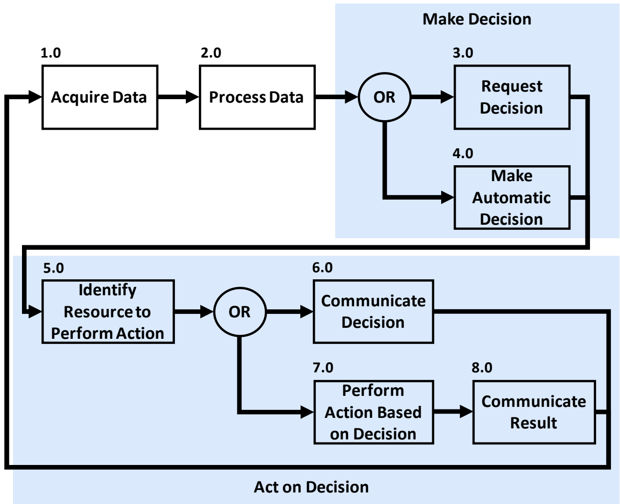

Figure 2. Functional Flow Block Diagram for a Human Digital Twin Solution

The functional block 1.0 in Figure 2 relates to obtaining sensor observations, or data from various sources, with which the state and behaviour of seafarers can be gathered and estimated. For example, data that is acquired with regards to human comfort could be accelerometer readings, which measure the structural vibration of the ship, or seafarer location readings of where the seafarer is on board.

Processing the data captured, considered at functional block 2.0 in Figure 2, could comprise of using models or standards to quantify human factors, such as using ISO 2631-1 (1997) to quantify human comfort due to whole-body vibration. It is important that at this stage the human digital twin is updated, based on the most up-to-date data acquired, to represent the state and behaviour of the seafarer in near real-time.

The functions to follow, blocks 3.0 to 8.0 in Figure 2, exist largely to facilitate decision-making. It is important that the processed data from functional block 2.0 can be used to make decisions and allow for the extraction of actionable insight from the information provided from sensor readings in near real-time. To make a decision, a decision-maker is required. The most suitable decision-maker could be the seafarer, the human digital twin or another asset (human or system). Cooperation between the seafarer and their human digital to select a decision-maker, encompassed by the "OR" logic in the "Make Decision" region, could take on a structure, mode or form tailored to preferred practices for an application (Pacaux-Lemoine & Flemisch, 2016). The human digital twin, however, should be able to identify favourable decision-makers from unique information about each person and asset stored in their digital twin, visible to peer digital twins, or could ask the seafarer to suggest who may be best equipped to make the decision.

In the case of making "automatic" decisions, seen in block 4.0 in Figure 2, the human digital twin is the decision-maker. An example decision may be an automated determination of the seafarer's comfort, based on thresholds. The human digital twin should also be able to learn from previous simple decisions made by the seafarer. This does not imply that humans will be subservient to their digital twins; rather, trivial or recurring decisions, that may lend themselves to frustration of the seafarer, are logged. This may also incorporate gaining permission from the seafarer at least the first time an "automatic" decision is made.

Functional blocks 5.0 to 8.0 represent acting on a decision made by means of performing an action as a response to the decision. Similar to requiring a decision-maker to make a decision, an action-performer is required to perform an action. Either the human digital twin, the seafarer or another asset can be the action-performer. The "OR" logic in the "Act on Decision" region may also require cooperation between seafarer and human digital twin, which can again be customised according to application requirements. An example scenario where an "automatic" decision and action may be useful is if the seafarer is unexpectedly busy securing equipment that shook loose during a storm and cannot request lunch be kept for them. The human digital twin may recognise this through knowledge that the seafarer had lunch scheduled, but is running late and may miss lunch. The human digital twin can decide on the most suitable lunch for the seafarer, based on previous lunch preferences, and order lunch to be kept. Once an action such as this is completed, it is important to note that although the functional flow is considered to numerically end at block 8.0, the last blocks flow to the first block again, indicating the system strives to achieve its missions on a continuous basis, not just once-off.

5.3 INTERACTION WITH OTHER DIGITAL TWINS

Although not shown in Figure 2, many functional flow blocks may require the human digital twin to interact with other systems. For example, in block 3.0, a seafarer may need assistance from someone else to make a decision. The seafarer may wish to consult others in person or through twin-to-twin communication. Thus, the human digital twin should facilitate communicating with other seafarers, twin-to-twin.

Twin-to-twin communication should not be limited among human digital twins, but include communication with digital twins of non-human assets and systems. For example, acquiring data in block 1.0 may require interaction with a digital twin of the ship that can supply ship vibration data to the human digital twin. Or if a seafarer decides a change in ship course is required to complete a task, at block 6.0, the seafarer could communicate this through their human digital twin to the ship digital twin. In turn, the ship digital twin would handle the necessary communications with navigational officers on duty to commission a change in ship heading.

Such interactions among digital twins implies that each resource on board, whether human or inanimate asset, is equipped with an associated digital twin. Each digital twin is responsible for maintaining a virtual representation of the state and behaviour of its physical counterpart, enabling communication between the associated physical and digital counterparts, and acting as the digital presence through which its physical counterpart can communicate with other digital twins.

6. ILLUSTRATIVE USE CASE: HUMAN COMFORT MONITORING AND MANAGEMENT

In order to realise a human digital twin solution, as shown in Figure 1, for monitoring and managing the comfort of seafarers on a seafaring vessel, the communication between the physical and digital twins, as well as the digital representation of the seafarer (the digital twin itself), needs to be developed. Communication from the seafarer to their digital twin would likely be acquiring data from sensors, integrating the data from various sources and processing the data into information. An example of the embodiment of this is presented in Figure 3. The human comfort information would be presented to perhaps navigational officers in the bridge in an insightful manner to monitor human comfort and assist with decision-making towards managing human comfort. The communication to the seafarer from the digital twin could be, for example, via a smart watch the seafarer is wearing.

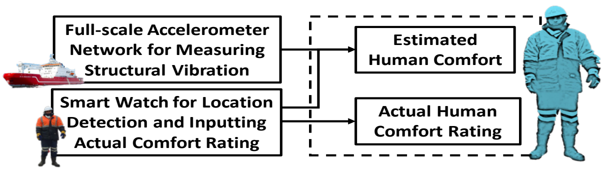

Figure 3. Example Embodiment of the Communication from the Physical World to the Digital World

6.1 MODELS OF HUMAN COMFORT

Shipping provides a complex, dynamic environment in which seafarers are exposed to various vibration stimuli from machinery on board, as well as the vessel's motion through the water. The human body is equally complex and dynamic, resulting in no simple or easily predictable response to vibratory stimulation (Griffin, 1996). Human comfort due to whole-body vibration, such as the structural vibration seafarers experience on a ship travelling through open water and ice, can be estimated and assessed by methods presented in ISO 2631-1 (1997).

The ISO 2631-1 methodology evaluates whole-body vibration comfort based on frequency weighted root mean squared (RMS) acceleration values. The whole-body vibration exposure frequency range, in which human comfort is influenced, is of interest between 0.5 and 80 Hz in all axes of vibration. The associated vibration of each axis can be measured using accelerometers proximate to the vibrating surface interface on which a seafarer's body weight is supported. The ISO 2631-1 methodology hinges on a basicentric axis system of the human body, not the same axis system of the vessel according to which structural vibration accelerometers are likely orientated, which means that the orientation of the seafarer with respect to the vessel is an important factor to consider. The severity of the whole-body vibration perceived is also dependent on the posture of the seafarer, whether standing, seated or recumbent. An example methodology for calculating the whole-body vibration comfort of a bow-facing, standing seafarer is shown in Figure 4.

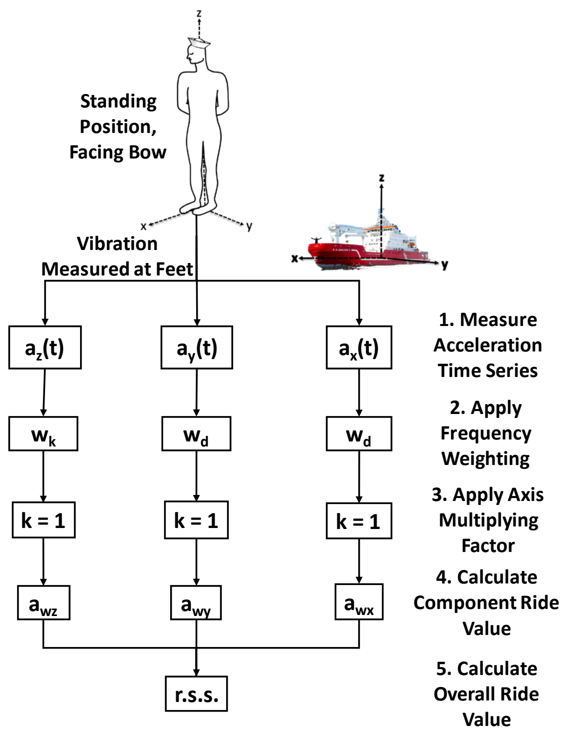

Figure 4. Method for Calculating the Whole-body Vibration Comfort of a Bow-facing, Standing Seafarer

First, acceleration measurements are frequency weighted in the time domain. The root mean square acceleration is calculated for each vibration axis to determine the component ride value. Whole-body vibration comfort is related to the overall ride value, which is determined by accruing the component ride values using root sum of squares (r.s.s.) of the RMS values. The overall ride value is then classified in terms of comfort by considering the likely human responses which are provided in the standard and are correlated with likely responses of persons to vibration in public transport.

Furthermore, the actual comfort of seafarers can be monitored by using the seafarer as a living sensor to rate their perceived comfort or discomfort through a convenient interface such as a smart watch or tablet. The perceived comfort of the seafarers captured in conjunction with the estimated comfort information can be used to develop personalised comfort models for seafarers over time. Such data could serve to improve the power and applicability of data-driven predictive models.

6.2 HUMAN COMFORT MONITORING DASHBOARD

An example of an envisioned interface, or monitor, which could be presented on a screen in the bridge for navigating officers to use as a dashboard for human comfort monitoring, is shown in Figure 5. This monitor displays various aspects of what could be presented to navigating officers, but would ideally be customised according to the vessel operator requirements.

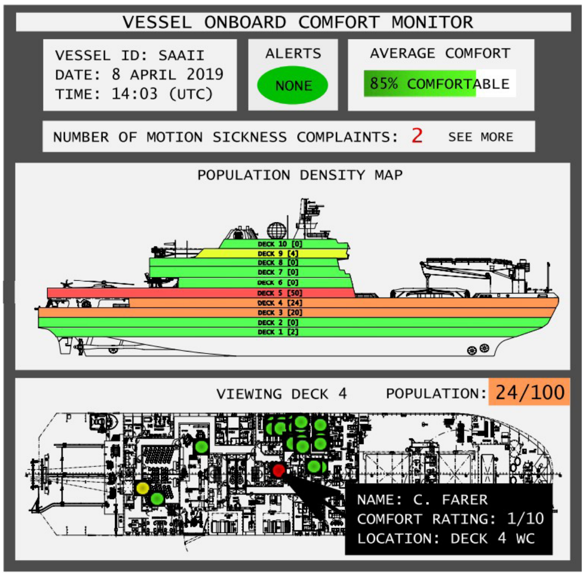

Figure 5. Onboard General Human Comfort Monitor Prototype

The monitor could enhance the officer's state awareness of seafarers by providing insight into the general comfort state of passengers shown via a bar graph indicator, as seen in Figure 5, that is supplemented with text and a green colour to indicate that the average seafarer is about 85 % comfortable. The monitor could similarly augment the officer's spatial awareness of seafarers on board by displaying the population density map for all decks. Furthermore, the situational awareness could be deepened by, for example, being able to view the location of a passenger that lodged a motion sickness complaint. By viewing the deck that the seafarer of interest is on, the said passenger can be indicated, as in Figure 5, with a red coloured dot (symbolising severe discomfort) to be situated at the deck 4 water closet.

To gain further insight into the situation, the officer could click on the likely motion sick passenger to view their personal comfort monitor - an example of which is shown in Figure 6.

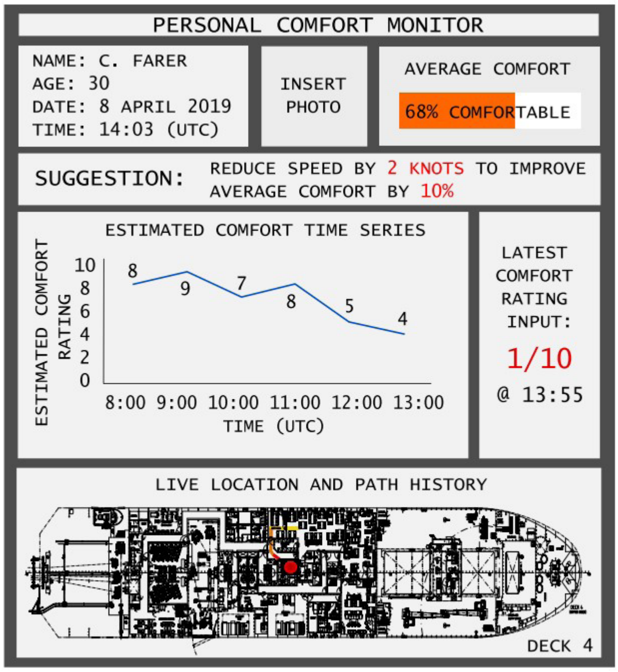

Figure 6. Onboard Personalised Human Comfort Monitor Prototype

Upon viewing the personalised human comfort dashboard for the passenger that complained of motion sickness, the officer's situational awareness is deepened by seeing that this passenger's comfort started declining around the time of a storm that started (not indicated on the dashboard here). Furthermore, the passenger is seen to recently have been in the dining room, which should explain why their current location at the water closet coincides with a motion sickness complaint. A message could be sent to the passenger to recommend taking motion sickness medication and laying down for a while before continuing with their planned activities.

7. CONCLUSIONS AND FUTURE WORK

Maritime 4.0 is transforming the maritime industry, including the working and living environment for seafarers. People are still integral to many vessel operations and, especially in the case of the passenger sector, critical to success. Human-centric development within the Maritime 4.0 movement, that is often machine and system focussed, is important for the future of the maritime industry. In this paper, human-related challenges in seafaring vessels were identified and discussed. A human digital twin solution which offers to facilitate the integration of seafarers into Maritime 4.0 environments, resulting in the development of a smart, connected Mariner 4.0, is proposed. This includes the current conceptual development of Mariner 4.0 on the SA Agulhas II. The expected value of a human digital twin solution is discussed, revealing a human-centric digital platform that, along with the link between the cyber and physical worlds, offers the potential to facilitate important communication, transfer of knowledge (or training), decision-making and data management. The result of such a solution is envisioned to lead to improved safety and efficiency of operations on board.

Though Maritime 4.0 offers potential solutions to current and future human-related challenges, human-centric research efforts within Maritime 4.0 are still essential. Planned future work includes further development of the Mariner 4.0 concept, involving practical implementation and in-situ deployment of human digital twins for the monitoring and managing of passenger comfort during a voyage on board the SA Agulhas II.

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