

Quantitative Processing of Situation Awareness for Autonomous Ships Navigation

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ABSTRACT: The first ever attempt at fully autonomous dock-to-dock operation has been tested and demonstrated successfully at the end of 2018. The revolutionary shift is feared to have a negative impact on the safety of navigation and the getting of real-time situation awareness. Especially, the centralized context onboard could be changed to a distributed context. In navigation safety domain, monitoring, control, assessment of dangerous situations, support of operators of decision-making support system should be implemented in real time. In the context of autonomous ships, decision-making processes will play an important role under such ocean autonomy, therefore the same technologies should consist of adequate system intelligence. At the same time, situation awareness is the key element of the decision-making processes. Although there is substantial research on situation awareness measurement techniques, they are not suitable to directly execute quantitative processing for the situation awareness of autonomous ships navigation. Hence, a novel quantitative model of situation awareness is firstly proposed based on the system safety control structure of remotely controlled vessel. The data source is greatly limited, but the main result still indicates that the probability of operator lose adequate situation awareness of the autonomous ship is significantly higher than the conventional ship. Finally, the paper provides a probabilistic theory and model for high-level abstractions of situation awareness to guide future evaluation of the navigation safety of autonomous ships.

1 INTRODUCTION

Autonomous ships are receiving significant attention from the academic community and industry in recent years. The new upsurge will have a profound impact on maritime industry to great extent, in which it will affect shipping companies, maritime operations, shipbuilders and their operational mode. In 2012 and 2015, the funding of the "Maritime Unmanned Navigation through Intelligence in Networks (MUNIN)" project by the European Union [1] and Rolls-Royce led "Advanced Autonomous Waterborne Applications Initiative (AAWA)" [2] to outline the concept of autonomous ships and the vision of turning remote and autonomous shipping into a

reality. At the same time, International Maritime Organization (IMO) also take some steps to investigate safety, security and legal issues for autonomous ships in IMO instruments [3-6, 29]. Regardless of the developing stage of autonomous ships, the key issue needs to be emphasized is that the ship be capable of an equivalent level of safety to the conventional ships.

The ability of a ship to monitor its own health, establish and communicate what is around it and make decisions based on that information is vital to autonomous operations. At the current stage, how to better achieve autonomous navigation has become a top priority. Fully autonomous navigation for the

duration of the whole voyage is extremely difficult to realize in recent years, which based on existing level of technological development. Remote-controlled mode will be a feasible solution. However, removal of vessels from direct control and the visual field of operator inevitably reduces their ability to directly attain adequate situation awareness (SA) of the vessel and its surroundings.

SA is a prerequisite to rational decision-making in many contexts, from individual operator to team cooperation, and reflects the ability of a human to perceive elements in their environment, comprehend their meaning and project their state in the near future [7]. It plays a crucial role in effective risk reduction for operators. Currently, because of the complexity of real ship maneuvering system, there are few research and method are applied to enhance SA successfully in the maritime industry. Previous research shows that the training procedure using simulator is an positive way to improve SA, operational effectiveness and safety [25]. In the relatively advanced training framework, different information can be collected from the simulator scene and from the real world to provide data support (Figure 1), such as audio, video, bio-metric data from eye-trackers. Furthermore, the application of Wearable Immersive Augmented Reality (WIAR) technology [26] also offer a new solution of next generation navigation system, enhanced and remote monitoring, and improve operator performance.

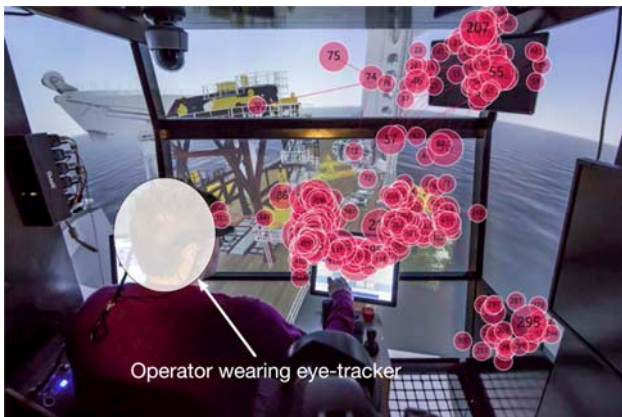


Figure 1. The gaze plot when operator wearing eye-tracker

However, the emergence of the concept of autonomous ships in remote-control mode, the complexity in autonomous navigation systems reaching a new high-level, and some unnecessary complexity adds to captains' or operator's confusions as it changes the context of the interaction. For example, captain's responsibility from the bridge to shore-based control centre (SCC), and the decision support system is integrated to maintain safety of navigation. For this reason, the centralized context onboard would shift to a distributed context [27]. In the substantive research of SA, the physics and cognition of operators are considered to be fixed in a centralized system. And few are paying attention to how SA might be influenced in distributed working domains. In such system, the operator needs to maintain an adequate situation understanding to ensure the safety of ships, which is critical.

At present, the research of remotely-controlled ships navigation possesses very little in the way of

shore-based situation awareness and focus on qualitative analysis. And the design of the system is still being developed and the final structure remains uncertain, therefore it is difficult to explore all the possible scenarios that may arise from the combination of components' behavior [8]. Any inaccuracy situational representation will propagate into decision-making process. When adding autonomy in order to increase situation aware-ness, it is important to take into account the possibility that operators located on shore may be unfamiliar with the technology or uncertain over its capability [9], and over-reliance may skew the decision-making process.

In order to maintain an equivalent safety level, better serve the construction of the remote control system and the training of shore-based operators, it is necessary to quantify the SA in autonomous ships navigation.

In this paper, we propose a novel model for quantifying the SA of autonomous ships navigation focuses on "remote control" mode. The next section lays down the overview of autonomous ships and determine the object in this paper. Section III introduces the theoretical background of SA and discuss the current SA measurement techniques. Section IV proposes a new quantitative method for modeling the SA of autonomous ships navigation considering the probability with each known awareness element. Section V discusses the result of model. The paper ends with conclusions and potential future works in section VI.

2 THE OVERVIEW OF AUTONOMOUS SHIPS

The idea of autonomous ships is partly derived from the Unmanned Surface Vehicle (USV), and the concept of autonomous ship was first described by Schönknecht in 1983 [10]. Subsequently, Japan explored this concept in more depth to minimize crew costs and built several automated ships. Recent technological advancements in big data and communication infrastructure, intelligent ships have entered people's field of vision as the highest level of automation. Compared with conventional ship, autonomous ship will be a highly integrated ship of various systems, which is the advanced stage of intelligent ship development.

According to the design concept of autonomous ships, nearly all subsystems of autonomous ships will be controlled by remote or autonomous mode, including collision avoidance decision-making and ship state monitoring. The vessel may be manned with a reduced crew or unmanned with or without supervision and have the capabilities to make decisions and perform actions with or without human in the loop. To a varying degree, it can operate independent of human interaction. In general, the control mode can be divided into four categories (Figure 2). The remotely-controlled merchant vessel will play an important role for maritime transportation system, and become a reality in recent years, even though there are many challenges. In this paper, we focus on the "remote control" mode supported by SCC.

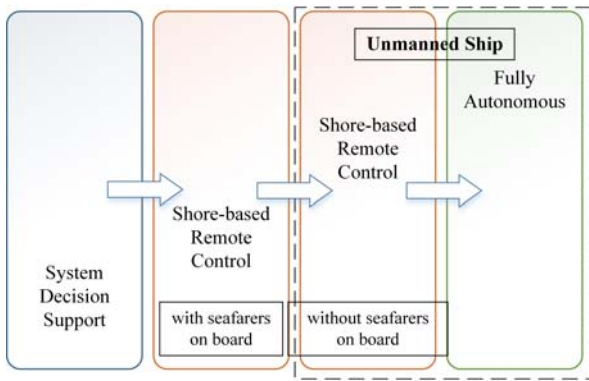


Figure 2. The development stages of autonomous ships

3 THEORETICAL BACKGROUND AND MEASUREMENT OF SITUATION AWARENESS

In the early 1980s, the situation theory was developed by Jon Barwise [11-13] and then was successfully extended and application [14, 15] in many domains, especially in the military. There are various definitions and understandings of SA. And most popularly cited one and firstly introduced by Endsley [16]. The summarized definitions that SA is perception of element of the environment within a volume of time and space (level 1 SA), the comprehension of the current situation (level 2 SA) and the projection of the status in the near future (level 3 SA). Figure 3 shows Endsley's three level SA models. The increased use of teams in complex environments has shifted the focus from individual operator SA onto the shared SA of teams of operators, which to deal with multiple information resources. Team or shared SA reflects the coordinated awareness that the team possesses as a whole unit [16, 17]. In this paper, we mentioned "team SA" as a generalization of individual SA, and be defined as the sum of the technical and non-technical skill of each member of the team.

Across the domains, an initial literature review was conducted in order to create an exhaustive database of existing SA measurement techniques, and determine whether any of these approaches could potentially be used in the assessment of SA in autonomous ships navigation. More than 30 different measurement techniques of SA have been identified and can be generally categorized as direct measures and indirect measures. Due to the limited space of this article, the following categories of SA measurement techniques were enumerated.

- 1 SA requirement analysis; including unstructured interviews and structured questionnaires [18].
- 2 Freeze probe techniques; such as Situation Awareness Global Assessment Technique (SAGAT) [16].
- 3 Real-time probe techniques; such as Situation Awareness Assessment Method (SPAM) [19].
- 4 Self-rating techniques; such as Situation Awareness Rating Technique (SART) [20], Situation Awareness Rating Scales Technique (SARS) [21] and Crew Awareness Rating Scale (CARS) [22].

- 5 Observer-rating techniques; such as Situation Awareness Behavioral Rating Scale (SABARS) [23].
- 6 Performance measures.
- 7 Process indices; typical measurement techniques such as eye tracker, verbal protocol analysis, etc.

Among them, SAGAT and SART approaches are by far the most commonly applied during individual and team SA assessment. SAGAT offer a direct measurement way of operator SA, which removes the numerous problems associated with collecting post-trial and subjective SA data. However, a real scenario with multiple information sources was frozen and managing SA queries to multiple agents in distributed SA model to be almost impossible. And the method carries a high level of intrusion upon primary task performance caused by the task freezes [28]. For SART, it is non-intrusive to task performance and can be obtained from different team members, but participants may not be able to accurately rate the level of SA when they have inadequate SA.

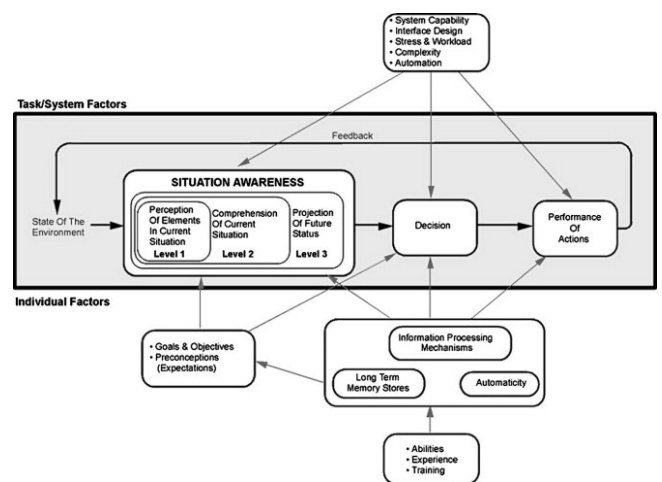


Figure 3. Endsley's decision-making, information processing and SA model

The existing SA measurement techniques is difficult to meet the requirements to assess SA across multiple locations at the same time, both individual and team SA for the same task and also assess SA in real time. Therefore, to properly assess how SA is influenced in a distributed ship-shore context during the tasks of monitoring and controlling autonomous ships, and quantify the observability and understandability in the human-automation interaction process would be affected intrinsically for the task of remote monitoring and controlling vessels, a novel and more quantitative approach need to be proposed which considers not only the attainment of elements of awareness but also their quality and reliability.

4 THE PROPOSED QUANTITATIVE MODEL

The fact that the remotely controlled merchant vessels will affect virtually all aspects of her operation, including navigation. Operators and full bridge team will be located in SCC to oversee decision making, supervision and trouble-shooting.

Here, an operator located onshore will have an overall command over a handful of vessels traversing different seas. However, the full bridge team can provide assistance to better deal with the problem, as soon as a situation develops in a significant difficulty and emergency. Because of the inherent uncertainty of quantifying these properties, we seek to calculate a probability of loss of SA, which can be presented as follow:

$$P(\overline{SA}) = 1 - P(SA), \quad (1)$$

where $P(\overline{SA})$ is the probability of a system not possessing adequate awareness.

The adequate SA is based on the accurate knowledge of systems and a genuine experience of the vessels' current state via multiple source information. In this paper, we do not attempt to define these performance criteria or even assess a particular element. Instead, a Bayesian inference based quantitative model is presented to quantify the awareness of autonomous ships navigation in abstract terms. In order to clarify the composition of remotely-controlled merchant vessel, we adopt the safety control structure was first developed by Wróbel [24] (Figure 4). The safety control structure is focus on the "remote control" mode of autonomous ships and built under Systems Theoretic Process Analysis (STPA) framework, which is a novel hazard identification method. Therefore, it is satisfying the requirement of quantitative SA model.

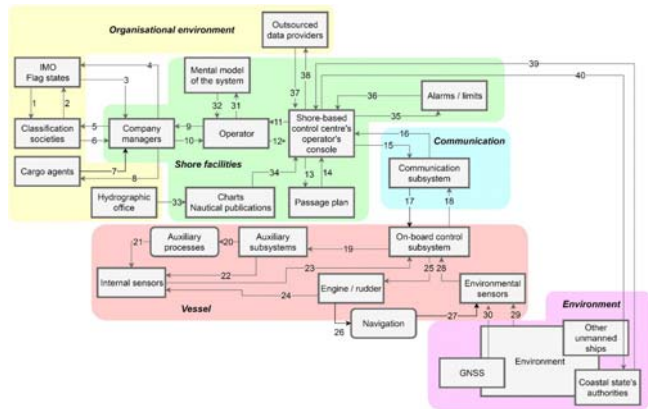


Figure 4. The system's safety control structure of remotely-controlled vessel [24]

The structure was divided into five parts, namely organizational environment, shore facilities (SCC), communication, vessel and environment. Data was supported by various sensors is used to provide SA for operator on shore to make system-level decisions. These sensors can be either environmental or internal. While the former will obtain the navigational situation around the vessel, and the latter will monitor the interior of vessel. Besides, the company managers will evaluate and audit the performance of operator. Meanwhile, the company managers will consistently improve the system with the feedback from the organizational environment, the experience sharing by the operators in the form of reports and meetings as well as their own interpretations. As such, the operational procedures are updated, prescriptive advices are inputted and the operators' ability of SA is enhanced. ζ is

defined as the impact of the company managers on the operator. When $\zeta > 0$, the impact is positive, otherwise is negative. The relationship with the probability of the operator of autonomous ships maintain adequate SA during navigation can be expressed as

$$P(SA) = P(SA_o) \cdot (1 + \zeta), \quad (2)$$

where $P(SA)$ is the probability of a system possess adequate SA, and $P(SA_o)$ is the probability that the operator maintain adequate SA during navigation. It should be noted that an operator may simultaneously full-control more than one vessel in the safety control structure of remotely-controlled merchant vessel.

Abstractly, we assumed that an operator can overall command over n vessels in the fleet. However, the probability that the operator adequately percept elements in the current situation, comprehend the current situation and project future status is different from different vessels. In this paper, an operator's ability of SA can be seen as a team SA consisted with n single vessels. The current situation and communication link of different vessels has a huge gap. It is unscientific and unreasonable to simply use arithmetic mean, geometric mean and harmonic mean to calculate $P(SA_o)$. Such these simple averaging methods would partly ignore the serious influence of low SA ability from a vessel. Therefore, we need to consider the interaction of each remotely-controlled ship on the operator. The mental models of the operator cannot be updated and reset when the operator continuously control different single vessel or manage the fleet at the same time. And the negative effects of multi-tasking interactions cannot be easily ignored. Based on the above analysis, an effective method for calculating team SA was proposed, which considering the interaction of multi-tasking. $P(SA_o)$ can be represented by the $P(SA_i)$, which is given by

$$P(SA_o) = P(SA_1) + \sum_{i=2}^{n-1} (P(SA_i) - P(SA_{i-1})) \cdot \frac{n-i+1}{n}, \quad (3)$$

where $P(SA_i)$ is the probability that an operator possess adequate SA with a single vessel. The example of shared (team) SA is demonstrated in Figure 5.



Figure 5. An example of shared (team) SA

The figure shows that the sum of the cross section of each vessel's SA weighted by numbers of vessels which can share confidence. $P(SA_1)$, $P(SA_2)$, $P(SA_3)$ and $P(SA_4)$ are assumed to be 0.1, 0.1, 0.6 and 0.8. The shared portion for all vessels is 0.1, and the shared portion for two vessels (SA_3 , SA_4) is 0.5.

The portion of SA that one vessel owns alone does not count.

Under the safety control structure of remotely-controlled vessel, $P(SA_i)$ should be quantitative calculation. Therefore, a novel theoretical setting based on the mathematical frame-work of Hierarchical Bayesian Inference was proposed. In this model, $P(SA_i)$ will be described by its complement. A probabilistic description of effects of different elements on one another is given by

$$P(SA_i) = 1 - P(\overline{SA_i}), \quad (4)$$

$$P(\overline{SA_i}) = P(\overline{SA_i} | SA_v) \cdot P(SA_v) + P(\overline{SA_i} | \overline{SA_v}) \cdot P(\overline{SA_v}), \quad (5)$$

where $P(\overline{SA_i})$ is the probability that the operator lose adequate SA with a single vessel, $P(SA_v)$ reflects the probability of single vessel obtain adequate SA rely on various sensors. Conversely, $P(\overline{SA_v})$ is complementary set that shows probability of not possessing adequate awareness. The operator located on SCC receive operational data via console. And the awareness of operator is reliant on information transferred from the vessel via communication channel Com , however, the communication link may be in available or unavailable status. $P(SA_i)$ considering the communication link can be described as

$$P(\overline{SA_i}) = P(\overline{SA_i}) + P(SA_v) \left(P(\overline{SA_i} | SA_v, Com) \cdot P(Com) + P(\overline{SA_i} | SA_v, \overline{Com}) \cdot P(\overline{Com}) \right) \quad (6)$$

where $P(\overline{Com})$ reflects the probability of communication link is unavailable. According to the characteristics of autonomous ships in "remote control" mode, operator cannot obtain any awareness when the communication link is valid, therefore, $P(\overline{SA_i} | SA_v, Com) = 1$, and

$$P(\overline{SA_i}) = P(\overline{SA_i}) + P(SA_v) \left(P(\overline{SA_i} | SA_v, \overline{Com}) \cdot P(\overline{Com}) \right) \quad (7)$$

In this equation, $P(\overline{SA_v})$ can be described in detail, which the vessel is equipped with a full set equipment for navigation as main devices. Additionally, the vessel needs to introduce the redundancy to some safety-critical subsystems, sensors or devices to mitigate many hazards and make sure the navigation safety. Although such a solution is said to be non-optimal, it is often named as the first-choice-solution to ensure the adequacy of control function. And the redundancy is proved successful when ensuring the safety of complex systems, which as a final line of defense against critical devices' failure.

The probability of loss of awareness given by vessel can be expressed as

$$P(\overline{SA_v}) = 1 - \prod_{j=1}^l \left(1 - \prod_{k=1}^{m+1} P(\overline{sensor_{jk}}) \right), \quad (8)$$

where the number of safety-critical subsystems or sensors is l . For every subsystem or sensor, there is one primary running device and m redundancy. Summing up, the proposed quantitative SA model as follows:

$$\begin{cases} P(SA) = P(SA_0) \cdot (1 + \zeta) \\ P(SA_0) = P(SA_1) + \sum_{i=2}^{n-1} (P(SA_i) - P(SA_{i-1})) \cdot \frac{n-i+1}{n} \\ P(SA_i) = 1 - P(\overline{SA_i}) \\ P(\overline{SA_i}) = P(\overline{SA_i}) + P(SA_v) \left(P(\overline{SA_i} | SA_v, Com) \cdot P(Com) + P(\overline{Com}) \right) \\ P(\overline{SA_v}) = 1 - \prod_{j=1}^l \left(1 - \prod_{k=1}^{m+1} P(\overline{sensor_{jk}}) \right) \end{cases} \quad (9)$$

where $\zeta \in \mathbb{R}$ and $l, m, n \in \mathbb{N}^*$.

5 DISCUSSION

SA is crucial in maritime operations to identify threats and to deal with them as soon as possible and is an instrument for analysis of specific characteristics and parameters of the monitored maritime object for the purpose the obtained information about its current status and forecasting its status in the near future. The proposed SA quantitative model can improve the accuracy of the collision risk identification [30] and assessment, which can make autonomous ships better comprehension of the current situation.

In this paper, an applicable case should be demonstrated to verify the validity of the quantitative model. However, since the design and final structure of autonomous ships is still being development, and the actual operation has not yet occurred in reality. It is temporarily impossible to obtain the data satisfying the accuracy to calculate the probability of loss of SA. At the same time, the model is constructed based on the existing concept and composition system of remotely controlled ship.

Therefore, it is necessary to make a lot of assumptions of situation and probability as shown the case in the paper. The assumptions based on the theoretical basis or empirical formula is not adequate sufficient, so the substantive value of the demonstration is not significant. However, we still make a numerical simulation in a specific context. The same probability of loss of same sensors and transmission link was assumed between the autonomous ship and conventional ship. According to characteristics of maneuvering, the crew control directly vessel and perceive the situation of a ship on the bridge. All ship-level information is shared with the operator via the stable communication link. Therefore, the probability that the operator lose adequate SA on normal merchant ship can be described

$$P(\overline{SA_i}) = P(\overline{SA_i}). \quad (10)$$

According to the results of the calculation, the failure probability of acquiring adequate SA of remotely controlling vessels is significantly increased compared to conventional vessels.

6 CONCLUSION AND OUTLOOK

In this paper, the concept of autonomous ships was briefly discussed and defines the four development stages under different control mode. According to the initial literature review, the existing SA measurement techniques provides a useful grounding in measuring the elements that play a role in situational awareness, but they cannot be applied to evaluate effectively the SA of autonomous ships navigation, especially for the remotely-controlled vessel.

On such a basis, the paper considers quantifying the situational awareness of autonomous ships navigation and proposed a model based on the mathematical framework of Hierarchical Bayesian Inference. The main result of numerical simulation shows the autonomous ship' failure probability of acquiring adequate SA is significantly higher than conventional ship.

The significance of this paper is to present firstly a quantitative processing of SA based on the system safety control structure of autonomous ship in "remote control" mode. In this model, more important elements should be considered and supplemented as the design and final structure continue to improve. In addition, the model helpful for detailed interface design and work domain constraints in SCC and the futuristic concept of autonomous unmanned shipping.

In future, we will study the obstacle avoidance in navigation, where the autonomous ships can be considered as intelligent agents or vehicles. Therefore, we will investigate the routing algorithms for both independent and cooperative agents (or vehicles) in land and marine transportation [31-38], to achieve the obstacle avoidance for autonomous ships.

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