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An Ontology-based Framework

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Distributed Situational Awareness for Maritime Autonomous Surface Ships in Mixed Waterborne Transport: An Ontology-based Framework

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***Abstract*—The safety of maritime autonomous surface ships (MASS) in mixed waterborne transport system (MWTS) depends on effective situational awareness (SA) distribution among MASS, manned ships, and various stakeholders, such as Vessel Traffic Service (VTS), Remote Control Center (RCC) and Fairway Shipping Agency. This paper focuses on the research question: How can situational awareness be effectively distributed among these entities in mixed waterborne transport? The research objective is to develop a distributed situational awareness framework that unifies SA among these stakeholders, ensuring safe navigation and compatibility with users of different roles. To achieve this objective, the proposed framework incorporates three key concepts: individual SA, authority-based SA, and distributed SA. Individual SA, previously introduced in our study, is responsible for each ship's SA, while authority-based SA accounts for the SA of human operators supervising the waterborne transport system, such as VTS operators and fairway agency personnel. Distributed SA generates guiding messages for ships based on the situational awareness from both individual SA and authority-based SA, thereby enabling regulation-based and traffic control-based recommendations for waterborne transport (e.g., ship speed and course adjustments). The research methodology employs ontology-based modelling to implement the framework, constructing a domain knowledge network. A case study is conducted as an essential part of the research methodology, presenting how the framework perform the situational awareness from different aspects and inconsistency detection among manned ships, MASS, VTS operators, and so on. Semantic Web Rule Language (SWRL) is utilized to detect inconsistencies and generate guidance messages for ships. Through these cases, we demonstrate how the proposed Ontology-based framework can reconcile inconsistencies between individual and authority-based SA, leading to a safer and more effective waterborne transport.**

Keywords—Distributed situational awareness, situation reconciling, ontology, mixed waterborne transport system

I. Introduction

The rapid development of maritime autonomous surface ships (MASS) has brought about a significant transformation in the waterborne transport industry. The integration of MASS within mixed waterborne transport systems, alongside manned ships and various stakeholders such as Vessel Traffic Service (VTS) operators and Fairway Shipping Agency personnel, has created new challenges in maintaining situational awareness (SA) for safe navigation. Efficient distribution of SA among these entities is crucial to minimize potential risks and ensure seamless coordination in the maritime transport system. This paper investigates the question: How can situational awareness be effectively distributed among maritime autonomous surface ships and other stakeholders in mixed waterborne transport?

Previous research has extensively explored individual situational awareness for both manned ships and MASS, primarily focusing on the ship's onboard systems and sensors. However, less attention has been given to authority-based SA, which encompasses the situational awareness of human operators supervising the waterborne transport system, such as VTS operators and fairway agency personnel. Furthermore, existing models for distributed situational awareness have not adequately addressed the challenges of unifying SA among multiple stakeholders and ensuring compatibility with users of different roles.

To fill this gap, the research objective of this paper is to develop a distributed situational awareness framework that unifies SA among maritime autonomous surface ships, manned ships, and various stakeholders, ensuring safe navigation and compatibility with users of different roles. The proposed framework incorporates three key concepts: individual SA, authority-based SA, and distributed SA. Individual SA, previously introduced in our study [1], is responsible for each ship's SA, while authority-based SA accounts for the SA of human operators supervising the waterborne transport system. Distributed SA generates guiding messages for ships based on a common goal, considering the SA from both the ship and the authority, thereby enabling recommendations for situation reconcile, such as instructing the ship to adjust her speed or course based on regulations.

This paper employs ontology-based modelling to implement the proposed framework, constructing a domain knowledge network to ensure the effectiveness of the distributed SA model. A case study is conducted as an essential part of the research methodology, demonstrating the framework by detecting inconsistency and generating guidance for ships based on specific regulations (International Regulations for Preventing Collisions at Sea, COLREGs).

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The rest of the paper is organized as follows. Section II provides an overview of related work on distributed SA. Section III describes the proposed distributed SA model and the ontology-based framework. Section IV presents the case study to demonstrate the framework. Finally, Section V concludes the paper and provides a summary of the contributions of this work.

II. Literature Review

The importance of Situational Awareness (SA) and its role in various systems and sectors have been well conducted in the existing literature.

The study conducted in [2] highlighted the impact of automation on human decision-making in the NextGen Air Traffic Management system and the need for effective human-computer interfaces. Similarly, a comprehensive overview of SA was presented in [3], addressing common misconceptions, and proposed a new definition and model that incorporates the cognitive processes involved in SA.

The concept of Distributed Situation Awareness (Distributed SA) has also been explored extensively. It was defined as the SA within teams separated by distance, time, and/or obstacles in [4]. This concept was applied to robot swarms in [5], proposing a framework that enhances group SA through information sharing and collaboration among individual robots.

The role of SA in specific sectors has been examined by several researchers. A study conducted in [6] focused on rail operations, specifically the complex signalling and control systems used. In the maritime sector, it was evaluated that the impact of distributed SA on ship bridge operations in [7], while [8] explored its role in pilotage operations.

The research [9] deepened the understanding of SA in complex systems with their Situation Awareness Weighted Network model, which represents the flow of information and interaction between system components. SA was investigated in the context of road transport in [10] [11], including the design of effective interfaces and training programs, as well as a distributed SA framework for intersection design.

Recently, the definition of distributed SA has been expanded to include not only individual and team awareness but also awareness of technological, sociotechnical, and societal factors [12]. [13] further formalized a framework for distributed SA in multi-agent networks, integrating concepts from network theory and distributed systems to foster effective information sharing and collaboration. This breadth of research underscores the importance of SA and distributed SA in diverse fields, pointing to its relevance in the future of waterborne transport systems.

Situational awareness (SA) is one of the essential elements of safe navigation for MASS. It is defined as the perception of the surrounding environment, comprehension of the current situation, and projection of future scenarios in [1]. A lack of unified SA from various aspects can lead to risky situations, potentially resulting in collisions, groundings, and other types of accidents. In addition, MASS must interact with various services such as Vessel Traffic Service (VTS) and Fairway Shipping Agency, as they navigate around land and fairways, further complicating the SA issue.

III. Ontology-based Distributed Situational Awareness

The proposed distributed situational awareness aims to unify SA among maritime autonomous surface ships, manned ships, and various stakeholders in mixed waterborne transport, ensuring safe navigation and compatibility with users of different roles. This section details the three key components of the framework: individual SA, authority-based SA, and distributed SA, followed by a description of the ontology-based modelling approach and the construction of the domain knowledge network. The architecture of distributed situational awareness can been seen in Fig 1.

Drawing on prior research, the foundational data for situational awareness serves as the bedrock of our proposed architecture for distributed Situational Awareness (SA). This data constitutes the fundamental layer of the system, which undergoes sophisticated processes of integration and analysis.

A knowledge map, previously proposed, plays a pivotal role in this processing and integration phase. Through this mechanism, situational awareness can be formulated at the individual level. At the same time, situational awareness data can provide insights into situational awareness formation of different stakeholders at the distributed SA layer.

At the same time, SA input from the Individual SA layer and the Authority-based SA layer is funnelled into the distributed SA component. Here, it undergoes inconsistency detection and subsequently forms the basis for generating guidance.

Finally, leveraging information from the guidance layer, stakeholders and vessels can engage in efficient and effective communication. This layer serves as a catalyst for better coordination among all actors involved.

A. *Framework construction*

1) Individual SA

Individual SA focuses on each ship's situational awareness, whether it is a MASS or a manned ship. This component encompasses the ship's onboard systems and sensors, which collect and process real-time information about the ship's position, speed, course, and surrounding environment. By continuously monitoring these factors, individual SA enables the ship to make informed decisions, anticipate potential threats, and adjust its behaviour accordingly.

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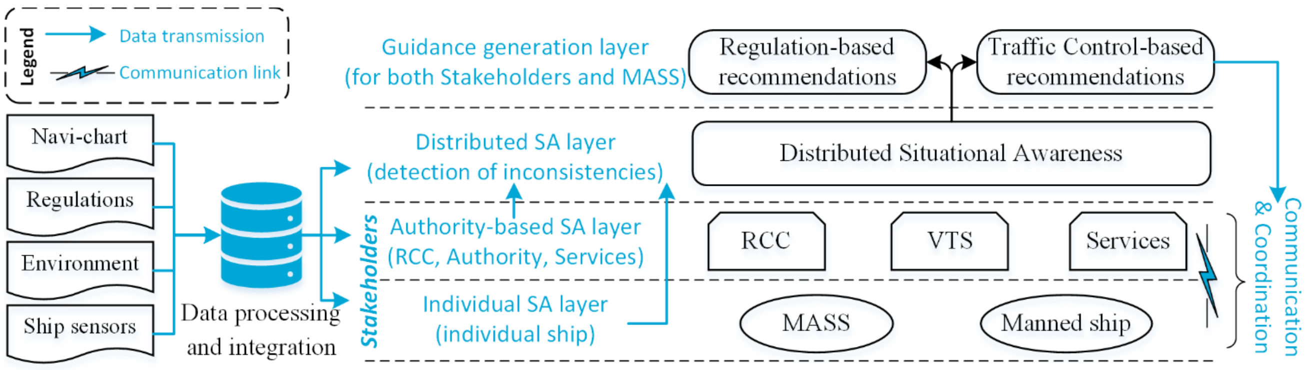

Fig. 1. The architecture of distributed situation awareness in a MWTS

2) Authority-based SA

Authority-based SA accounts for the situational awareness of human operators supervising the waterborne transport system, such as RCC, VTS operators, and fairway agency personnel. These operators monitor and manage various aspects of the maritime transport environment, including ship movements, weather conditions, navigational hazards, and regulations. By maintaining up-to-date and accurate SA, the human operators can effectively communicate with ships, provide guidance, and ensure the overall safety and efficiency of the waterborne transport system.

3) Distributed SA

Distributed SA is the central component of the proposed framework, responsible for unifying individual SA and authority-based SA, and generating guiding messages for ships. The messages are generated mainly based on two-folds considerations, incorporating the regulation for navigation, such as COLREGs and local navigation laws, and traffic control considering broader waterborne transport safety. This component takes into account the SA from both the ship and the authority, enabling recommendations for traffic control, such as ship speed and course adjustments. By providing a shared understanding of the current and future states of the maritime transport system, distributed SA facilitates seamless coordination and collaboration among all stakeholders, ultimately enhancing safety and efficiency.

B. Ontology-based modelling

Ontology is a tool for representing domain knowledge and reasoning potential information based on fact and relationships. It is anticipated that each object within the MWTS would be aware of situation correctly and consistently, and taking actions accordingly. Ontology can therefore be employed to synthetize knowledge pertinent to the MWTS realm in order to comprehend circumstances through the exchange of ideas between people.

To implement the proposed distributed situational awareness architecture, an ontology-based modelling approach is employed, as shown in Fig 2. Ontologies are formal, explicit specifications of a shared conceptualization, making them well-suited for representing domain knowledge and providing a common understanding of concepts, relationships, and constraints. In the context of the proposed framework, ontologies are used to construct a domain knowledge network, which captures the essential elements of the maritime transport system, including ships, stakeholders, and guidance generation.

The domain knowledge network serves as the foundation for the distributed SA model, enabling the efficient integration and processing of information from various sources. By utilizing reasoning mechanisms, the ontology-based model can infer new knowledge and identify potential inconsistencies, thereby facilitating effective decision-making.

IV. Case Study

In this section, we discuss two cases that illustrate the utility of distributed SA in a MWTS, particularly in reconciling inconsistencies between individual and authority-based SA. SWRL is utilized to detect inconsistency and generate guidance for ships in this section.

A. Case 1: The MASS #1 and MannedShip #1 Scenario

MASS #1 (an autonomous ship) is preparing to overtake *MannedShip* #1 (a human-operated ship) within the channel. Both are being monitored by VTS operator #1.

1) Individual SA: *MASS* #1's decision-making system is designed to follow COLREGs, which state that any vessel overtaking another should keep out of the way of the vessel being overtaken (Rule 13). The system determines that it can safely overtake *MannedShip* #1 within the narrow channel.

On *MannedShip* #1, the captain is aware of *MASS* #1's intent to overtake. However, according to Rule 9 of COLREGs, a vessel should not be overtaken in a narrow channel. The captain expects *MASS* #1 to maintain its course and speed.

2) Authority-based SA: VTS operator #1, observing both vessels, is aware of the narrow channel and knows about the COLREGs. The operator also knows that while *MASS* #1 is technically capable of a safe overtaking maneuver, it goes against the COLREGs' rule for narrow channels.

3) Distributed SA: The distributed SA component in our system receives all of this information. It knows about the planned actions of *MASS* #1, the expectations of *MannedShip* #1, and the regulations that apply from VTS operator #1.

Given this, the distributed SA system determines that *MASS* #1 should not overtake *MannedShip* #1 within the narrow channel despite its ability to do so safely. This is because it goes against the COLREGs (Rule 9), which *MannedShip* #1 is expecting to be followed.

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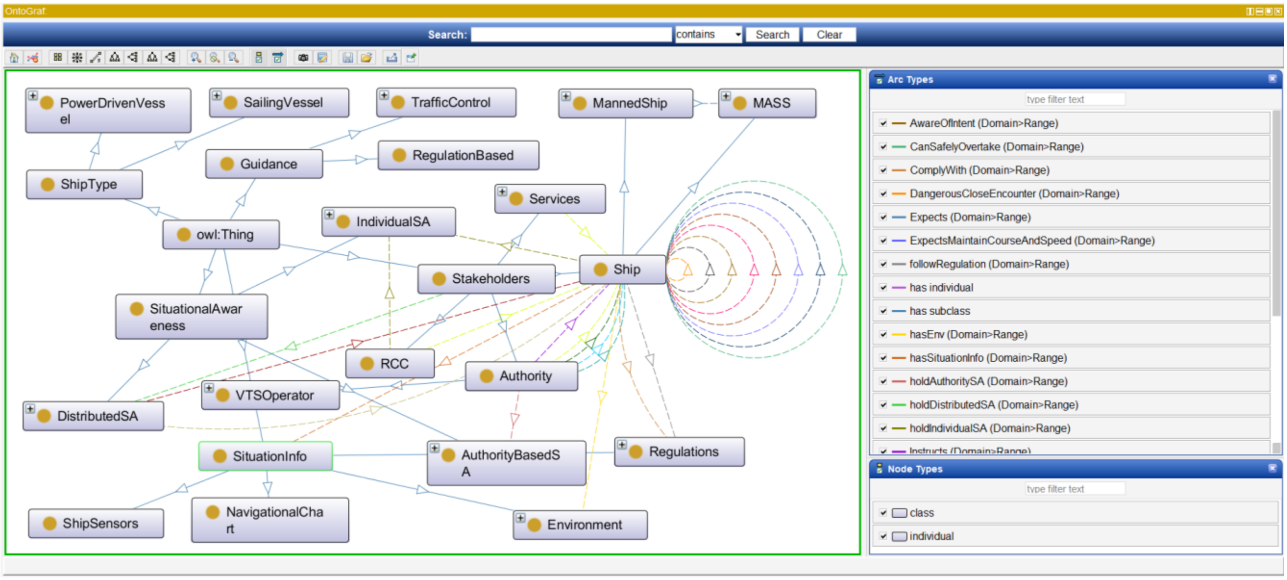

Fig. 2. The ontology representation of distributed situational awareness

The system communicates this decision to *MASS* #1, instructing it to maintain its course and speed, and not to overtake. This reconciles the inconsistency between the individual SA of *MASS* #1 and the authority-based SA held by VTS operator #1 and *MannedShip* #1. The corresponding SWRL rules are shown as follows:

Regulation-based

Rule 1:
MASS(?v1) ∧ MannedShip(?v2) ∧ PlansToOvertake(?v1, ?v2) ∧ ComplyWith(?v1, COLREGsRule13) → IntendsToOvertake(?v1, ?v2)

Rule 2:
MannedShip(?v2) ∧ AwareOfIntent(?v2, ?v1) ∧ hasEnv(?v2, narrowChannel) ∧ Complywith(?v2, COLREGsRule9) → ExpectsMaintainCourseAndSpeed(?v2, ?v1)

Rule 3:
VTSOperator(?o) ∧ monitors(?o, ?v1) ∧ monitors(?o, ?v2) ∧ hasEnv(?o, narrowChannel) → RecommendsMaintainCourseAndSpeed(?o, ?v1)

Rule 4:
IntendsToOvertake(?v1, ?v2) ∧ ExpectsMaintainCourseAndSpeed(?v2, ?v1) ∧ DistributedSA(?dsa) ∧ RecommendsMaintainCourseAndSpeed(?o, ?v1) → InstructsMaintainCourseAndSpeed(?dsa, ?v1)

* *where "?" is used as a variable symbol to represent unknown values or variables in rules.*

In this example, distributed SA works as a crucial mechanism for ensuring the adherence to regulations and maintaining safety despite the capability of advanced autonomous systems to perform otherwise "safe" but non-regulation-compliant actions.

B. *Case 2: The MASS #2, MannedShip #2, and MannedShip #3 Scenario:*

Consider a situation in a busy port area where *MASS* #2 (an autonomous ship) is about to cross paths with *MannedShip* #2 (a human-operated ship) while *MannedShip* #3 (another human-operated ship) is also navigating nearby.

1) Individual SA: *MASS* #2's decision-making system is designed to follow COLREGs. According to Rule 18, a power-driven vessel (*MASS* #2) should give way to a sailing vessel (*MannedShip* #2). Thus, *MASS* #2 plans to adjust its course to port to give way to *MannedShip* #2.

On *MannedShip* #2, the human captain is aware of *MASS* #2's presence and expects it to give way according to the COLREGs.

Both *MASS* #2 and *MannedShip* #2 are not fully aware of *MannedShip* #3's presence as it is further away and their focus is more on their immediate surroundings.

2) Authority-based SA: VTS operator #2, observing all three vessels, is aware of the broader traffic situation. The operator sees that while *MASS* #2 is correctly planning to give way to *MannedShip* #2, this adjustment would bring it dangerously close to *MannedShip* #3.

The operator knows that the best solution would be for *MASS* #2 to reduce speed, let *MannedShip* #2 cross first, and then continue on its course, thus avoiding any close encounter with *MannedShip* #3.

3) Distributed SA: The distributed SA receives all of this information. It knows about the planned actions of *MASS* #2, the expectations of *MannedShip* #2, and the broader traffic situation observed by VTS operator #2.

Given this, the distributed SA system determines that *MASS* #2 should reduce its speed and let *MannedShip* #2 cross first to avoid a close encounter with *MannedShip* #3. It communicates this decision to *MASS* #2, altering its initial plan. The corresponding SWRL rules can be formulated as follows:

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Traffic control-based

Rule 1:
PowerDrivenVessel(?v1) ∧ SailingVessel(?v2) ∧ ComplyWith(?v1, COLREGsRule18) ∧ hasRiskWith(?v1, ?v2) ∧ NotFullyAwareOf(?v1, ?v3) ∧ NotFullyAwareOf(?v2, ?v3) → ShouldGiveWay(?v1, ?v2)

Rule 2:
VTSOperator(?o) ∧ monitors(?o, ?v1) ∧ monitors(?o, ?v2) ∧ monitors(?o, ?v3) ∧ DangerousCloseEncounter(?v1, ?v3) → RecommendsReduceSpeed(?o, ?v1)

Rule 3:
DistributedSA(?dsa) ∧ ShouldGiveWay(?v1, ?v2) ∧ RecommendsReduceSpeed(?o, ?v1) → InstructsReduceSpeed(?dsa, ?v1)

This reconciles the inconsistency between the local focus of individual SA and the broader focus of authority-based SA.

These case studies highlight the importance of distributed SA in maritime navigation, particularly in reconciling inconsistencies between individual and authority-based SA. By considering both local and broader perspectives, distributed SA can enhance the safety and efficiency of maritime navigation.

V. CONCLUSION

In conclusion, this study has proposed a new distributed situational awareness framework to enhance the safety and efficiency of maritime autonomous surface ships (MASS) in mixed waterborne transport. The framework integrates individual SA from each ship, authority-based SA from human operators, and incorporates a novel distributed SA layer that collectively forms a unified SA model. The ontology-based implementation of this model has demonstrated its applicability in identifying inconsistencies and providing regulation-based recommendations, ensuring the compatibility of the model with users in different roles.

The proposed model can provide regulation-based and traffic control based recommendations for ships, indicating its potential to significantly enhance the operational safety of mixed waterborne transport.

Furthermore, the framework is flexible and scalable, allowing for the incorporation of future elements and layers as the waterborne transport system evolves. The layered architecture of the framework provides a comprehensive overview of the SA in the maritime transport environment, facilitating seamless integration of new elements such as environmental factors, regulations, and RCC.

However, there is still room for further exploration and improvement. Future work can be directed towards more concrete modelling and real-world testing and refinement of the model, further integration of human factors for improved decision-making support.

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REFERENCES

[1] Song R, Papadimitriou E, Negenborn R, and van Gelder P, "Constructing Knowledge Maps for Situation Awareness of Maritime Autonomous Surface Ships," Tech. Rep., 11 2022. [Online]. Available: https://library.imarest.org/record/10722

[2] D. Chiappe, K.-P. L. Vu, and T. Strybel, "Situation Awareness in the NextGen Air Traffic Management System," International Journal of Human–Computer Interaction, vol. 28, no. 2, pp. 140–151, 2012. [Online]. Available: https://doi.org/10.1080/10447318.2012.634768

[3] M. R. Endsley, "Situation Awareness Misconceptions and Misunderstandings," Journal of Cognitive Engineering and Decision Making, vol. 9, no. 1, pp. 4–32, 2015. [Online]. Available: https://doi.org/10.1177/1555343415572631

[4] Endsley and W. Jones, "A model of inter- and intrateam situation awareness: implications for design, training and measurement," 2001.

[5] S. Jones, E. Milner, M. Sooriyabandara, and S. Hauert, "Distributed Situational Awareness in Robot Swarms," Advanced Intelligent Systems, vol. 2, p. 2000110, 8 2020.

[6] D. Golightly, J. R. Wilson, E. Lowe, and S. Sharples, "The role of situation awareness for understanding signalling and control in rail operations," Theoretical Issues in Ergonomics Science, vol. 11, no. 1-2, pp. 84–98, 2010. [Online]. Available: https://doi.org/10.1080/14639220903009961

[7] S. Parisi and A. Lüdtke, Evaluation of Distributed Situation Awareness on a Ship Bridge, 9 2016.

[8] A. Sharma and S. Nazir, Distributed Situation Awareness in pilotage operations, 6 2017, vol. 11.

[9] A. Kalloniatis, I. Ali, T. Neville, P. La, I. Macleod, M. Zuparic, and E. Kohn, "The Situation Awareness Weighted Network (SAWN) model and method: Theory and application," Applied Ergonomics, vol. 61, pp. 178–196, 5 2017.

[10] P. M. Salmon, N. A. Stanton, and K. L. Young, "Situation awareness on the road: review, theoretical and methodological issues, and future directions," Theoretical Issues in Ergonomics Science, vol. 13, no. 4, pp. 472–492, 7 2012. [Online]. Available: https://doi.org/10.1080/1463922X.2010.539289

[11] P. M. Salmon, G. J. M. Read, G. H. Walker, M. G. Lenné, and N. A. Stanton, Distributed Situation Awareness in Road Transport: Theory, Measurement, and Application to Intersection Design, 1st ed. Boca Raton : Taylor & Francis, 2018. Series: Human factors of simulation and assessment "A CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa plc.": Routledge, 11 2018. [Online]. Available: https://www.taylorfrancis.com/books/9781317054580

[12] P. M. Salmon and K. L. Plant, "Distributed situation awareness: From awareness in individuals and teams to the awareness of technologies, sociotechnical systems, and societies," Applied Ergonomics, vol. 98, p. 103599, 1 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003687021002465

[13] S. Yusuf and C. Baber, "Formalizing Distributed Situation Awareness in Multi-Agent Networks," IEEE Transactions on Human-Machine Systems, pp. 1–10, 1 2022.

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