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Statistical Analysis of Delay Times for Remote Control Applications

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Abstract : *Time delay in the remote control of maritime autonomous surface ships (RC-MASS) is a critical factor and a significant area of research. However, current studies are fragmented and lack a cohesive understanding of these delays. This study aims to review and analyze relevant literature on time delays, including policy documents, technical reports, and research papers, to provide valuable insights into RC-MASS operations. Through a systematic search, sources from the past 25 years were examined, and time delay data were extracted and categorized for statistical analysis. The findings indicate an average delay of 56.17 seconds across all categories, with considerable variability. Delays associated with navigation equipment, ship maneuvering, and ship control are prevalent across all vessels, exhibiting large values and wide variability. Although communication delays had a smaller average, they warrant further investigation due to their critical role in RC-MASS operations. This research sheds light on time delay patterns in RC-MASS, helping to identify key areas for improvement and supporting future technological advancements.*

Key words : *time delay, remote control, maritime autonomous surface ships, mean time delay*

1. Introduction

With the rapid advancement of artificial intelligence technology, the development of intelligent ships has also progressed significantly. The International Maritime Organization (IMO) has categorized their development into four levels(IMO, 2021). Lv1 involves human-operated ships assisted by intelligent systems. In Lv2, there is further integration of intelligent technologies, but the ships remain under crew supervision. Moving to Lv3, it advances to the remote control of Maritime Autonomous Surface Ships (RC-MASS), with ship operators remotely controlling the ship from shore control center. Finally, Lv4 represents fully autonomous ships, which is a challenging long-term goal. Among these levels, RC-MASS at Lv3 has received the most attention and research interest(Rodeseth et al., 2023).

Time delay refers to the time required for a signal to travel through the system and reach the operational element, which is a common phenomenon in control systems(Fridman, 2014). The RC-MASS, which relies on command transmission and feedback from a shore control center, exemplifies such a control system. Time delay is a critical factor in RC-MASS research, as it can significantly affect the effectiveness of collision avoidance and other maneuvering in RC-MASS (Rodeseth et al., 2012; Porathe et al., 2014; Wang et al., 2023). In both conventional ships and intelligent ships such as the RC-MASS, various types of time delays exist, resulting from different sources such as communication, navigational equipment, ship handling. Despite the importance of time delay, existing research often treats it as a general factor without focused examination. No comprehensive analysis has been conducted on the categorization or statistical characteristics of various time delays. Therefore, it is crucial to thoroughly investigate these time delays, particularly in current RC-MASS research, and analyze their classifications and statistical properties.

This study aims to address this gap by systematically analyzing time delays. To do this, a literature review was conducted to identify relevant time delay data points from various policy and research documents. By categorizing these delays and calculating their mean values and standard deviations, this research offers a detailed understanding of time delay characteristics accumulated over decades. The findings of this study are expected to contribute to optimizing RC-MASS operations and provide a foundation for future research on various aspects such as collision avoidance, navigation efficiency, and overall operational safety.

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2. Literature review

With the advancement of maritime studies, spanning from conventional ships to RC-MASS, the issue of time delay has consistently attracted attention. This review draws upon documents from IMO, technical reports from classification societies like the American Bureau of Shipping(ABS), research initiatives such as the Maritime Unmanned Navigation through Intelligence in Networks(MUNIN) project, and various academic studies.

The IMO has played a foundational role in setting performance standards for navigation systems, with a strong focus on mitigating time delay issues. In 1998, new performance standards were adopted for GPS/GLONASS and AIS to address delays in data processing(IMO, 1998). The need to address GNSS time delays for reliable navigation was highlighted(IMO, 2001). Standards for minimizing delays in the Bridge Navigational Watch Alarm System and prompt responses in ship maneuverability were also established(IMO, 2002a; IMO, 2002b). Limitations in AIS data, including update delays, were identified in revised guidelines(IMO, 2015). Effective management of time delays for safety during MASS trials was stressed in 2019(IMO, 2019), followed by the identification of regulatory gaps related to control center and remote operation delays(IMO, 2021). In 2022, challenges posed by remote operation delays, especially for autonomous control and collision avoidance were noted(IMO, 2022).

Classification societies and related project reports have emphasized the importance of addressing time delay in ship operations. ABS(2003) provided guidelines to reduce time delay to improve decision-making on navigation bridges, while ABS(2006) emphasized minimizing response times to enhance ship maneuverability, particularly during turning and stopping operations. DNV-GL(2019) discussed the effects of time delay in dynamic positioning systems, stressing the importance of low delay in control communications. Additionally, the MUNIN project reports by Rodeseth et al.(2012) and MacKinnon et al.(2016) emphasized communication requirements for autonomous ships and the importance of effective latency management in the shore control centre to ensure ship-shore coordination.

Academic studies have provided detailed analyses of time delays. In particular, Jang et al.(2017) investigated latency in Real Time Kinematics, demonstrating the need for accurate time delay estimation to maintain positioning precision. Similarly, Esfahani et al.(2019) proposed a sliding mode control algorithm for MASS that incorporates time delay estimation to handle disturbances. In addition, Zhou et al.(2021) developed a coordination system for autonomous collision avoidance, aiming to minimize time delay. Yim et al.(2021), on the other hand, estimated the critical time delay affecting collision risk in remote-controlled ships, which highlights a different approach to understanding delay impacts. Moreover, Wang et al.(2022) introduced a sliding mode control algorithm to address time delays in MASS, contributing to the field of control strategies. Miyashita et al.(2021) developed a prototype system for remote ship control, further emphasizing the importance of managing communication delays to ensure effective maneuvering.

In summary, the literature reflects a comprehensive and evolving understanding of the effects of time delay on both conventional and autonomous maritime navigation. Regulatory documents have established foundational standards for managing time delays, while technical reports and research projects have provided practical insights into addressing these delays. Academic studies have explored innovative methods to reduce and compensate for time delays, thereby enhancing the safety and efficiency of ship operations. These documents have mentioned various time delay values. However, no research to date has systematically categorized or analyzed these data. Therefore, building on existing research, this study aims to categorize, calculate, and analyze the time delay values to better address the associated challenges for the RC-MASS.

3. Research Methodology

This section describes the approach used to gather time delay data from various source. It covers the data scope and search criteria, providing an overview of the methodology applied in this study.

3.1 Data Scope

In this study, data were gathered from four primary sources. Firstly, policy documents published by the IMO provided official guidelines on maritime operations, including early frameworks that have since evolved to support the development of autonomous ship technologies. Secondly, technical reports issued by various classification societies such as ABS, DNV, and others outlined the standards for the design, construction, and operation of maritime technologies, which later contributed to the development of autonomous ships, providing reliable insights. Thirdly, research reports from the MUNIN project contributed valuable information on remote control and communication delays for autonomous ships. Finally, recent research papers were reviewed to capture the current research trends related to remote control and time delay in autonomous ship operations.

3.2 Search Methodology

The data collection methods and criteria for this study varied depending on the type of source. For documents from IMO, ABS, and similar entities, data were gathered from official websites, industry databases, and publicly available records from relevant organizations. To ensure the precision of the search, keywords relevant to the research topic, such as "delay," "latency," "remote control," and "autonomous ship," were employed to extract technical reports and guidelines related to time delays and the autonomous ships. The search was conducted within the time frame of 1998 to 2022 to encompass the historical progression and advancements in maritime technologies.

For research papers, keywords were selected in two categories: primary and secondary. The primary keywords included "delay," "latency," and "time," while the secondary keywords comprised "autonomous," "automated," "remote," "control," and "operation." These keywords were selected based on the research objectives. They aimed to capture literature on emerging technologies and concepts related to RC-MASS, including the evolution of related terminologies over time. The literature search was conducted using databases such as Web of Science and IEEE Xplore. The selection criteria included (a) content, specifically focusing on titles, abstracts, and the scope of the study; (b) language, limiting the search to publications in English; (c) publication type, including only peer-reviewed journals and conference proceedings; and (d) publication date, covering the period from 1998 to 2022.

4. Data Analysis

This section provides a comprehensive analysis of time delays, focusing on categorized delay types, as well as their average values and standard deviations.

4.1 Data Extraction and Categorization

According to the described research methodology, time delay data were extracted from 25 relevant documents, resulting in 67 identified delay data points. For a structured analysis, these data were categorized into four groups: C1 (navigation equipment), C2 (ship maneuvering), C3 (ship control), and C4 (communications), as presented in Tables 1 to 4.

Table 1 Summary of time delay data for category C1

Author(s), Year	Delay time (s)	Data counts	Document type
IMO,1998	1; 10; 30; 60; 120; 300	6	IMO document
IMO,1998	30	1	IMO document
IMO,1998	2; 3; 4; 6; 12; 180	6	IMO document
IMO,1998	300; 300	2	IMO document
IMO,2001	10	1	IMO document
IMO,2002a	15; 30; 120	3	IMO document
ABS,2003	30	1	Technical reports
IMO,2015	2; 5; 15; 30; 180	5	IMO document
Jang et al., 2017	12.62 ; 9.33 ; 10.84 ; 55.4 ; 7.47	5	Research paper

Table 2 Summary of time delay data for category C2

Author(s), Year	Delay time (s)	Data counts	Document type
IMO,2002b	60	1	IMO document
IMO,2002c	10; 30; 10; 30	4	IMO document
ABS,2006	10; 74.1; 60	3	Technical reports
DNV-GL,0219	1; 0.1; 300	3	Technical reports

Table 3 Summary of time delay data for category C3

Author(s), Year	Delay time (s)	Data counts	Document type
Porathe et al., 2014	30; 120	2	Research paper
Sasaki et al., 2016	120	1	Research paper
Esfahani et al., 2019	20; 30; 60; 100	4	Research paper
Esfahani et al., 2021	30	1	Research paper
Zhou et al., 2021	100; 20	2	Research paper
Yim et al., 2021	7.2; 46.2; 86.4; 129.6	4	Research paper
Wang et al., 2021	100; 150	2	Research paper
Sutulo et al., 2002	60	1	Research paper

Table 4 Summary of time delay data for category C4

Author(s), Year	Delay time (s)	Data counts	Document type
MacKinnon et al., 2016	2	1	Research report
Rodeseth et al., 2012	2.5; 1; 10	3	Research report
Huang et al., 2021	0.06; 0.3; 60	3	Research paper
Miyashita et al., 2021	2; 0.3	2	Research paper

4.2 Summary statistics and visualization

To provide a clearer view of the time delay data distribution, the above data points are visualized, as shown in Fig. 1.

As shown in Fig. 1, the horizontal axis represents the data number, while the vertical axis indicates the delay values (in seconds). The red dashed line marks the average delay value of 56.17s. Different colored points represent the four categories of delay data. It can be observed that the data for category C1 are widely distributed, with some high delay values, and category C3 shows a similar pattern. On the other hand, the data points for categories C2 and C4 are relatively concentrated.

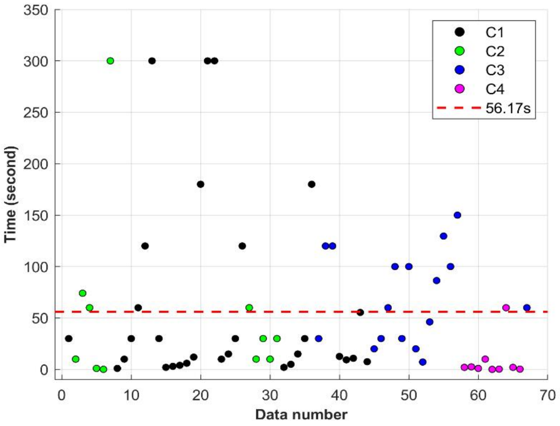

Fig. 1 Distribution of delay time across categories

To understand the central tendency and variability of the time delay data, the mean and standard deviation were calculated for each category. The mean time delays were calculated for each category, as presented in Table 5. This table provides a detailed summary, including the number of data points, the mean delay time, and the standard deviation for each category, providing a comprehensive overview of the time delay characteristics. The overall mean delay time across all categories was found to be 56.17s, with a standard deviation of 77.03s.

Table 5 Mean delay time according to 4 categories

Category	Number	Mean (second)	Standard deviation (second)
C1	30	63.02	94.12
C2	11	53.20	85.82
C3	17	71.14	45.01
C4	9	8.68	19.48
All	67	56.17	77.03

4.3 Analysis of the time delay

Following the statistical summary of time delays presented in Section 4.2, a deeper analysis was conducted to understand the impact of each category on RC-MASS performance and safety.

The analysis shows that each category of delay has distinct characteristics, with both mean and standard deviation values providing insights into their variability. Navigation equipment (C1) has a mean time delay of 63.02s and a standard deviation of 94.12s, indicating significant variability. This inconsistency in response times may lead to delayed navigation adjustments, thereby increasing operational risks. The mean delay for ship maneuvering (C2) is 53.20s, with a standard deviation of 85.82s, reflecting moderate variability. Although this delay is relatively low, the complexity of maneuvering operations means that delays can hinder timely responses to obstacles, raising the risk of collisions. Ship control (C3) has the highest mean delay of 71.14s and a standard deviation of 45.01s, reflecting the inherent complexity of control processes. Such a high delay may impair the system's ability to make effective corrections, reducing maneuverability and safety, especially under challenging conditions.

The communication (C4) has the shortest mean delay of 8.68s, with a standard deviation of 19.48s, indicating minimal variability. However, the available raw data on C4 are limited and mainly focus on maritime communications. Although advancements in technology are expected to reduce delays, some data still report delays up to 60s. In RC-MASS operations, delays can occur not only when sending commands to the ship but also when transmitting data back to the shore control center. These delays, influenced by multiple factors, including human intervention, can significantly impact RC-MASS performance. As the "lifeline" of RC-MASS, even small delays or interruptions in communication can have significant consequences. In critical situations requiring rapid decision-making, any delay may lead to loss of ship control, threatening safety and efficiency. Therefore, communication issues have received considerable attention in RC-MASS research(Porathe et al., 2013; Wahlström et al., 2015; Miyashita et al., 2021; Zhang et al., 2024).

Overall, delays in navigation equipment, ship maneuvering, and ship control are longer and more variable compared to communication. Such time delays are common across various ship types, including RC-MASS, with comparable impacts. However, for RC-MASS, communication is of paramount importance, serving as the critical link for maintaining effective ship control.

5. Conclusion

This study systematically analyzed time delays related to maritime operations, with a focus on RC-MASS, using time delay data collected from various sources. The data were categorized into four main groups: navigation equipment, ship maneuvering, ship control, and communications. The key findings are as follows:

(1) The average delay across all categories was 56.17 seconds, but the range of delay variability was substantial.

(2) Navigation equipment, ship maneuvering, and ship control are common sources of delays across all types of ships, and they exhibited relatively high delays, indicating a need for overall improvements to minimize these delays in the future.

(3) Communications had the shortest mean delay, but given its critical importance to RC-MASS, the various factors affecting communication delays should be further investigated to ensure reliability.

This study conducted a comparative analysis of time delays in RC-MASS through a systematic review, categorizing these delays and clarifying future directions for time delay research. These findings contribute to enhancing the safety and efficiency of RC-MASS operations. This study has certain limitations. The data used in this study were collected from sources spanning almost 25 years, including some from before the emergence of RC-MASS. While these data provide valuable insights, their applicability may vary as the field continues to evolve. Additionally, the study focused on a limited set of delay categories. As technology evolves, delay values and their impacts may change. Future research should expand data collection and incorporate the latest advancements to ensure continued relevance and accuracy.

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