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The Challenges of Building Trust in Autonomous Navigation Systems: A Perspective on the Tester

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This study seeks to enhance understanding of the tester's role in building trust in autonomous maritime systems. As ongoing maritime developments point towards the implementation of advanced navigation systems with the potential to enable autonomous- and remotely operated ships, the industry aims to enhance safety, efficiency and reduce its environmental footprint. However, assessing the reliability and robustness of intelligent and complex systems, envisioned to operate in complex and dynamic environments, poses significant challenges towards existing regulatory frameworks and assessment practices. Hence, to build trust in autonomous systems and ensure that safety requirements are met, comprehensive and systematic testing is necessary. In this context, automated testing through simulation is an important method. This approach involves automatically and iteratively probing the system under test with a range of scenarios. However, considering the potential size of the scenario space, an automatic approach to evaluating system outputs is needed. Still, whilst automatic evaluation can greatly improve the efficiency and coverage of the test process, human testers provide significant added value through their domain expertise, knowledge, and experience. This includes evaluating the overall results of the automatic process, performing spot-checks on individual cases, and investigating specific results. Together, the aggregate of these evaluations supports the tester in building confidence in the system's test results, and trust in the system's overall performance. Considering the novelty of autonomous navigation systems, this paper reviews relevant regulations, challenges related to requiring safety equivalence, and the need for testing. Furthermore, this paper explores the anticipated role-change of human testers and reflects on how to support them in their new tasks.

Keywords: Autonomy, Autonomous navigation, Collision Avoidance, Testing, Human tester, Human-machine

1. Introduction

The development of autonomous and remotely operated ships continues, and future ships are foreseen to be increasingly equipped with advanced novel navigation systems, promising to enhance safety, efficiency, and environmental sustainability. In response, the International Maritime Organization (IMO) is developing the Maritime Autonomous Surface Ships (MASS) code, set to become mandatory in 2030 (IMO 2024).

Within the developments towards ship autonomy, systems that can perform collision and grounding avoidance without human involvement receives much attention (Chang et al. 2024). Unlike human navigators, autonomous systems use algorithms and sensor technologies to drive decision making. However, such systems typically lack the inherent adaptability and resilience found in humans. Human navigators can use their training, education, intuition, experience, and expertise to adapt to unexpected situations, and make decisions based on a contextual understanding. This enables navigators to efficiently adapt to changes in their environment, such as nearby vessels or changing weather.

Autonomous navigation systems, in contrast, follow programmed protocols and may overlook subtleties unless explicitly designed to detect them. In other words, autonomous system capabilities are confined to the knowledge and expertise of developers, which often differs from that of human navigators. Due to the high risk of major accidents from inadequate performance, autonomous navigation systems must undergo thorough testing. A comprehensive process can identify potential flaws, vulnerabilities, and evaluate system performance under various conditions. Testing is therefore an essential part of development, commissioning, and deployment and ensures the system meets the requirements for maritime safety and efficiency (Barr et al. 2015; Pedersen et al. 2023; Karolius et al. 2024). However, real-life testing may be infeasible due to its complexity and cost. Consequently, virtual- or simulation-based testing can enable a more cost-effective- and scalable testing approach (Pedersen et al. 2020). Additionally, simulation allows for testing of potential failure scenarios without any associated risk from real-world testing.

A considerable amount of research is available on methods, strategies and frameworks for testing autonomous systems in the maritime domain. For example, Xiao et al. (2023) introduced a virtual test rig using advanced 3D ocean models, along with a method to evaluate the performance of obstacle avoidance. Furthermore, Pedersen et al. (2020) used a simulation-based test framework, implementing evaluation metrics developed by Woerner (2016). Also, Torben et al. (2022) introduced formal methods, and described how this can be combined with contract-based design to automate simulation-based testing. Moreover, Tornese et al. (2022) applied hardware-in-the-loop testing to evaluate autonomous collision avoidance system. Finally, Vatle et al. (2024) implemented Adaptive Stress testing, a method developed for testing safety-critical systems in the automotive and aircraft domain.

While these methods introduce novel test methods and frameworks, they often overlook the role of the tester. Typically, the final decision-making authority resides with the human tester, considering their knowledge of informal specifications, expectations, norms and domain-specific information that can guide the testing process (Barr et al. 2015). Consequently, this sets expectations to the integration of the tester's role in testing autonomous systems.

While there is currently no mandatory code for autonomous maritime systems, future regulations are likely to be based on existing procedures and requirements for conventional ships. Therefore, it is important to bridge the gap between the test methods used for conventional systems and those anticipated for autonomous systems to understand the evolving role of the tester in the context of autonomy. To explore this further, this paper elaborates on the challenges in current practices when conducting automatic testing of autonomous navigation systems and how human testers can play a role in addressing these.

2. Background

2.1 Regulatory framework

Currently, human navigators are responsible for carrying out collision avoidance maneuvering with the assistance of bridge equipment such as radar, Global Navigation Satellite System (GNSS), Automatic Identification System (AIS), and steering and control systems.

The International Convention for the Safety of Life at Sea (SOLAS) outlines the minimum standards for the equipment and operation of ships with respect to safety (IMO 2009). Flag states are responsible for ensuring that vessels under their flags comply with these requirements. Specifically, the regulations under Chapter V of SOLAS apply to all ships on voyages not exempted by SOLAS Chapter V Reg. 1, setting broad requirements for navigational safety and equipment. SOLAS Ch. V Reg. 15 describes principles for safe navigation and outlines how support systems shall aid the bridge team in providing situational awareness and navigating the ship safely, thereby minimizing the risk of human error. In addition, Ch. V Reg. 34 outlines the requirements for safe navigation and avoidance of dangerous situations set towards the master.

IMO resolutions MSC.191(79) (2004) and MSC.252(83) (2007) establish the performance standards for integrated navigation systems and presentation of navigational information to support safe navigation. The former outlines the various navigational tasks that an integrated navigation system (INS) must support. For instance, in the context of collision avoidance, the radar system is employed to acquire targets and assess collision risks. IEC 61924-2:2021 (2021) specifies the testing methods and the expected test results for the INS, ensuring compliance and reliability.

Performance criteria for the collision avoidance task are depicted in the Convention on the International Regulations for Preventing Collisions at Sea (COLREG; IMO 1977). COLREG establishes the "rules of the road" for all vessels navigating at sea. It outlines the responsibilities and actions required by each vessel, making adherence to these regulations essential for safe and efficient navigation.

It is the responsibility of the flag state to ensure that vessels sailing under their respective flag complies with these regulations. SOLAS Ch. V Reg. 18 requires type approval of maritime of navigation system. Many flag states have appointed *notified bodies*, organisations designated by the national administration, to inspect, survey, and verify compliance on their behalf (EU 2014). Such independent third parties have strict requirements to competence, integrity and impartiality of their judgements as they are responsible for examining and verifying technical designs and attest that these meet relevant safety requirements.

2.2 Safety equivalence

An important principle regarding ship autonomy is the "equivalence principle". This principle states that if a system is built with alternative designs, it should be demonstrated that its safety performance is equivalent to, or better than, conventional designs (IMO 2013). This principle is also reflected in the guidelines from various classification societies (DNV 2021; Korean Register 2024; Bureau Veritas 2019). However, measuring and capturing human behavior is a complex task, making it difficult to establish a human baseline for comparison (Koopman and Widen 2023). Also, autonomous systems may introduce new risks or have effects unaccounted for by traditional risk analysis methods. For example, differences in responses to a vessel on collision course may create confusion in environments where both humans and autonomous ships interact. Consequently, it is unclear whether this change in operational behavior may affect the operational risk picture and thereby the system's safety equivalence. Hence, systematic testing is needed to adequately evaluate the collision avoidance system's performance.

2.3 The need for testing

Testing is the process of assessing a function or system to determine its performance, quality, or reliability (IEEE 2022). This typically involves conducting tests to measure specific characteristics or identify any deviations from the intended behavior. In this approach, the system is methodically stimulated under various conditions, and its responses observed and analyzed (Barr et al. 2015). This stimulation is achieved by designing and executing a range of test cases to expose the system to various scenarios. This way, the system is evaluated in the complete Operational Design Domain (ODD), assessing the system's robustness during normal operation and failure modes (Rødseth et al. 2021).

The entity that performs the assessment is also referred to as the test oracle; a human or an automated system (IEEE 2022). Determining whether a test passes or fails can be achieved by quantitative or qualitative evaluation metrics. Consequently, there is an important relationship between test case generation and the test oracle, as the test cases are directed towards what is being measured. Similarly, the response from stimulating the system should guide the tester towards areas requiring further attention.

In the test regime, system developers, quality assurance testers, and user acceptance testers, contribute towards verification and validation of the system. In addition, third-party testers typically verify compliance with established standards or regulatory frameworks. Unlike system developers, third-party testers may treat the system as a black box, focusing on the behavior of the final system rather than its internal mechanisms. Additionally, extensive expertise within the domain is used in the evaluation. Consequently, regulatory bodies mandate and conduct third-party testing to ensure compliance with standards and regulations (European Commission 2024). However, testing autonomous navigation systems is not without its challenges.

3. Challenges in testing autonomous navigation systems

3.1 Extent of the problem space

Considering the number and combinations of parameters constituting a test scenario, the number of possibilities becomes exponentially large. This makes it extremely challenging for a human tester to manually process and evaluate possible scenarios and results. Consequently, a major obstacle is to determine which, and how many, simulations are needed to reach satisfactory test coverage. Pedersen et al. (2023) used a long-tail distribution to describe this challenge. The head of the distribution represents scenarios that have a high probability of occurring, e.g., within months of operation. These are scenarios that must be identified pre-deployment through testing. As possible encountered failures are mitigated, the scenario distribution moves to the right reaching scenarios that have a low probability of occurring, e.g., every 100 years. At some point along the curve, it may be assumed that the testing has reached an acceptable residual risk level after which it can be decided that the system is sufficiently tested to enable deployment. To arrive at this point, a large number of- and variation in scenarios is needed.

3.2 Interpretability of collision regulations

Since ships equipped with autonomous navigation systems are designed to operate alongside conventional vessels, it is reasonable to assume that they should comply with existing regulations such as the COLREG. However, the rules were intentionally made flexible to apply to a wide range of situations, which introduces challenges in terms of how to interpret qualitative terms such as "safe speed", "ample time", "readily apparent", and "good seamanship" (IMO 1977).

Consequently, several research activities exist aimed to formalize the COLREG into testable criteria. Torben et al. a (2022) introduced formalization of COLREG using temporal logic, a method suitable for capturing temporal and spatial dependencies, which facilitates the modelling of complex traffic encounters. Based on a similar approach, Krasowski and Althoff (2024) proposed a framework to evaluate COLREG. Woerner (2016) used a different approach introducing mathematical formulations to evaluate COLREG through penalties and scores for single-ship encounters. However, despite these efforts, converting qualitative terms into a clear and explicit format to assess the performance of the collision avoidance system remains challenging.

3.3 Dependency on software

As autonomous systems are heavily software dependent, potential imperfections in the software code may affect system functions (Sullivan and Chillarege 1991). Hence, the potential for coding errors and feature changes, post-deployment software updates are expected throughout its lifecycle (Saravanos and Curinga 2023). Due to the complexity of the code, it is challenging to predict how these updates will affect the overall behaviour of the system. Although current regulations require that changes in design and characteristics are considered, they do not explicitly mandate additional software testing (EU 2014). This is a significant challenge, as updates are expected to continuously improve on the software's performance and functionality.

Also, autonomous navigation systems may use learning algorithms that enables them to adapt and improve their performance over time (Ye et al. 2023). This changeability of the system implies that its ODD, tested during the initial conformity assessment, may evolve over time (Charmet et al. 2023). As the system adapts, its behaviour may diverge from what was originally documented, posing challenges for ensuring ongoing compliance with safety and performance standards. Hence, the traditional approval approach may not be sufficiently satisfactory and may require continuous assessments to ensure safety and performance standards are met.

4. Testing autonomous navigation systems

4.1 An automated test framework

Pedersen et al. (2020) introduced a prototype automated framework for testing autonomous navigation systems. Here, a scenario manager is responsible for generating the scenarios. It uses information describing the environment and system, such as metocean data and vessel configuration, to generate scenarios. This information is then interfaced towards a simulated environment containing the system under test and dependant systems. The scenario manager is responsible for configuring the internal parameters in the system and setting up the positions, courses and speeds of interacting vessels. The output of the simulation is then interfaced to the test oracle and subsequently evaluated. The test evaluation module builds upon rules and regulations such as COLREG to determine the performance of the system. To automate the test process, the framework applies a search method that uses the results from the test oracle to automatically generate new test scenarios targeting areas where the system performs insufficiently. Consequently, the system is iteratively probed with numerous scenarios that are automatically evaluated and input to new scenarios are made based on the outcomes of earlier ones (see Figure 1).

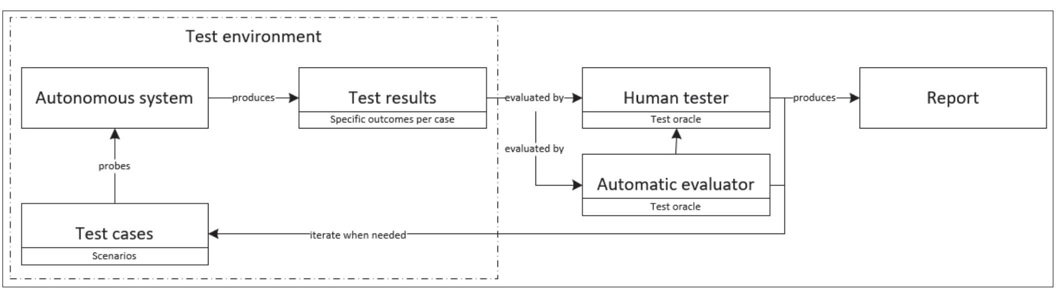

Figure 1. The test process.

4.2 The role of the tester

While automated testing frameworks may significantly enhance efficiency of the test process and the coverage of the scenario space, human testers can provide significant added value by contributing with their domain expertise (Fraser et al. 2015). That is, despite a high degree of automation in both the creation, execution, evaluation, and iteration of the tests, a human tester is involved to initiate, configure, and monitor the test process, scrutinize the automatically generated test results, perform spot checks, and perform manual evaluations of individual test cases where needed. By being closely involved in the automatic test process, and perform manual testing where needed, testers can build an intricate mental model of the system (Rouse and Morris 1986, 7). In doing so, testers learn the system's limitations, capabilities, reliability, functioning, and gain an understanding of its logic and components (Endsley 2023). This way, they can assess the trustworthiness of the system (Lee and See 2004).

Considering the uncertainties and vulnerabilities associated with collision avoidance maneuvering, trust in the system's ability to handle possible collision situations is an important consideration for testers in their evaluation of the system for operational use. In performing individual tests of specific scenarios based on previous test experiences, known problem areas, edge cases, risk assessments, observed weaknesses of the tested system, and/or documented collision accidents, the trustworthiness of the system can be evaluated. As such, experience with how the system handles overall- and individual test cases is an important determinant of the tester's confidence in the system. Together, automated results, combined with the human tester's experience-based testing approach should provide a degree of insight into the system's capabilities that is sufficient to form an educated assessment of its performance.

5. Conclusion

With increased degrees of autonomy, the role of the navigator transitions from one *performing* collision avoidance maneuvering to one *supervising* a system performing collision avoidance maneuvering (van de Merwe et al. 2024). As systems with increasing degrees of autonomy take on more of the tasks previously performed by navigators, testers "inherit" some of the operational responsibilities that typically reside with navigators.

Consequently, increased degrees of autonomy add a burden of responsibility previously not present in third-party testing of maritime systems. Considering this change, increased focus should be given to how to support human testers in this new role, and ensure methods, tools, and knowledge is made available to engender trust in the system, and confidence in the test results.

This paper discussed how the complexity and uncertainty associated with autonomous systems introduce new challenges in the form of automatic testing. As a result, the role of the tester must evolve to effectively address these challenges.

6. References

Barr, Earl T., Mark Harman, Phil McMinn, Muzammil Shahbaz, and Shin Yoo. 2015. "The Oracle Problem in Software Testing: A Survey." *IEEE Transactions on Software Engineering* 41 (5): 507–25. https://doi.org/10.1109/TSE.2014.2372785.

Bureau Veritas. 2019. "Guidelines for Autonomous Shipping." 2019. https://marine-offshore.bureauveritas.com/ni641-guidelines-autonomous-shipping.

Chang, Chia-Hsun, Isuru Bandara Wijeratne, Christos Kontovas, and Zaili Yang. 2024. "COLREG and MASS: Analytical Review to Identify Research Trends and Gaps in the Development of Autonomous Collision Avoidance." *Ocean Engineering* 302 (June):117652. https://doi.org/10.1016/j.oceaneng.2024.117652.

Charmet, Thibault, Véronique Cherfaoui, Javier Ibanez-Guzman, and Alexandre Armand. 2023. "Overview of the Operational Design Domain Monitoring for Safe Intelligent Vehicle Navigation." In *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, 5363–70. https://doi.org/10.1109/ITSC57777.2023.10421823.

DNV. 2021. "Autonomous and Remotely Operated Ships." DNV-CG-0264. Høvik, Norway: DNV. https://www.dnv.com/maritime/autonomous-remotely-operated-ships/class-guideline.

Endsley, M.R. 2023. "Supporting Human-AI Teams: Transparency, Explainability, and Situation Awareness." *Computers in Human Behavior* 140 (March):107574. https://doi.org/10.1016/j.chb.2022.107574.

EU. 2014. "Directive 2014/90/EU of the European Parliament and of the Council of 23 July 2014 on Marine Equipment and Repealing Council Directive 96/98/EC Text with EEA Relevance." 2014. https://eur-lex.europa.eu/eli/dir/2014/90/2021-08-11/eng.

European Commission. 2024. "Standards and Conformity Assessment." 2024. https://trade.ec.europa.eu/access-to-markets/en/content/standards-and-conformity-assessment.

Fraser, Gordon, Matt Staats, Phil McMinn, Andrea Arcuri, and Frank Padberg. 2015. "Does Automated Unit Test Generation Really Help Software Testers? A Controlled Empirical Study." *ACM Trans. Softw. Eng. Methodol.* 24 (4): 23:1-23:49. https://doi.org/10.1145/2699688.

"IEC 61924-2:2021 ED2." 2021. Standard Online. February 2021. https://online.standard.no/nb/iec-61924-2-2021-ed2.

IEEE. 2022. "NEK ISO/IEC/IEEE 29119-1:2022." Standard Online. February 2022. https://online.standard.no/nb/nek-isoiecieee-29119-1-2022.

IMO. 1977. "Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs)." July 15, 1977. https://www.imo.org/en/About/Conventions/Pages/COLREG.aspx.

———. 2007. "Resolution MSC.252(83) Adoption of the Revised Performance Standards for Integrated Navigation Systems (INS)." 2007. https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/MSC-2007-09.aspx.

———, ed. 2009. *SOLAS: Consolidated Text of the International Convention for the Safety of Life at Sea, 1974, and Its Protocol of 1988: Articles, Annexes, and Certificates*. Consolidated ed. 2009, 5th ed. London: International Maritime Organization.

———. 2013. "Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments." MSC.1/Circ.1455. Montreal, Canada: International Maritime Organisation.

———. 2024. "Autonomous Shipping." 2024. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Autonomous-shipping.aspx.

Karolius, Kristian, Grunde Løvoll, Jakub Cichowicz, Are Jørgensen, and Øystein Engelhardtsen. 2024. "Navigating the Challenges of Assuring Safe Autonomous Navigation." In . Wuxi, China.

Koopman, Philip, and William H. Widen. 2023. "Breaking the Tyranny of Net Risk Metrics for Automated Vehicle Safety." SSRN Scholarly Paper. Rochester, NY. https://doi.org/10.2139/ssrn.4634179.

Korean Register. 2024. "Guidance for Autonomous Ships." Korean Register. https://www.krs.co.kr/KRRules/KRRules2024/data/data_other/ENGLISH/Guidance%20for%20Autonomous%20Ships_2024.pdf.

Krasowski, Hanna, and Matthias Althoff. 2024. "Provable Traffic Rule Compliance in Safe Reinforcement Learning on the Open Sea." *IEEE Transactions on Intelligent Vehicles*, 1–18. https://doi.org/10.1109/TIV.2024.3400597.

Lee, John D., and Katrina A. See. 2004. "Trust in Automation: Designing for Appropriate Reliance." *Human Factors* 46 (1): 50–80. https://doi.org/10.1518/hfes.46.1.50_30392.

Maritime Safety Committee IMO. 2004. "Resolution MSC.191(79) Performance Standards for the Presentation of Navigation-Related Information on Shipborne Navigational Displays." December 6, 2004. https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/msc-2004-06.aspx.

Merwe, Koen van de, Steven Mallam, Salman Nazir, and Øystein Engelhardtsen. 2024. "Supporting Human Supervision in Autonomous Collision Avoidance through Agent Transparency." *Safety Science* 169 (January):13. https://doi.org/10.1016/j.ssci.2023.106329.

Pedersen, Tom Arne, Jon Arne Glomsrud, Else-Line Ruud, Aleksander Simonsen, Jarle Sandrib, and Bjørn-Olav Holtung Eriksen. 2020. "Towards Simulation-Based Verification of Autonomous Navigation Systems." *Safety Science* 129 (September):104799. https://doi.org/10.1016/j.ssci.2020.104799.

Pedersen, Tom Arne, Chanjei Vasanthan, Kristian Karolius, Øystein Engelhardtsen, Koen Pieter Houweling, and Are Jørgensen. 2023. "Generating Structured Set of Encounters for Verifying Automated Collision and Grounding Avoidance Systems." *Journal of Physics: Conference Series* 2618 (1): 012013. https://doi.org/10.1088/1742-6596/2618/1/012013.

Rødseth, Ørnulf Jan, Håvard Nordahl, Lars Andreas Lien Wennersberg, Bård Myhre, and Stig Petersen. 2021. "Operational Design Domain for Cars Versus Operational Envelope for Ships: Handling Human Capabilities and Fallbacks." In *Proceedings of the 31st European Safety and Reliability Conference (ESREL 2021)*, 2022–29. Research Publishing Services. https://doi.org/10.3850/978-981-18-2016-8_113-cd.

Rouse, William B., and Nancy M. Morris. 1986. "On Looking into the Black Box: Prospects and Limits in the Search for Mental Models." *Psychological Bulletin* 100 (3): 349–63. https://doi.org/10.1037/0033-2909.100.3.349.

Saravanos, Antonios, and Matthew X. Curinga. 2023. "Simulating the Software Development Lifecycle: The Waterfall Model." *Applied System Innovation* 6 (6): 108. https://doi.org/10.3390/asi6060108.

Sullivan, M., and R. Chillarege. 1991. "Software Defects and Their Impact on System Availability-a Study of Field Failures in Operating Systems." In *[1991] Digest of Papers. Fault-Tolerant Computing: The Twenty-First International Symposium*, 2–9. https://doi.org/10.1109/FTCS.1991.146625.

Torben, Tobias, Øyvind Smogeli, Ingrid Bouwer Utne, and Asgeir Johan Sørensen. 2022. "On Formal Methods for Design and Verification of Maritime Autonomous Surface Ships." *Proceedings of the World Maritime Technology Conference*. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3058210.

Tornese, Riccardo, Edoardo Polimeno, Claudio Pascarelli, Stefania Buccoliero, Luca Carlino, Emanuele Sansebastiano, and Luca Sebastiani. 2022. "Hardware-in-the-Loop Testing of a Maritime Autonomous Collision Avoidance System." In *2022 30th Mediterranean Conference on Control and Automation (MED)*, 514–19. https://doi.org/10.1109/MED54222.2022.9837250.

Vatle, Jan-Marius, Bjørn-Olav Holtung Eriksen, and Ole J. Mengshoel. 2024. "Green Urban Mobility with Autonomous Electric Ferries: Studies of Simulated Maritime Collisions Using Adaptive Stress Testing." *Swedish Artificial Intelligence Society*, June, 47–56. https://doi.org/10.3384/ecp208006.

Woerner, Kyle. 2016. "Multi-Contact Protocol-Constrained Collision Avoidance for Autonomous Marine Vehicles." PhD Thesis, Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/104118.

Xiao, Guoquan, Guihong Zheng, Chao Tong, and Xiaobin Hong. 2023. "A Virtual System and Method for Autonomous Navigation Performance Testing of Unmanned Surface Vehicles." *Journal of Marine Science and Engineering* 11 (11): 2058. https://doi.org/10.3390/jmse11112058.

Ye, Jun, Chengxi Li, Weisong Wen, Ruiping Zhou, and Vasso Reppa. 2023. "Deep Learning in Maritime Autonomous Surface Ships: Current Development and Challenges." *Journal of Marine Science and Application* 22 (3): 584–601. https://doi.org/10.1007/s11804-023-00367-1.