Develop and evaluate of intelligent autonomous-ship framework

Kyeong Deok Moon[1], Chi Yoon Jeong[1], Moo Seop Kim[1], Yun Kyung Park[1], Kwangil Lee[2*]
[1] ETRI, 218 Gajeong-ro, Yuseong-gu, Daejeon, 34129, KOREA
[2] KMOU, 727 Taejong-ro, Yeongdo-Gu, Busan 49112, South Korea

[*] E-mail:leeki@kmou.ac.kr

Abstract. The Autonomous Ship(AS) is a dream ship which navigates the sea on its own without any captains or crews. Many related studies on AS and the advent of deep learning technologies enable ASs voyage in the near future. They have been focused on proposing and verifying feasibility of their concept. However, there have not been little tried to compare results of ASs to that of captains. In this paper, we propose an Intelligent Autonomous-Ship Framework(IASF) which enables to develop ASs based on deep-learning while supporting fundamental functions necessary for ASs such as collecting navigational information, recognizing navigational status, and controlling route. The IASF-based AS was evaluated through simulation with compared to results of captains.

1. Introduction

An Autonomous Ship(AS) is a dream ship that is a human continuous challenge to develop. An AS safely voyages to its destination without any human intervention. In particular, the AS is gaining importance as a new breakthrough to overcome the crisis of the shipbuilding industry due to stagnation that has persisted over the past several years and to reduce ship accidents due to human errors, which have been rapidly increasing. Because an AS must recognize navigational situation and maneuver throughout its voyage, artificial intelligence technology that recognizes and situations makes decisions like humans will be one of the major factors in deciding whether AS will be the successful or not. With the advent of deep-learning technology, artificial intelligence technology has made breakthroughs, and expectations for the success of ASs with artificial intelligence technology are also increasing. In an AS, as the number of crew members on board decreases, the space for crews can be used as space for cargo. This leads to changes the structure of the ship. The AS will also bring a paradigm shift that has not been experienced in the shipbuilding industry. For example, data that are collected during navigation will have added value, and various services will be deployed which causes new businesses.[1]

Research on AS has been actively began conducted in Europe since around 2010. Since the mid-2010s, semi-ASs have been deployed that are controlled from the shore centers by using navigational conditions determined by ships. In recent years, ASs have been tested in a restricted environment. However, most of these studies have been performed to verify the feasibility of proposed their concepts of ASs. ASs must navigate the sea where not only other ASs but also human maneuvered ships are exist. Thus, it is important to evaluate that ASs act as like maneuvered by captains. Because they have just

tried to navigate their ASs in a test area, it is difficult to say whether the performance of ASs is better than that of captains. There wewe not any tries to compare performance of ASs to that of captains. [2]-[7]

In this paper, an Intelligent Autonomous-Ship Framework(IASF) is proposed. The IASF makes it possible for an AS to safely and economically navigate by itself from departure to destination without the involvement of a captain or crew. The IASF provides fundamental functions for performing the process of "collecting navigational environment information ⬝ recognizing navigational conditions ⬝ determining and controlling routes" performed by ASs.[8] The IASF is composed of two layers, namely, the Functional Layer(FL) and the Abstraction Layer(AL). The FL provides fundamental functionalities for navigation without human intervention. The FL is composed of 3 sub-systems: Navigation Information Aggregator(NIA), Navigational Situation Recognizer(NSR), and Navigational Path Controller(NPC). The NIA collects information on the ocean, weather, and topography that affects the navigation of ships from various sources. The NSR analyzes the status of the own ship by determining the performance indexes of restoration and movement of the own ship, which are affected by external forces, such as the weather and sea. The NSR also recognizes navigational patterns, such as the trajectories of other ships, by fusing information collected from various devices. The NPC determines the risk of collision using the navigational situation obtained from the NSR, and then maneuvers the voyage of the own ship. The IMB which is a component of AL, provides interworking through message exchange among the subsystems of the IASF and between subsystems of the IASF and devices on the own ship. We evaluate performance of AS based on IASF by comparing to that of 6 captains by simulation on 3 defined scenarios.

The remainder of this paper is organized as follows. Related researches on ASs is summarized in Chapter 2. Chapter 3 describes the details of IASF, and Chapter 4 reports experimental results obtained through simulations that were performed to evaluate the navigational performance of the IASF-based AS. Finally, conclusions are presented with directions for future works.

2. Related works

Research on ASs has been conducted in Europe since 2010, and related studies have been increasing. Those projects have proposed concepts of ASs and have tried to verify their feasibility. They have not focused on comparing performance to performance of captains.

Maritime Unmanned Navigation through Intelligence in Networks(MUNIN) developed the AS technology since 2012. The AS, which is autonomously executed on a ship, is a consisted of advanced decision support systems and capabilities for remote and autonomous operation. The monitoring and controlling functionalities are executed in the Shore Control Centre. MUNIN defines the following systems and entities for AS. An Advanced Sensor Module handles the lookout duties continuously fusing data from navigational devices, such as radar, Automatic Identification System(AIS), and cameras. An Autonomous Navigation System follows a pre-defined navigational plan, but with adjusting the route in accordance with legislation, collision risks or weather changes. An Autonomous Engine and Monitoring Control system enables ship engine automation systems while maintaining the optimal efficiency. It also handles additionally installed pump-jet that function as a certain rudder and propulsion back up. The Shore Control Centre, which continuously monitors and controls the AS after it is released from its crew by its skilled nautical officers and engineers. It also assesses its technical, economic and legal feasibility.[2]-[5] The MUNIN project focused on the proof of feasibility of the concept of an AS. As they found it feasible, DNV GL ReVolt and YARA Birkeland perform took one step further with the learning from MUNIN. The AS of YARA Birkeland is the world's first fully electric autonomous container ship, with zero emissions. YARA Birkeland will be operated semi-autonomously near future, but fully autonomously lastly.[6][7]

3. Architecture of Intelligent Autonomous Navigation Framework

The IASF allows ships to determine their navigating environment and their route in order to safely arrive at their destination without human intervention. The IASF is composed of the FL and the AL, as mentioned earlier. The FL is a layer that provides fundamental and practical algorithms necessary for the vessel to determine its course and voyage on its own, and the AL is a layer that provides interworking among algorithms provided by the FL and between algorithms and navigational devices. This chapter describes the details of structure of the IASF in detail.
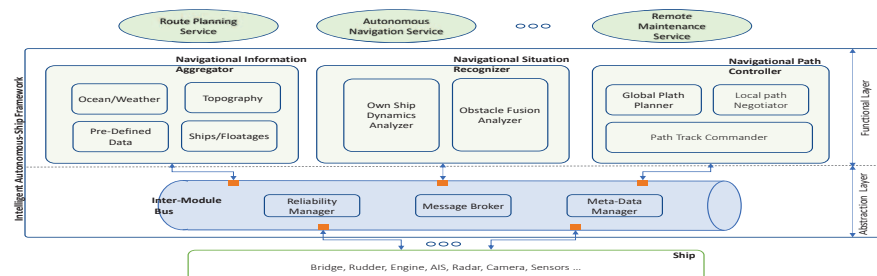

Figure 1. Architecture of Intelligent Autonomous-Ship Service Framework

3.1. Navigational Meta-Data(NMD)

The information collected by the IASF can be classified into two types: static information and dynamic information. Static information does not change during a voyage. It includes the voyage plan and ship information. Dynamic information which continuously changes while the ship is navigating along its route. It can be divided into the following types: information that changes geographically such as sea, weather, and charts; and information that changes over time, such as a navigation route or operation status of an own ship or other ships. The ocean information managed by the IASF is composed of weather information, chart information, and risk information. Weather information includes waves, water temperature, density, and wind tide, which are acquired from weather forecasting centers or sensors of the ship. Chart information includes coastline, water depth, and dangerous areas. Risk information includes other ships and obstacles. Moreover, the route of a ship and its navigational situations are changed over time. So far, ship's routes and situations have been managed based on the waypoints, which are intermediate points or places on a route or line of travel. IASF manages information related to the starting position, and distance, direction, and turning radius for entering the next waypoint, and the average speed of a waypoint. Moreover, the IASF manages navigational information by dividing a route into several waypoints and a waypoint into intermediate maneuver points, called action points in this paper. An action point is an intermediate point or place on a waypoint where a ship is maneuvered to maintain its course to next waypoint. The IASF collects and manages the navigational status of its own ships and information on other ships at regular intervals - 0.5 seconds to 1 second - so that the ASs can predict and handle navigation in relation to other ships that violate COLREGs' navigational regulations.

3.2. Abstraction Layer

The framework should support that researchers develop the ASs based on IASF without considering environments. The IASF can adapt various environments through the AL. The AL consists of an Message Broker(MB), Reliability Manager(RM), and Meta-Data Manager(MM). The AL is designed to comply with IEC 61162-450/460 to increase the possibility of future use.

The MB provides basic transmission and receiving functions to allow seamless interworking among algorithms or between algorithms and the ship. Because various physical media and protocols can be used simultaneously, the MB handles a variety of communication protocols by supporting the parsing, encapsulation, and protocol conversion of messages. In addition, in order to deliver a message to the desired algorithm or device, the MB determines the message passing route by managing basic and connection information on algorithms of the FL and devices. The MB also manages group information for group communication. It is important to provide a reliable and stable environment for ASs. To

prevent malicious access to an AS, the RM allows access only to modules that are authenticated based on a certificate. It guarantees the reliability of messages by providing access rights management. Access rights management includes a firewall and a function to determine whether the communication is due to an attack by analyzing the communication pattern. The RM guarantees stable message exchange by performance management, error handling, and log management of the IMB. The MM provides a function to store and manage the NMD. The MM registers and manages information related to the vessel in real time. The MM also retrieves the NMD to manage information related to the navigation changes that occur during the navigation of the vessel. The NMD makes it possible to not only manage the condition occurring during the operation, and to review the navigation of the ship after the navigation is terminated, or analyze the navigational situation.

3.3. Functional Layer

A captain uses information collected from navigational devices such as AIS and radar and visually confirms information to analyze the ship's navigational status and maneuver the ship so that it can safely reach its destination. Like captains, ASs should navigate to the destination by collecting information from various devices and determining everything by themselves without any human assistance. A framework for AS should provide the functions that are necessary to maneuver the ship by analyzing the risk factors and the ships navigational performance using the collected information, and deciding the route so that it can safely navigate to the destination accordingly. In the IASF, the FL provides the fundamental functions for the AS. The FL consists of three sub-systems: The Navigation Information Aggregator(NIA), Navigational Situation Recognize(NSR), and Navigational Path Controller(NPC). New functions can be continuously added for functions for various situations through the AL.

Ships are mainly affected by the temperature, current, wind, wave, and swell of the sea around them. The NIA provides functions for collecting information around ship. The NIA collects weather data from NOAA or sensors on navigation areas. In addition to weather information, the NIA enables the collection of data directly from users. Those data are a voyage plan, ship-related data, and chart-related information. In addition, it collects information from marine devices, such as AIS and radar, or from cameras and sensors so that it is easy to collect information regarding surrounding conditions while the ship is navigating.

The NSR analyzes and provides the navigational status of the own ship and that of other ships by using navigational situation information collected from the NIA. The navigational status is used to determine the route. External forces, such as water density, water temperature, wind, waves, tide, swell, and so forth affect the ship's desired speed and direction, which the ship tries to maintain. The Own Ship Dynamics Analyzer(OSDA) provides a basic function that determines the additional resistance and safety indices, such as restoration and wave tuning performance, which are caused by external forces. To determine the risk of collision with other ships, the Obstacle Fusion Analyzer(OFA) analyzes the navigational trajectories of other ships by integrating data from AIS, radar, and images obtained by camera that acts as a captain's eye. In particular, the OFA provides a deep-learning algorithm[9][10], which analyzes information about other ships in the vicinity from camera images.

The NPC determines the route of an AS during navigation, which avoids the risk of collisions of the own ship. The NPC analyzes the risk of collisions of the own ship based on the navigational status of own ship and other ships from the NSR. It then replans the route and finally maneuvers the engine and rudder of a ship accordingly while keeping the COLREG rules and guaranteeing the safety. The Global Path Planner(GPP) of the NPC generates the entire path from the departure to the destination before departure according to the weather forecast and navigational conditions. At this time, a global path is created using a multi-purpose optimization algorithm to consider the navigation time and fuel consumption at the same time, and the route with the lowest fuel consumption is selected among routes that satisfy the prescribed navigational constraints. The Local Path Planner(LPP) analyzes the risk of collision due to head on situation, crossing situation, and overtaking situations. The LPP also replans a path to perform collision avoidance maneuvers complying with COLREGs according to the analyzed

situation. The Path Track Commander(PTC) provides the function of maneuvering the ship's operation so that the ship can follow the path created by the GPP and LPP by itself.[11][12]

4. Experiments and Results

ASs should also evaluate their navigational performance in ports, coasts, and oceans, like other vessels. However, in the case of ports, there are too many factors to consider when evaluating, and there are too many variables, such as applying a separate navigation method for each port. In this paper, we evaluate the navigational performance of the proposed AS-based IASF in coastal and ocean travel by using a ship's track chart. It is possible to understand the ability to avoid collisions between ships and understand navigational status as a whole by analyzing a ship's track chart. To this end, we defined scenarios with head-on situations, crossing situations, and overtaking situations that occur frequently in the real world. Because a simulator can regenerate the same conditions repeatedly, we evaluated the navigational performance of the IASF-based AS by using a simulator and comparing the simulation results with those obtained by six captains who have extensive experience in operation.

4.1. Experiments

Figure 3 shows a testbed based on a simulator to evaluate the performance of an IASF-based AS. The testbed consisted of a PC, a simulator, and an IASF-Simulator Interface Device(ISID). The IASF-based AS ran on a PC, and the simulator simulated the own ship, other ships, and the ocean. The ISID connected the IASF-based AS and the simulator. The navigational status of ships, such as position, speed, and heading of own ship and other ships generated by the simulator, was transmitted from the simulator to the IASF-based AS through the ISID. The IASF-based AS sent an engine and rudder control commands to the simulator through the ISID. Because the simulator generated NMEA messages, the ISID and the simulator exchanged data through the NMEA protocol over serial communication. The sub-modules of the IASF-based AS were connected to the IMB over ethernet which supports 61162-450 protocol. The IASF-based AS was connected to the ISID which, ran on the IMB via ethernet. For interworking between the IASF-based AS and the simulator, the IMB installed on the ISID performed NMEA-to-450 protocol conversion. To perform the simulation, Pre-Defined Data, such as Departure, Arrival, ESTIMATED Arrival Time, Specification of Vessel, Policies for Navigation, and Navigational Information, were input as an XML document. Information about the sea on which the ship navigated, which was necessary for the analysis of the navigational characteristics in advance, received the information generated by the simulator, such as information about the sea.
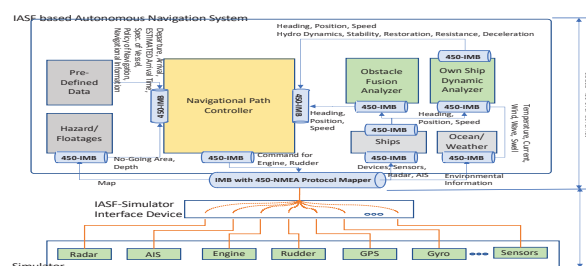

Figure 2. Test-Bed for Experiments

In this paper, the navigation regulations of '72 COLREG's were applied for the performance evaluation. We took into account situations that can frequently occur during voyages to evaluate the navigational performance of the IASF-based AS from the perspective of the ability of the ship to maintain its course and change its way. We have defined 3 scenarios with complex situation which are combinations of head on situations, crossing situations, and overtaking situations. In particular, it has temporal and spatial margins to sufficiently recognize other ships. In addition, we consider the minimum visible distance and situations in which the risk of collision is considerably high although it does not occur often during voyages. We also consider the case of the use of the engine. Scenario 1 is a typical

head on situation, which occurs frequently and is suitable for evaluation in case of the collision avoidance navigation regulations. Scenario 2 is a typical scenario for the state of overtaking a ship. Scenario 2 is very frequent and is suitable for evaluating compliance with collision avoidance navigation when overtaking. Scenario 3 is used to evaluate the relationship of navigation in a complex relationship in which head-on, crossing, and overtaking all exist. It is a scenario that can evaluate whether or not an IASF-based AS keeps regulations when a complex regulation relationship is established.

We defined simulation environment as follows: The wind blows to the north at a speed of 10 knots; the tide flows to the east at a current velocity of 0.5 knots; and the field of view is set to be relatively calm with a distance of 10 miles. To perform the simulation, we defined three rules. First, the movement of the ship is identified from at least 6 miles where the bow mast, and so forth can be seen. Second, action for collision avoidance is taken within 3 miles which is the minimum distance according to the regulations. Last, the closest distance to the other ships can be more than 1 mile.
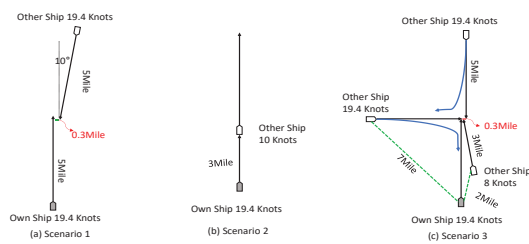

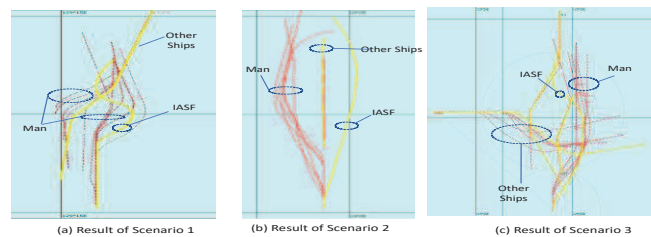**Figure 3.** 3 Scenarios for Simulation

Figure 4. Results of simulation

4.2. Its Results
The navigational performance of the IASF-based AS was evaluated by comparison with the results obtained by experienced captains. For each of 3 scenarios, each of the 6 captains conducted the simulation 6 times. Captains have many experiences on board and have a sailor's license. As a result, the navigational performance of the IASF-based AS showed no major problem in terms of collision avoidance, and the overall navigational performance did not show much difference from the captains'. In the case of collision avoidance, many captains take actions to divert the course of their own ship to avoid the course of the other ship which have a right to keep the course. However, the IASF-based ASs maneuvered toward other ship's course when the proximity distance between ships was sufficient. As a result, proximity distance of the IASF-based AS to other ships was closer than that of captains. In addition, when taking the countermeasures, the usage of the rudder by the IASF-based AS was relatively higher than that of the captains, so the IASF-based AS often took a rapid turn. Because most ships have large displacements, it may be difficult to control the course of a ship in the case of sudden changeover. The captains slowly returned to the planned course after completing the collision avoidance, but the IASF-based AS rapidly returned to the planned course after completing the collision avoidance. Thus, the IASF-based showed a tendency to return rapidly when returning.

5. Conclusions and Future Works
An AS that navigates the sea by itself without human assistance is a dream ship that can only be seen in movies. Many studies have been conducted to realize ASs so far; hence, ASs may be seen navigating in the sea in the near future. As yet, concepts for ASs are developed and applied to ASs to verify the feasibility of AS technology. There has been little research on performance evaluation by comparison to performance of captains. In this paper, we propose the IASF, which collects navigation information necessary to develop ASs, provides a function to determine the navigational status, and determines the route. The IASF provides a message-based architecture that can develop ASs without considering the environments. In addition, we evaluated the navigational performance of the IASF-based AS through simulation. The IASF-based AS avoids collision well and achieves a navigational performance similar to that of 6 captains. The IASF-based AS makes a sudden turn by using a rapid rudder movement to maintain the route in some cases.

For ASs to navigate in ports where traffic is heavy and considerably changed, they must be able to determine the best course in very complex situations. We have a plan to develop a more sophisticated IASF based on a deep reinforcement learning model to enable navigation in port. In addition, we will develop evaluation metrics that can quantitatively evaluate ASs, and conduct research to establish a test environment similar to the real sea by linking multiple simulators.

References
[1]   G. Koikas, M. Papoutsidakis, and N. Nikitakos 2019 New Technology Trends in the Design of Autonomous Ships *International Journal of Computer Applications*, Volume 178 – No. 25
[2]   Ørnulf Rødseth, Åsmund Tjora and Pål Baltzersen, 2014 D4.5: Architecture specification *MUNIN*, MUNIN-FP7GA-No 314286
[3]   Ørnulf Jan Rødseth and Åsmund Tjora 2014 A system architecture for an unmanned ship *COMPIT 2014*
[4]   Hans-Christoph Burmeister 2016 AUTONOMOUS NAVIGATION RESULTS FROM THE MUNIN TESTBED *Autonomous Ship Technology Symposium*
[5]   Ørnulf Jan Rødset 2016 The unmanned ship according to MUNIN *EMPA 50th General Meeting Unmanned ships: A real challenge for pilotage*
[6]   Ziaul Haque Munim 2019 Autonomous ships: a review, innovative applications and future maritime business models *SUPPLY CHAIN FORUM: AN INTERNATIONAL JOURNAL* Volume 20
[7]   VOLKER BERTRAM (2013), Towards Unmanned Ship, DnV-GL
[8]   Andrzej Felski and Karolina 2020 Zwolak The Ocean-Going Autonomous Ship—Challenges and Threats *Journal of Marine Science and Engineering*
[9]   Chiyoon Jeong, Hyun S. Yang, and Kyungduk Moon 2018 Horizon detection in maritime images using scene parsing network *Electronics Letters*
[10]   Chiyoon Jeong, Hyun S. Yang, and Kyungduk Moon 2018 Fast horizon detection in maritime images using region-of-interest *International Journal of Distributed Sensor Networks*
[11]   Byeong Hyeon Ryoo, and Jin Whan Kim 2018 Ship route optimization considering on-time arrival probability under environmental uncertainty *OCEANS '18 MTS/IEEE Kobe*
[12]   Byeong Hyeon Ryoo, and Jin Whan Kim 2018 Ship route optimization under weather uncertainty considering port arrival time constraint *ICMASS 2018*