TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 17
Number 2
June 2023
DOI: 10.12716/1001.17.02.16

Control of Electric Drive Tugboat Autonomous Formation

W. Koznowski & A. Łebkowski
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The automation of maritime transport is an indispensable trend towards full autonomy of maritime vessels. In this paper, an attempt was made to present the control system for port autonomous vessels using an agent system. On the basis of the conducted research, in order to optimize the energy consumption related to the movement of tugboats, the shape of the hull and the shape of the formation in which 4 tugboats are moving were selected. Several scenarios of navigational situations that may take place in port waters have been recognized. The conducted analysis have shown that the optimal shape of the hull of tugboats, the shape of the formation in which they move, as well as the determination of the passage route for the implementation of a specific task, can contribute to reducing both the carbon footprint and the energy consumption of the propulsion systems of tugboats. This is of significant importance in terms of reducing exhaust gas emissions in and around ports.

1 INTRODUCTION

Intelligent, machine-controlled transportation systems are becoming increasingly popular due to their increased efficiency relative to systems relying on human operators. The ever-increasing performance of computer systems, as well as the development of new remote sensing systems, coupled with the falling costs of implementing the latest solutions, allows for the continued expansion of automated transportation systems application range.

In the field of maritime transportation, there is considerable interest in the issue of its automation, both among researchers and shipowners. These efforts are centered around the idea of MASS (Maritime Autonomous Surface Ships). MASS are expected to use a range of developing technologies that will allow them to move autonomously through the water and perform tasks, first under constant operator supervision and eventually under incidental supervision.

The main advantage of the widespread introduction of MASS will be the increased safety of navigation caused by two factors [1]. The absence of a crew on a commercial vessel eliminates the risk of loss of life in the event of a serious accident, including sinking (excluding passenger vessels). Secondly, the increased number of sensors, and their coupling with a powerful computer data processing system, can allow a much more precise assessment of the situation by the algorithms controlling the unmanned vessel.

Another advantage of MASS will be the optimization of the unit's operating costs [2]. Regardless of the propulsion system used: conventional, hybrid (e.g., diesel-electric) or all-electric, the control algorithms will be able to take into account the current operating point of the propulsion system at any time during the voyage. Knowing the performance characteristics of the propulsion system allows the ship to adjust the sailing conditions found by the vessel, such as existing and forecast hydrometeorological conditions, current navigation conditions, or anticipated waiting periods for service in port.

If there arises a need to speed up the voyage, the autonomous system will also be able to take into account the aforementioned constraints and carry out the appropriate optimization of its passage route, so, for example, it hits the previously released time window for immediate port entry, right on time.

An aspect that is closely linked to operating costs is energy consumption and the associated amount of pollution emitted into the environment. There is no doubt that proper planning of the route, and a quick and appropriate response to changing sailing conditions have a significant impact on the amount of fuel required to cover a given distance.

Practical examples of MASS units currently exist in the prototype phase and in some cases there are already offered as products. These are usually small ships, equipped with many different types of sensors and computer systems using their signals. An example of such a prototype vessel is the Mayflower ship [3]. It is a 15-meter trimaran, equipped in addition to classic navigation devices such as AIS, GPS, Electronic Chart, Echosounder, and Radar, also with 6 cameras supported by artificial intelligence (AI) technology.

Figure 1. Autonomous ship Mayflower [3].

Additional information on the condition of the Mayflower is provided by sensors of the physical position of the hull, an on-board diagnostic system providing information on the status of the propulsion and telecommunications systems, and a remote weather forecast service.

Another example of a prototype is AutoNaut [4], a small test vessel designed to study a propulsion system that uses wave energy to move. It does not have such a developed autonomy system as Mayflower, but it uses radar and AIS for automatic collision avoidance. An additional feature that increases safety is the painting of the hull in a bright color, aimed at improving visibility. Remote control of the unit and data reading was carried out using a satellite link.

Figure 2. Autonomous vessel AutoNaut [4].

An example of a MASS unit already in production is the C-Worker 7, offered by L3Harris Technologies. It is an offshore vessel with a length of 7.5 m, a width of 2.3 m and a maximum speed of 6 knots. C-Worker 7 is intended mainly for inspection tasks or as a base for positioning systems. It is equipped with a moonpool and has the ability to carry an underwater vehicle (ROV) or various types of transponders of positioning and measurement systems, such as Ultra Short Baseline acoustic positioning system (USBL), Acoustic Doppler Current Profiler (ADCP), or multi-beam sonar. This ship is equipped with a typical set of classic navigation systems, including: radar, compass, inertial navigation system (INS) and AIS. The autonomous system is based on 4 cameras operating in visible light and 6 cameras operating in the thermal infrared (IR) range.

Figure 3. Autonomous ship C-Worker 7 [5].

Autonomous ships offered by L3Harris, including C-Worker 7, use the ASview software, consisting of 4 elements: the core, integrating signals from the ship's sensors and the autonomy system processor, radio communication system, operator station, and optional, portable remote control system. The manufacturer declares that the autonomous navigation system complies with the COLREG rules.

The ASview software also allows vessels to operate in a formation mode limited to 4 units, mainly to allow a single operator to send several vessels to the same area of operation.

The subject of this publication is to present an outline of the structure and capabilities of the agent system designed to control a formation of electric tugboats. The main purpose of the system, in addition to safe control of the formation's route in accordance with the adopted COLREG rules, will be to minimize the consumption of energy intended for moving the formation on the route leading to the destination point.

Against the background of the existing literature, there is currently no system that allows the VTS operator to automatically perform various port tasks using a formation of autonomous tugboats. The system proposed by the authors, will allow the operator to indicate the purpose of the task. Then the system will make it possible to plan and carry out the route of the tugs from the docking point to the place of operation, perform the ordered tasks and return the tugs to the place of docking.

2 ELECTRIC TUGBOAT FORMATION

The proposed agent system will be used to control a formation consisting of port tugboats, equipped with an electric propulsion system, using at least two azimuth propellers to ensure adequate maneuverability. The size of the supported formation starts with a minimum number of two units, with no fixed maximum. However, the practical number of tugboats used will depend on the type of tasks performed, and for typical harbor tugs tasks, such as ship escort, it will be between 2 and 5 tugs.

The basic task of the tugboat formation control system will be to carry out operations related to securing the ships entering the port, leaving the port, and moving inside the port. The control system will also enable the use of tugboats of the formation to perform other types of tasks, which, due to the highly economical propulsion system and the lack of crew, could be successfully performed by tugboats in place of other units usually used for this purpose.

An example of such tasks may be ice actions performed in the waters of the port. In weather conditions causing the waters of the port to freeze, unmanned tugboats free from other tasks can be sent to break the ice layer, which will not require the use of icebreakers. Another possible application of waiting tugboats may be performing patrol functions, combined with continuous measurement of the depth of the port basin.

After appropriate adaptation of the tugboat itself, it would be possible to perform additional functions, e.g.: transporting the Pilot to a ship waiting in the roadstead or getting the Pilot back from a ship leaving the port, performing pollution monitoring operations [6], and cleaning the port waters from spills and floating garbage, using hull-mounted collecting devices [7].

2.1 *Electric propulsion and recharging*

The energy to propel the tugs' propellers will come from the on-board energy store using electrochemical cells, recharged from an external charging station located on the quay. One of the important tasks of the agent system will be to take care of the state of charge of the batteries of all vessels in the formation.

This task includes following aspects: monitoring the actual State of Charge (SOC) of the energy storage, monitoring differences in the State of Charge and energy consumption between each of formation vessels, monitoring the availability of various types of energy sources available at a given moment, with a particular focus on renewable energy sources.

In order to monitor the State of Charge of the store and to detect differences in the operation of stores located on different vessels, the system can use sets of sensors built into the energy stores. Knowledge of data from twin vessels will enable the use of statistical methods to capture symptoms heralding the imminent failures.

On-board energy store can be recharged via a charging station located near the mooring place for tugboats of the formation. In order to reduce the impact on the natural environment, the charging station can use energy available from local renewable sources, such as photovoltaic, wind, and wave and sea current power plants. The employment of modern weather forecasting systems may enable planning the charging process for periods when the appropriate amount of energy from these sources will be available.

In the event of unfavorable conditions for access to renewable energy, e.g.: during night, cloudy weather, or windless weather, it may be necessary to carry out the charging process using energy from the grid, which may involve the emission of CO_2 and other pollutants, proportionally to the grid load by the charging station. Minimizing the energy consumed by tugboats therefore has a direct impact on the amount of pollutants emitted and the available methods and possibilities should be used to reduce its consumption in order to achieve the highest level of sustainability [8].

2.2 *Multiagent control system*

It is planned to employ an agent system to control the formation of electric tugboats. According to the definition [9], agents are autonomous units that have the ability to operate in a specific environment. Agents can communicate with other users of the environment and use owned, or foreign resources. Agents may have specific tasks, or objectives, which may be general, or specific. An environment is a certain space where agents are placed, where they can act, and influence this environment. Agent systems are one of the many methods of artificial intelligence imitating natural phenomena. Another well-known bio-derived method of artificial intelligence are Artificial Neural Networks (ANN) [10].

The operating environment of the agent system controlling the formation of tugboats is the physical space covering the waters of the port in which the system operates, and the virtual space of computer systems located in the port area and on board the formation tugboats. The environment is located in the area of limited waters [11] and therefore the required response time to a change in navigation conditions is shorter than in open waters, while the possibility of interference with navigational instruments is greater.

On board a single tugboat there is a computer system that collects signals from navigation devices and sensors of the tugboat's devices [12]. The navigation devices used may include: radar, GPS, AIS, compass, Inertial Navigation System (INS), echo sounder, and an electronic map [13] of the area in which the formation operates. The sensors include, among others: sensors of the propulsion system, sensors of the electric energy store, and optionally remote sensing sensors used by the tugboat to detect objects in the vicinity of its hull. It is possible to use, in particular, sensors such as: lidar and camera systems operating in visible light, near infrared or thermal infrared. The tugboat must also be equipped with an appropriate telecommunications infrastructure, providing at least a basic and backup communication channel to other system participants. The structure of the control system for an autonomous formation of port tugs is shown in Fig. 4.

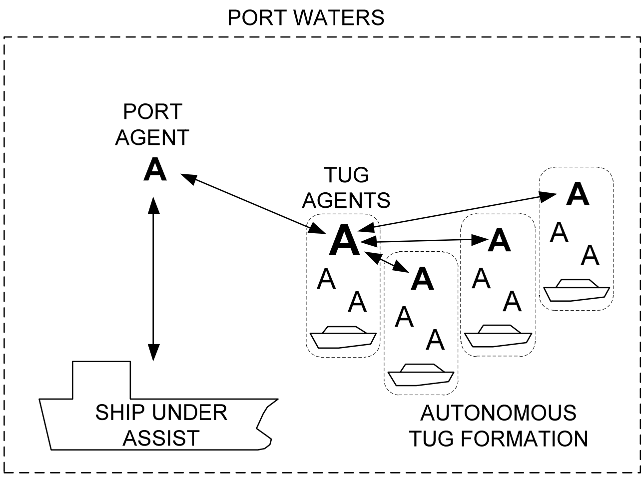

Figure 4. Autonomous formation control system structure.

The structure of the system is hierarchical, where the basic level of the hierarchy is a single tug. There are several agents in its on-board computer system whose tasks include: communication with the environment and supervision over the work of on-board agents, observation of the environment using available sensors and signals from other participants in the environment, control of the propulsion system, supervision of on-board systems, in particular electricity storage.

The second level of the hierarchy is the formation itself, made up of individual tugs. Its composition can be dynamic when, for example, it becomes necessary to replace a tugboat that has failed, or when, due to unforeseen deterioration of hydro-meteorological conditions, it becomes necessary to increase the number of tugs constituting a formation.

3 SIMULATION RESEARCH

On the basis of the previously mentioned assumptions regarding the tasks possible to be performed by the formation, tests were carried out using a simulated formation consisting of 4 tugs operating in the port of Gdańsk. A scenario was performed where a formation of 4 tugboats leaves the basin, where it is waiting for the assignment of tasks, in order to meet the ship awaiting on the roadstead for assistance in entering the port. The situational view of the analyzed scenario is shown in Fig. 5. As a result of previous research, it was determined that the most energy-efficient shape of the formation of 4 tugboats is a linear formation with a small gap between the tugboats flowing one after the other. Such arrangement of the tugboats allows for the reduction of hydrodynamic resistance by approx. 57.6%. In turn, the use of an electric drive powered by an energy storage system instead of a conventional diesel drive reduces energy consumption by up to 75.23% compared to the potential energy contained in diesel oil.

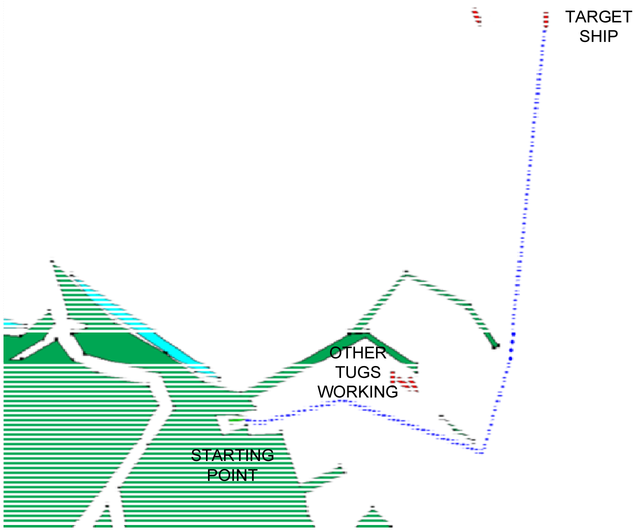

Figure 5. View of the simulated port of Gdańsk with superimposed plot of route traveled by the formation.

In Fig. 5, the dotted blue line shows the route traveled by the tugboats of the formation controlled by the agent system. Each dot represents the position of the first tugboat of the formation approximately every 16s of the simulation time. After traveling about 1 km, the agent responsible for navigation, located in the first tugboat (the formation leader), has detected a ship leaving the quay, accompanied by two other tugboats. The agent decided to avoid the working area of the foreign tugboats and changed the formation route, sailing around the island breakwater from the eastern side, and then continued sailing north towards the target ship.

Figures 6÷9 show graphs of the data obtained as a result of the simulation.

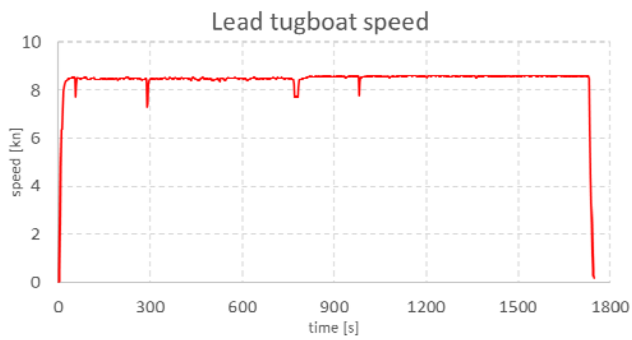

Figure 6. Tug formation leader speed plot.

Fig. 6 shows the speed chart of the first tugboat (leader) of the formation. There are slight slowdowns in places where the course changed.

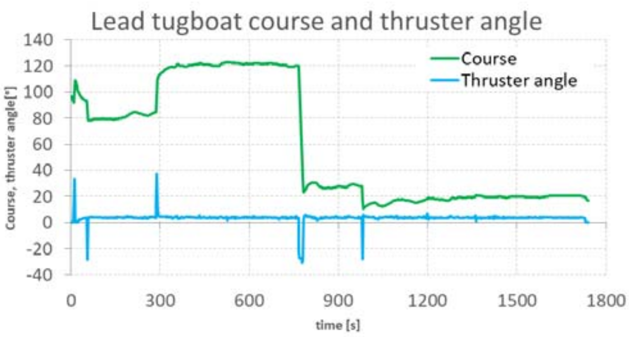

Figure 7. Plot of the course and angle of the thrusters of the first tug of the formation.

In Fig. 7, the green line shows the course of the first tug of the formation, and the blue line shows the deflection angle of the tug's azimuth thrusters.

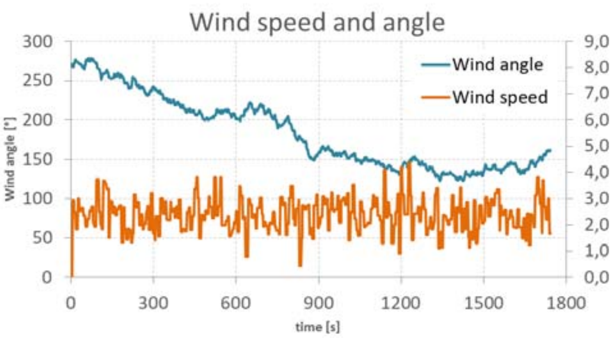

Figure 8. Plot of wind speed and wind angle felt by the leading tug of the formation.

In Fig. 8, the teal line shows the direction of the wind, and the orange line shows the wind speed. Both values correspond to the conditions measured by the first tug of the formation.

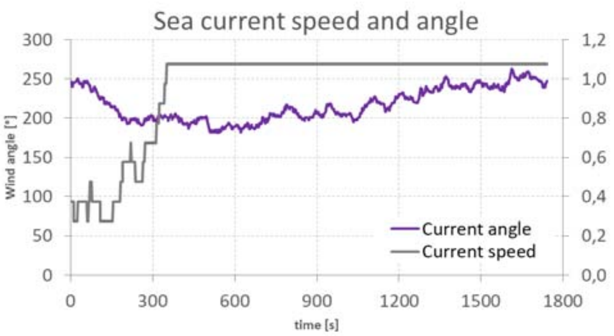

Figure 9. Plot of the speed and angle of the sea current felt by the leading tug of the formation.

In Fig. 9, the purple line shows the direction of the sea current, and the gray line shows its speed. Both values correspond to the conditions measured by the first tug of the formation.

As a result of simulation tests, the following results were obtained for a formation consisting of 4 tugs. Distance covered: 7581 m, energy consumption by the formation for electric drive: 214.9 kWh, respectively diesel consumption of conventional propulsion 71.6 dm3 (761.8 kWh). CO2 emission for electric propulsion assuming energy use from the public network was 71.8 kg, and 189.1 kg using a conventional drive.

For comparison, in the case of 4 free-flowing tugboats, not maintaining a particular formation, the electric energy consumption was 366.6 kWh, and the diesel consumption was 122.2 dm3 (1300.2 kWh). The CO2 emission for the considered navigation situation was respectively: 122.4 kg for electric drive and 322.6 kg for diesel propulsion.

As a result of only the use of electric propulsion, a reduction of CO2 emissions of 62.0% was achieved, and 77.7% as a result of combining the benefits of electric propulsion and the effects of reducing hydrodynamic resistance due to the movement of tugboats in a linear formation.

4 SUMMARY

The article presents the concept of an agent system designed to control an unmanned formation of electric tugboats. The use of an agent system embedded in the physical environment of the port and the computer system of tugboats made it possible to define a system that significantly extends the scope of tasks previously performed by tugboats. In addition to typical assistance operations, idle tugboats will be able to perform diagnostic or cleaning tasks without the need to engage additional vessels and their crews.

The research showed that a formation controlled by an agent system can react in accordance with the COLREG rules to unforeseen situations, such as finding a pair of tugboats starting to steer a ship out of the port within the working area.

The use of an agent system allows for continuous monitoring of the navigation situation and reacting to changing conditions that may increase energy consumption. When there are several options for dealing with an urgent situation requiring a course correction, the tug formation's team of agents can analyze each of the possible candidate maneuvers to select the most energy-efficient one.

The application of an electric drive system also reduces operating costs by reducing energy consumption and reducing pollutant and CO2 emissions. The conducted research showed a reduction in energy consumption by approx. 72% by the electric drive compared to the combustion drive and a reduction of pollutant emissions at the level of approx. 78%.

REFERENCES

1. Vos, J. de; Hekkenberg, R.G.; Valdez Banda, O.A. The Impact of Autonomous Ships on Safety at Sea – A Statistical Analysis. Reliability Engineering & System Safety 2021, 210, 107558, doi:10.1016/j.ress.2021.107558.
2. Krell, E.; King, S.A.; Garcia Carrillo, L.R. Autonomous Surface Vehicle energy-efficient and reward-based path planning using Particle Swarm Optimization and Visibility Graphs. Applied Ocean Research 2022, 122, 103125, doi:10.1016/j.apor.2022.103125.
3. Mayflower Autonomous Ship. Available online: https://mas400.com (accessed on 20 February 2023).

4. AutoNaut, wave propelled uncrewed surface vessels. Available online: https://www.autonautusv.com/vessels-0 (accessed on 22 February 2023).
5. L3Harris. C-Worker 7 ASV. Available online: https://www.l3harris.com/all-capabilities/c-worker-7-asv (accessed on 22 February 2023).
6. Veettil, B.K.; Hong Quan, N.; Hauser, L.T.; Doan Van, D.; Quang, N.X. Coastal and marine plastic litter monitoring using remote sensing: A review. Estuarine, Coastal and Shelf Science 2022, 279, 108160, doi:10.1016/j.ecss.2022.108160.
7. Choe, Y.; Lee, J.; Jung, W.; Park, J.; Lee, J.; Jho, J.Y.; Lee, K.T.; Kim, T.; Kim, Y.H. Gravity-based oil spill remediation using reduced graphene oxide/LDPE sheet for both light and heavy oils. Process Safety and Environmental Protection 2021, 156, 617–624, doi:10.1016/j.psep.2021.10.045.
8. Przybyłowski, A.; Kałaska, A.; Przybyłowski, P. Quest for a Tool Measuring Urban Quality of Life: ISO 37120 Standard Sustainable Development Indicators. Energies 2022, 15, 2841, doi:10.3390/en15082841.
9. Rossi, F.; Bandyopadhyay, S.; Wolf, M.; Pavone, M. Review of Multi-Agent Algorithms for Collective Behavior: a Structural Taxonomy. IFAC-PapersOnLine 2018, 51, 112–117, doi:10.1016/j.ifacol.2018.07.097.
10. Staniek, M.; Czech, P. Self-correcting neural network in road pavement diagnostics. Automation in Construction 2018, 96, 75–87, doi:10.1016/j.autcon.2018.09.001.
11. Kaizer, A.; Winiarska, M.; Formela, K.; Neumann, T. Inland Navigation as an Opportunity to Increase the Cargo Capacity of the Tri-City Seaports. Water 2022, 14, 2482, doi:10.3390/w14162482.
12. Buc, A.; Bielecka, A.; Iwaszkiewicz, J. The Use of Wireless Networks and Mobile Applications in the Control of Electric Machines. Applied Sciences 2023, 13, 532, doi:10.3390/app13010532.
13. Weintrit, A. Time to Revise the IMO's Guidance on Good Practice for the Use of Electronic Chart Display and Information System (ECDIS). TransNav 2022, 16, 523–531, doi:10.12716/1001.16.03.15.