

Port Tugboat Formation Multi-Agent Control System

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ABSTRACT: The publication presents the structure of the agent system, tasked with control of the formation of unmanned port tugboats capable of performing pilot and towing services. The use of autonomous tugboats with installed software was presented with respect to the existing regulations related to Resolution MSC.467 developed by the Maritime Safety Committee (MSC) belonging to the International Maritime Organization (IMO), which creates guidelines for the definition and harmonization of the structure and format of maritime services in the context of e-navigation. The use of a multi-agent system structure enables synergistic cooperation of tugboats carrying out joint port operations, such as: assistance in maneuvers of ships, precision movement of ships and other objects in port areas, monitoring and patrolling of port areas, carrying out ice operations, carrying out inspections of quays, the possibility of assistance in liquidation of petroleum and similar pollutant spills. The paper presents the structure of the agent system and the description of possible scenarios of port operations. The control algorithms and the applied methods of artificial intelligence, such as evolutionary algorithms with elements of fuzzy logic, were discussed. The recorded traffic parameters from the actions carried out in the simulator of the marine navigation environment were presented.

1 INTRODUCTION

The Resolution MSC.467 (101) [16] was adopted in the 2019 at the 101st session of the Maritime Safety Committee (MSC), which is part of the International Maritime Organization (IMO). The resolution defines and harmonizes the format and structure of existing maritime services in the context of e-navigation. The intense development of technology in the field of digitization of equipment in maritime applications begins reaching the point where it will be possible to further continue the process of replacement of crew members by machines [13].

There are several reasons for this process. The first one is the constant development of industrial technology, which translates into increased durability

and reliability of the manufactured devices. A ship built of modern materials and components requires less and less maintenance and the service intervals can become longer. At the same time, the use of computer diagnostic techniques allows for early detection of emerging problems, which allows planning of specialized service actions that would avert failures during normal operation.

The second reason for replacing the crew with machines is the increased precision and safety of the operations performed. Thanks to this, the most common cause of accidents, human error, is eliminated. Years of gathering experience during the operation of specific systems can be translated into the language of algorithms and implemented procedures, which mean that repetitive activities can be carried

out by machine systems that are much faster and more accurate than when staffed by humans.

The ultimate goal of the ship automation process is to achieve a level that allows the construction of fully autonomous marine vessels, initially operating under continuous human supervision [7], and ultimately not requiring even this type of control.

A similar trend in the development of automation applies to typical offshore support units, such as port tugs, pilot boats or bunker boats. Automation of tug operations can help to improve the safety [1] of ships entering and exiting ports. The problems necessary to solve in the course of the development of these type of units are mainly related to:

- the necessity of frequent approach / departure from the quay,
- moving through congested port waters, which requires tight navigation,
- coexistence (initially) in an environment dominated by manned units, the behavior of which, from the point of view of the machine, is somewhat unpredictable,
- the necessity of performing precise approaches to the ship being the target of an unmanned unit, often much larger than it and less maneuverable.

Another direction in the development of transport systems [9], including maritime transport, is the gradual departure from fossil fuels, in favor of alternative propulsion systems [10], using low-carbon fuels such as LNG [12] or hydrogen, and electricity stored in energy storage systems or generated from using fuel cells. The combination of an electric drive in combination with a battery energy storage is particularly advantageous, allowing for a high overall efficiency of such propulsion system [8].

The development of autonomous ship technology, including tugs, seems inevitable. So far, no operating systems have been presented, but intensive research has been carried out in this direction [5], and the first tests were carried out with the use of full-size tugs by the co-op between Rolls-Royce and Svitzer [11] and another one by Samsung [4].

This article presents the concept of a multi-agent formation control system for unmanned port tugs. This system has the ability to control one or more formations of unmanned port tugs, including tugs using electric propulsion. One of the features of the presented system is compliance with the COLREGS convention.

2 MULTI-AGENT SYSTEMS

Multi-agent systems belong to the set of methods used to search for optimal solutions, classified as artificial intelligence methods. These systems use standalone entities called agents that can interact with each other. Agents are most often computer programs specialized in the performing specific tasks. A feature of multi-agent systems is the possibility of cooperation between various agents. Thanks to this, the results obtained by the multi-agent system are characterized by properties that reach beyond the sum of the specializations of individual agents, and have a high

flexibility of response to the changing environmental situation. In marine applications, multi-agent systems can be used to direct ship traffic in congested ports [14], or inland waters [17]; during oil spill cleanup operations [18], the evacuation of passenger ships [3], or for the purpose of ship course keeping [15].

The agent platform is the agents' area of operation. It is an environment that enables mutual communication between agents. In the case of multi-agent systems in which the agents are physically dispersed, platforms using communication techniques based on computer networks are frequently used [6].

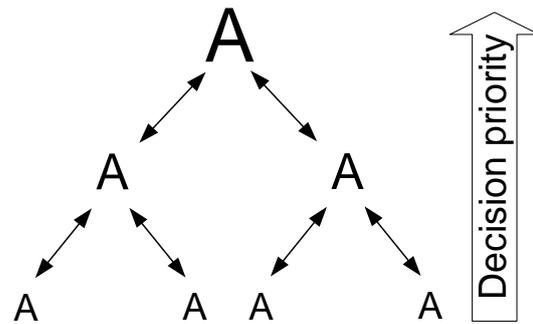


Figure 1. An example of a hierarchical structure of an agent system. The votes of the agents higher in the hierarchy have a higher weight.

The topology of connections between agents in a multi-agent system can assume various configurations [2]. Often employed structures of agent systems are hierarchical topologies (figure 1), in which decisions made by agents standing higher in the hierarchy, are binding on subordinate agents, and team topologies (figure 2), in which there are sets of closely cooperating agents (teams) that can communicate with other teams.

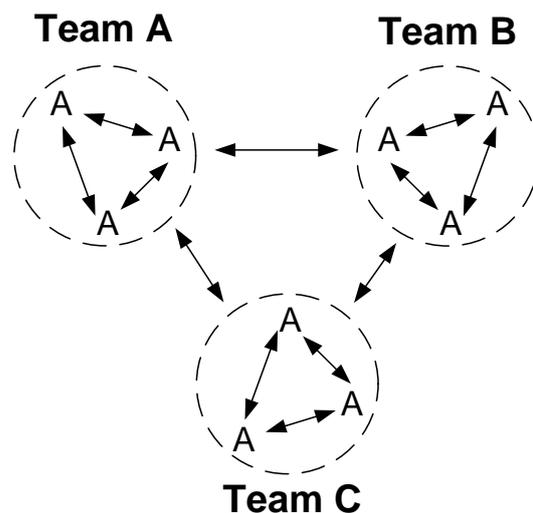


Figure 2. An example of an agent system structure using teams of closely cooperating agents.

There are also indirect topologies, such as holonic topology [2] which has a fractal structure, where each of its components - holons - has a similar internal structure as the environment in which the holon is located (figure 3). Each of the holons is an independent entity, however they may be nested

where the master holon contains several child holons within it. In the holonic topology, one of the agents inside his holon is appointed as an overriding agent that can communicate with the environment.

The holonic structure seems to be the correct topology to be used in the unmanned port tugboat formation control system, due to the way it corresponds to the classic manned tug structure shown in figure 4. At its lowest level there is the tug itself, which has its own crew (blue figures) led by the Captain (white figure). The work of the group of tugboats providing assistance is coordinated by the Pilot (yellow figure) on board of the assisted unit, while the supervision of all operations taking place in the waters controlled by the port is carried out by the Port Authority Office.

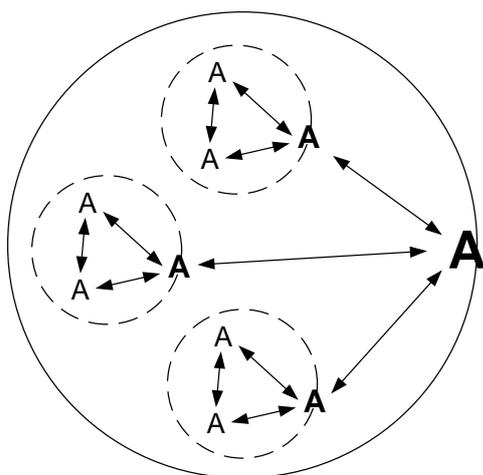


Figure 3. Holonic structure of an agent system, with overriding agents marked in boldface.

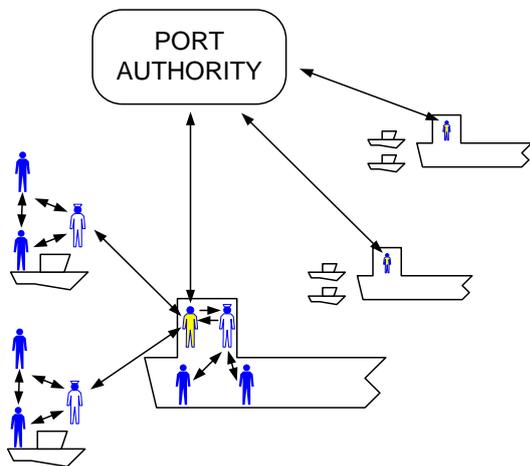


Figure 4. Command structure in a manned tug assistance operations. Sailors in blue, captains in white, pilots in yellow.

Based on the above command structure, figure 5 shows the architecture of the multi-agent formation control system for unmanned port tugboats. The equivalent of the crew of a single unmanned tug is a set of agents responsible for: the operation of the tug's propulsion mechanisms (P), the navigation situation around the tug (N), commanded by a designated commander agent (C), who will be able to communicate with the environment. All of the formation tugs report through their agents of

commanders C, under the counterpart of the Pilot – FP agent (Formation Pilot).

The fractal nature of a single tug's holonic command structure is reflected at a higher level where several tugs work together in a formation under the direction of a formation pilot. Going one step further, the control structure of several tug formations is again similar in nature, with several formations under the command of the Port Authority Office.

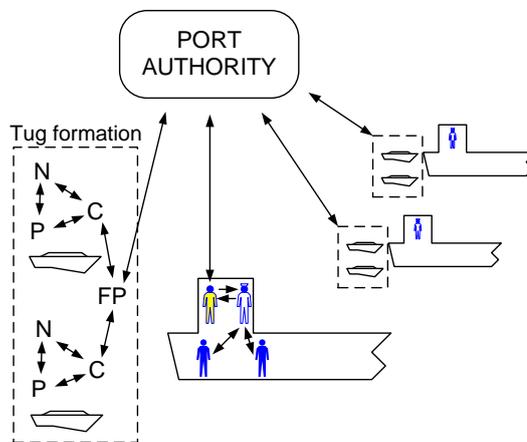


Figure 5. Command structure using the multi-agent formation control system of unmanned tugs. Command (C), navigation (N) and propulsion (P) agents report to the formation pilot (FP).

The task of the propulsion (P) agent is to control and supervise the tug's propulsion mechanisms. In the case of a conventional drive, the scope of tasks includes: starting and stopping the drive motors, monitoring the operating parameters of the drive system (temperatures, pressures, levels, etc.), handling emergency situations such as: exceeding the permissible ranges of operating parameters, failures disabling some of the mechanisms, unexpected leaks. In the case of alternative drives, e.g. hybrid or fully electric drives, there are also function of supervision over energy storage and its periodic charging.

The duties of the navigation (N) agent include: supervision of the navigational situation during the tug's movement and during the performance of precision maneuvers, determining the route of passage if it is necessary to travel longer distances, maintaining the position of the tug during the movement of the tug formation in a preset formation. The navigation agent on the leader tug has an additional task of determining formation anti-collision maneuvers, in the event of a collision threat with other ships. The navigation agent has at his disposal navigation devices available on board the tug, including RADAR + ARPA, AIS and GPS with satellite compass function. The precision nature of the maneuvers performed requires a high-resolution GPS receiver using RTK technology.

The agent C commanding the tugboat communicates with the environment, i.e. with the other tugboats, through their C agents and the FP formation pilot agent. The FP formation pilot provides him the tasks to be performed, e.g. the task of sailing the route from the current position to the area of the given ship as a leader, or as one of the other tugboats of the formation.

2.1 Possible tug formation application scenarios

The presented multi-agent system for controlling the formation of port tugboats allows performing of operations typical for tugs, such as assisting ships during maneuvers (entering and leaving the port, mooring and unmooring) or the precision movement of ships and other objects in port waters.

The possibility of equipping the tugs with additional specialized instruments, the formation control capabilities allow, among others:

- monitoring and patrolling of port areas - when equipping tugs with vision systems,
- carrying out waterway deicing actions - assuming that the hulls of the tugs have the appropriate ice class,
- carrying out inspections of quays - when tug boats are equipped with appropriate vision systems and sensors,
- automated monitoring of the depth of port basins and fairways - with the implementation of a connection of the agent system with the tug's onboard echo sounder,
- assisting in the cleanup of spills of petroleum substances and other pollutants - with the use of specialized equipment, e.g. scoops or by using the tugs to erect floating barriers.

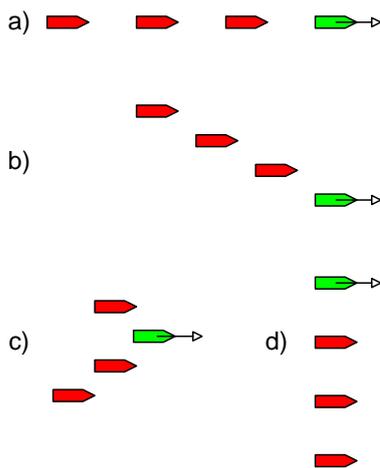


Figure 6. Formation shapes used for tug formation movements. a) line formation, b) echelon formation, c) V formation, d) column formation. Formation leader shown in green, other members in red. Formation follows the direction of leader (shown with arrow).

By using appropriate formation shapes, it is possible to perform various additional tasks during the movement of the tug formation. Possible formations are shown in figure 6. The possibility of monitoring the depth of waters in the port area, carried out during the movement of the tugboats, seems to be extremely interesting. For this task, the column formation (figure 6d) is particularly useful, in which the echo sounder of each tugboat can collect information about a slightly different fragment of the bottom than, for example, in the case of a line formation (figure 6a).

3 PRELIMINARY TESTING OF PORT TUGBOAT FORMATION MULTI-AGENT CONTROL SYSTEM

To verify the work of the algorithms of the multi-agent port tugboat formation control system, the proprietary navigation environment simulator was used. This simulator makes it possible to study the behavior of ships in a common simulated environment, and to visualize the test results in a 3D view and in the form of result files.

Using network technologies, each holon representing one tugboat, and containing three agents: command (C), navigation (N) and propulsion (P) was launched on one of the simulator's computers. The master computer controlling the simulation acted as the formation pilot (FP), giving orders to individual tugs.

The simulation was carried out, covering 3 successive stages of the tug formation job: creation of the formation from the group of tugs waiting at berths, the transition of the formation of tugs in the set formation shape from the rally point to the vicinity of the vessel waiting for assistance, and finally surrounding of the assisted vessel by the formation tugs.

The first stage of the job was to create a formation using the required number of tugs. In the case of the simulated maneuver, it was assumed that the formation will consist of 4 identical tugs. It was chosen to employ the linear formation, using one of the tugs as the leader of the formation. The leader was selected by checking which of the four available tugs was closest to the vessel waiting for assistance.

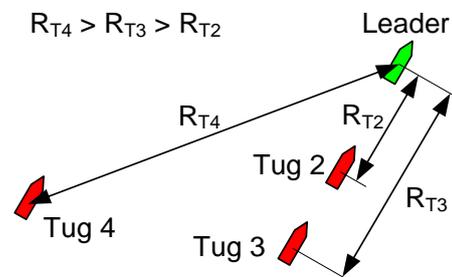


Figure 7. The principle of determining the order of tugs in a linear formation.

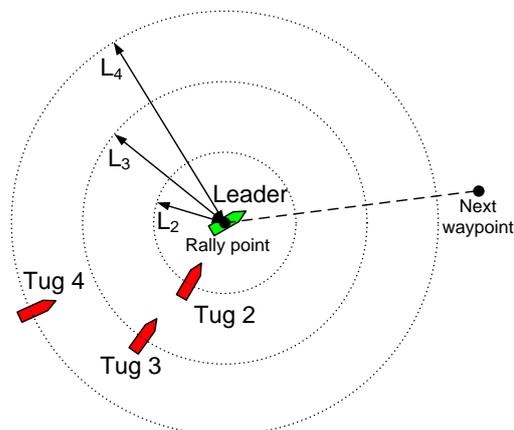


Figure 8. The point at which the assembly of a linear formation begins, when the leader reaches the rally point

and the rest of the formation members are within a set distance from it.

After selecting the leader, he takes over the task of laying out the route to the vicinity of the ship waiting for assistance. This task is the responsibility of his navigational agent (N), which defines the route as a list of waypoints, the first of which is in the vicinity of the available tugs and is also the rally point of the formation. The last of the waypoints lies in the vicinity of the ship waiting for assistance.

The formation leader sends information about the location of the rallying point to the other tugboats, at the same time engages his tug's propulsion and proceeds towards it at a speed of 80% of the speed defined as the formation movement speed V_f . The remaining tugs determine their distance R_t from the rally point as shown in figure 7, based on the inequality:

$$R_{T_{n+1}} > R_{T_n} \quad (1)$$

where:

R_{T_n} – distance of n-th tugboat from the rally point,
 $R_{T_{n+1}}$ – distance of (n+1)-th tugboat from the rally point.

Then, the process of forming a line formation is initiated, where each tug boat moves towards the rally point at such a speed, that when the leader reaches this point, each of the tugs is at a predetermined distance L_n defined by the equation:

$$L_n = (n-1) \cdot D_f \quad (2)$$

where:

L_n – Distance of n-th tugboat from the leader,
 n – number of the tug, n leader = 1,
 D_f – distance between neighboring tugboats in the line formation.

When the formation leader reaches the rally point, he starts to turn towards the next waypoint on the computed path. The remaining tugs, already at appropriate distances L_n from the assembly point, move towards it, simultaneously adjusting their speed to the same as leader's speed, as shown in figure 8. Then each of the tugs, reaching the assembly point, starts a turn, from then on following the tug preceding them, keeping a defined distance D_f . The assumed distance is selected in such a way that in the event of a failure on the preceding vessel, it would be possible to perform an avoidance maneuver. Another aspect taken into account when determining the value of D_f is the amount of hydrodynamic resistance that could affect the hull of the tug if it was moving in the water stream of the preceding vessel. When the last tug, after reaching the rally point, positions itself at a distance D_f from the penultimate tug, the line formation creation process is completed and the leader along with the other tugs accelerates to the set speed V_f .

After assembling the formation, it moves to the place of assistance operation. The journey is divided into phases of: leaving the port, and then the phase of straight passage towards the waiting ship, during both respecting the right of way. During the

movement phase, the tugboats maintain the speed V_f equal to 8.5 knots and the mutual distance D_f , therefore, for the purposes of anti-collision calculations, the formation length LF can be assumed according to the equation:

$$L_F = L_H + (k-1) \cdot D_f \quad (3)$$

where:

L_F – Total length of line formation [m],
 L_H – Length of one tugboat [m],
 k – Number of tugboats in the formation.

Table 1 shows the parameter values used for simulation in the navigation environment simulator. Both the number of tugs k and the distance between the tugs D_f have a direct impact on the operation of the formation, especially in congested waters, because for the purposes of performing anti-collision maneuvers, the whole formation is treated as single object.

Table 1 Parameters used during simulation.

Parameter	Symbol	Value
Number of tugboats in the formation	k	4
Tugboat length	L_H	25m
Mutual distance between tugboats	D_f	150m
Line formation length	L_F	475m

Figure 9 shows the data view from the navigation environment simulator, showing the trajectories of the simulated vessels: four tugs, one vessel waiting for assistance and one other vessel, placed against the map of the Port of Gdynia. The route of the other ship crossing from the southern part of the port to the north was deliberately synchronized with the route of the formation passage in order to create a collision situation with the tugs of the formation.

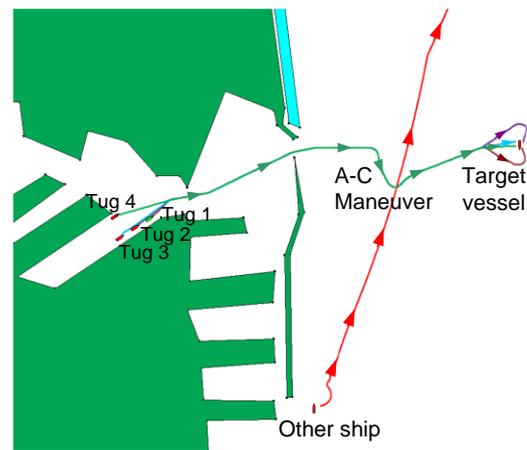


Figure 9. The paths of simulated vessels against the map of the Port of Gdynia. Visible assembly of the line formation, sailing in formation in the port area, performing an anti-collision maneuver after leaving the port heads, and reaching the destination next to the ship waiting at port road.

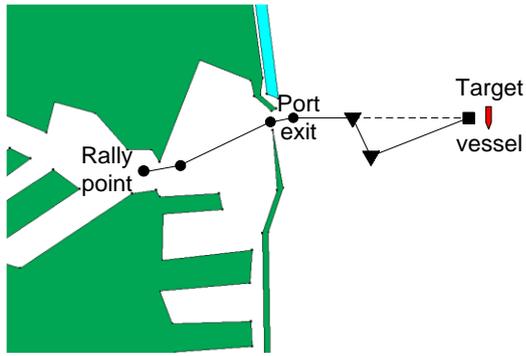


Figure 10. Stages of line formation assembly in the Port of Gdynia. Visible features: rally point, path in the port (circles), anti-collision maneuver waypoints (triangles), final waypoint (square), and unperturbed transition path (dashed line).

Figure 9 shows the reaction of the formation leader who, after identifying the threat of a collision with the other ship coming from starboard, made a starboard turn in order to pass behind the stern of the other ship. The determination of the anti-collision maneuver in accordance with COLREGs rules resulted in the modification of the formation transition route by adding additional waypoints, directing the formation to the route leading behind the other ship. Additional waypoints are shown in figure 10 as triangular markers, the actual route as a solid line, and the originally planned route as a dashed line.

The first additional waypoint lies on the original route from the port exit area to the point in the vicinity of the waiting vessel. This waypoint is created at the place where the leader of the tugboat formation starts the turn that marks the beginning of the anti-collision maneuver. Subsequent tugs reaching this point follow the leader's footsteps, also making a turn, heading to the second waypoint located in such a way that the entire formation could safely bypass the other ship, maintaining a linear formation at all times. After the tug boats have reached the second additional waypoint, the route continues to the original destination, located in the vicinity of the vessel awaiting assistance, marked with a square in Figure 10.

After individual tugs reach the destination point next to the vessel awaiting assistance, the line formation is gradually disbanded and the tugs are directed to their designated work stations around the vessel. The trajectories of the tugs at this stage of the formation's operation are shown in figure 11.

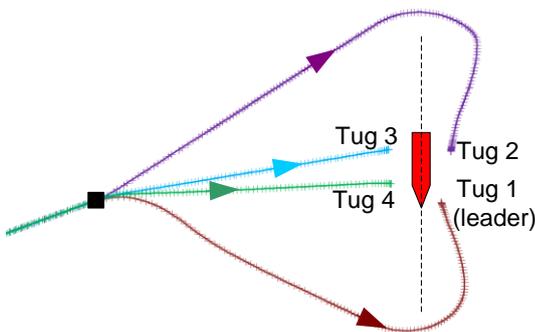


Figure 11. The phase of surrounding the target ship by the formation member tugs. Visible final formation waypoint marked with a square symbol, the silhouette of the ship

awaiting assistance, and the imaginary bow-stern line of the awaiting ship.

The arrangement and routes of the tugs around the target ship, shown in figure 11, required the tugs 1 and 2 to perform additional maneuvers in order to safely reach the opposite side of the ship than the direction from which the formation came. The maneuver consisted of avoiding the stern and the bow of the target vessel at a safe distance, and then going to assigned positions. Due to the favorable location of the designated work stations in relation to the bow-stern line of the target vessel (not needing to cross this line), the tugboats 3 and 4 could proceed to their positions immediately after reaching the final formation waypoint.

An additional condition considered while determining the placement of tugs around the assisted vessel was to assign the places furthest from the final formation waypoint to the first two tugs. This made it possible to remove the need to avoid the tugs already in the required positions if the assisted vessel was positioned exactly with its stern or bow towards the arrival direction of the tugs. Figure 12 shows a 3D view of the final mutual position of the tugs and the assisted vessel.

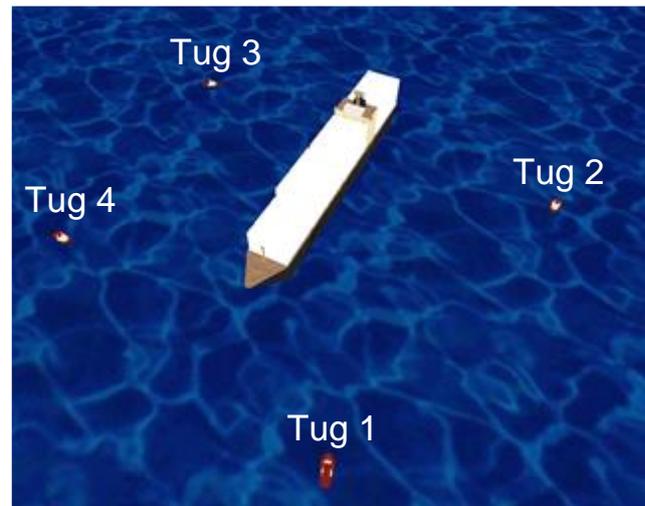


Figure 12. 3D view from the navigational simulator, showing the situation around the target vessel at the end of the target surrounding phase.

Figure 13 shows the plot of changes in wind speed during the simulation. Figure 14 presents the course and rudder angle of the leader tugboat, tug 1, during the course of the simulation. The leader tug's speed plot has been shown in the figure 15. The visible dips in the speed are associated with the turns while underway. The initial 80% setpoint of V_f speed is seen in the beginning of the plot. It is intended to allow the rest of the tugs to settle behind the leader as the formation was being assembled.

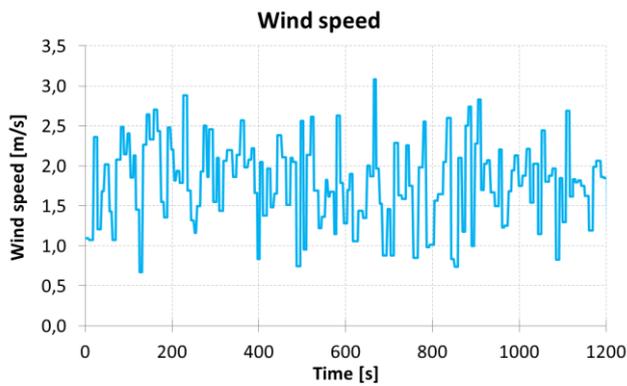


Figure 13. Wind speed plot in a simulated navigation environment simulator environment.



Figure 14. Plot of the course and the angle of the rudder of tug 1 - the leader of the formation.

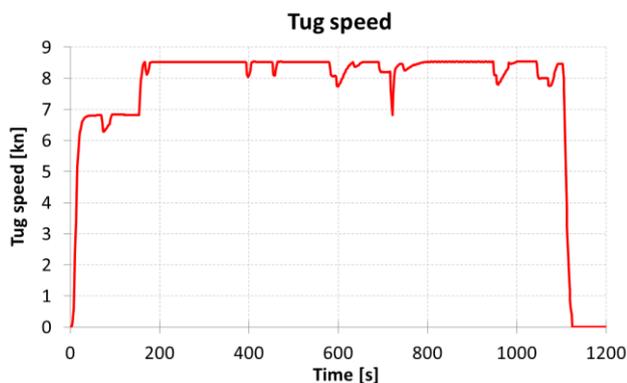


Figure 15. Speed plot of tug 1 - formation leader.

4 CONCLUSIONS

The article presents the concept of a multi-agent traffic control system for unmanned port tugboats. The trends in the development of modern ship traffic control systems are presented. A holonic agent connection structure is described, corresponding to the traditional manned tug command system. The cooperation of agents placed on individual tugs allows performing complex operations, such as creating specific formations, moving in formation along a specific route or a precise approach to the ship waiting for assistance.

The results of simulation studies confirm the possibility of controlling the formation of autonomous tugs with the use of an agent system, including the controlled assembly and disbanding of formations with a specific shape, and the possibility of commanding the passage of formation in a specific shape along a given route. It is possible that the example shown using a linear formation shape would have limited applicability in congested waters and with larger number of tugs. Further research could consist in testing other formations, e.g. multi-column formations or employing dynamically changing distance between tugs. Reducing the mutual distance would shorten the formation length, but would require a reduction in speed. A lower speed would extend the transition time, but could also facilitate the performance of anti-collision maneuvers.

Additionally, the possibility of reacting to unforeseen disturbances on the route in the form of other ships on a collision course with the formation was successfully tested. The sailing formation under the command of the leader made a controlled turn maneuver, in accordance with the rules of the right of way of the sea, in order to avoid the other vessel having the right of way. After performing the anti-collision maneuver, the formation correctly returned to the interrupted task. After reaching the vicinity of the target vessel, the formation orderly disbanded and the tugs took up positions around the vessel, ready for the assist. The use of a multi-agent system may contribute to an increase in the level of safety in a given body of water and a reduction of fuel, which translates into a reduction in exhaust emissions to the atmosphere.

ACKNOWLEDGEMENT

This research was funded by a research project of the Electrical Engineering Faculty, Gdynia Maritime University, Poland, WE/2021/PZ/08 titled "Optimization of low-emission surface vessel control processes."

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