Prototype of a remotely controlled model of a tugboat with an azimuth rudder and a hazard identification function

S N Stukonog
Admiral Ushakov Maritime State University, 93 Lenin Ave., Novorossiysk, 353924, Russian Federation
E-mail: 1010-95@list.ru

Abstract. The author's approach, based on the technology of control actions, is proposed for the interface display of the algorithm for the operation of an automatic tugboat with an azimuth rudder and a hazard assessment function. To define the object as presumably dangerous, the article used the formulas of the direct and inverse navigation problems. To compare the coordinates of the vessel and the perceived "hazard", one first needs to enter data, process the information, and display information that is understandable for the decision-maker. To eliminate the misunderstanding of this situation, the operation of the danger prevention algorithm was demonstrated using the visual basic programming language as an example. When constructing an algorithm for the safe movement of the vessel and the existing danger, each object, even a stand-alone one, has many coordinate points. Knowing the number of points of coordinates of the vessel and "danger", they were taken as n and m, respectively. The algorithm searches for the optimal point-object. The scheme of interaction of the components of the automatic tug azimuth model (ABA) is proposed. It is based on a Raspberry Pi single-board computer with an Arduino Mega board connected to it. A program has been written to control the ABA model using omnidirectional wheels to simulate maneuvering on water.

1. Introduction
The research laboratory "Automation of navigation" of the Federal State Budgetary Institution of Higher Education State Maritime University named after Admiral F. F. Ushakov effectively solves the problem of unmanned navigation in a modern port. The modern seaport works with the maximum use of innovations and discoveries in the technical and technological maritime perception of progressive and scientific achievements. In the development of the E-navigation concept, the problem of unmanned navigation is effectively solved, including in port activities. An important part of solving this problem was the mode of remote control of mobile objects. Pilotage and mooring of ships in the sea zone and on the approaches to it requires the introduction of modern technical solutions.

2. Statement of the problem
The location of the port's berths is often difficult to moor due to the geographic and hydrological factors in the location. Considering the problem of different dimensions of transport vessels, several situations arise that impede the timely delivery of goods. Slow development of infrastructure leads to delays in delivery and, consequently, to a loss of confidence in ports on the part of consignees.
The solution to this problem can be the optimization of technological and technical solutions for the transport infrastructure in the sea zones of ports through the introduction of the function of remote control of the ships of the port fleet.

An increase in the volume of cargo traffic is possible due to a decrease in the influence of the human factor and a decrease in the time spent on pilotage and mooring in the sea zone. To ensure the positive dynamics of this process, it will be necessary to study all the factors influencing the solution of this problem.

According to the mandatory regulations of the maritime administration for the port, for example, the port of Novorossiysk, several specialists should participate in the process of pilotage and mooring – a port state control inspector, a marine terminal dispatcher, a pilot, an operator of the port’s vessel traffic control system [1,2]. Currently, the technical means of the port infrastructure provide control over the movement of vessels in the water area of the seaport and on the approaches to it not in full. This is due to the insufficient accuracy of positioning a moving object in the working area of action for solving problems in full pilotage, and especially for mooring a vessel to the cargo terminal.

Further development of technological and technical solutions for non-experimental navigation can become the basis for the real implementation of remote control of ships in the seaport at present. It is proposed to use a group of specialized automatic tugs to implement remote control using multi-agent control systems using the “flock” method [4,5,6] based on the instrumental digital platform of the water basin administration. For this, tug models were created using omnidirectional wheels to simulate movement on the water.

Determine whether the object is presumably dangerous can be solved using the formulas of direct and inverse navigation problems [3, 4].

3. Materials and methods
We will propose and solve the problem of hazard identification. In navigation, we will use the method of transferring coordinates from one point to another. The direct navigation task is that the coordinates of the end point $B( X_B , X_B )$ are calculated from the known coordinates of the starting point $A( X_A , X_A )$, line $AB$, the directional angle of this line $\alpha_{AB}$ and its horizontal distance $S_{AB}$ (see Figure 1).

Figure 1. Direct navigation problem

The direct navigation problem has different solutions. For points located on a spheroid, the solution of this problem presents significant difficulties. For points on a plane, it is solved as follows. You will need point coordinates $A( X_A , X_A )$, horizontal distance $S_{AB}$ and $\alpha_{AB}$, to find $B( X_B , X_B )$ the point. From the figure we have:
\[ \Delta X = X_b - X_A \]
\[ \Delta Y = Y_b - Y_A , \]  
(1)

Differences between \( \Delta X \) and \( \Delta Y \) coordinates of points of the next and previous ones are called coordinate increments. They represent the projection of the \( AB \) segment onto the corresponding coordinate axes. Their values are found from the right-angled triangle \( ABC \):
\[ \Delta X = S_{AB} \cdot \cos(\alpha_{AB}) \]
\[ \Delta Y = S_{AB} \cdot \sin(\alpha_{AB}) , \]
(2)

In these formulas, \( S_{AB} \) is always a positive number, therefore, the signs of the increments of the coordinates \( \Delta X \) and \( \Delta Y \) depend on the signs \( \cos(\alpha_{AB}) \) and \( \sin(\alpha_{AB}) \). For different values of the angles, the signs \( \Delta X \) and \( \Delta Y \) are presented in Table 1.

Table 1. Signs of increments of coordinates \( \Delta X \) and \( \Delta Y \)

| Coordinate increments | 1(SV) | 2(YV) | 3(YZ) | 4(SZ) |
|-----------------------|-------|-------|-------|-------|
| \( \Delta X \)       | +     | -     | -     | +     |
| \( \Delta Y \)       | +     | +     | -     | -     |

Coordinate increments are calculated using the "rumba" by the formulas:
\[ \Delta X = S_{AB} \cdot \cos( r_{AB} ) \]
\[ \Delta Y = S_{AB} \cdot \sin( r_{AB} ) , \]
(3)

The signs for the increments are given depending on the name "rumba". Having calculated the increments of coordinates, we find the required coordinates of another point:
\[ X_b = X_A + \Delta X \]
\[ Y_A = Y_A + \Delta Y , \]
(4)

All this means that you can find the coordinates of any number of points according to the rule: the coordinates of the next point are equal to the coordinates of the previous point plus the corresponding increments.

The inverse navigation problem differs from the direct one in that already with the known coordinates of points \( A( X_A, X_A ) \) and \( B( X_B, X_B ) \) it is necessary to find the length \( S_{AB} \) and the direction of the line \( AB \): "bearing" \( r_{AB} \) and the directional angle \( \alpha_{AB} \) (see Figure 2).
First you need to find the increments of the coordinates:

\[
\Delta X = X_B - X_A, \quad \Delta Y = Y_B - Y_A,
\]

(5)

The value of the angle \( r_{AB} \) is determined from the ratio:

\[
\frac{\Delta Y}{\Delta X} = \tan(r_{AB}),
\]

(6)

By the signs of the increments of coordinates, the quarter in which the "bearing" is located, and its name are calculated. Using the relationship between directional angles and "bearings", we find \( \alpha_{AB} \).

For control, the distance \( S_{AB} \) is calculated twice using the formulas:

\[
S_{AB} = \frac{\Delta X}{\cos(\alpha_{AB})} = \frac{\Delta Y}{\sin(\alpha_{AB})} = \Delta X \cdot \sec(\alpha_{AB}) = \Delta Y \cdot \csc(\alpha_{AB})
\]

\[
S_{AB} = \frac{\Delta X}{\cos(r_{AB})} = \frac{\Delta Y}{\sin(r_{AB})} = \Delta X \cdot \sec(r_{AB}) = \Delta Y \cdot \csc(r_{AB})
\]

(7)

Distance \( S_{AB} \) is determined by the formula:

\[
S_{AB} = (\Delta X + \Delta Y)^{\frac{1}{2}}
\]

(8)

The relationship between directional angles and points, as well as the signs of the increment of coordinates are presented in Table 2.

The formulas for solving the given problem used in GIS have a simple structure. To compare the coordinates of the vessel and the "danger", you first need to enter data, process the information, and display information that is understandable for the decision-maker. To eliminate the misunderstanding of this situation, we will demonstrate the operation of the danger prevention algorithm using the visual basic programming language as an example. When constructing an algorithm regarding the safe movement of the vessel and the existing danger, we note that each object, even a stand-alone one, has many coordinate points.
Table 2. Signs of increments of coordinates $\Delta X$ and $\Delta Y$

| Coordinate increments | 1(SV) | 2(YV) | 3(YZ) | 4(SZ) |
|-----------------------|-------|-------|-------|-------|
| Dependence between directional angles and points | $r = \alpha$ | $180^\circ - \alpha$ | $\alpha - 180^\circ$ | $360^\circ - \alpha$ |
| $\Delta X$ | + | - | - | + |
| $\Delta Y$ | + | + | - | - |

Knowing the number of points of coordinates of the vessel and "danger", we will accept them as $n$ and $m$, respectively. Let's use the ImputBox function, by pressing the "ENTER COORDINATES OF VESSEL" button, the number of points of the vessel coordinates is entered.

Next, all the coordinates of the vessel are added; performing similar actions regarding the "danger", we get two filled arrays. An example of the user interface, as well as the arrays filled in it, are shown in Figure 3.

![Figure 3. Vessel coordinates and "danger"](image)

After pressing the "CHECK FOR DANGER" button, the general algorithm of hazard identification, provided that each point of the vessel and each point of the alleged danger are not equal, displays the entry "No Danger" on the screen and ends (see Figure 4).

In the opposite situation, that is, if the vessel and the "danger" have one common point, with the same coordinates, and after pressing the "CHECK FOR DANGER" button, the general algorithm for identifying the danger on the screen displays the entry "The Danger!" (see Figure 4) and goes out.

![Figure 4. Algorithm results](image)
The algorithm searches for the optimal point-object. Let’s designate each individual tug with an ABA agent. There is a division into ABA groups, which move in different directions and exchange information with each other.

Differential model for reaching consensus by \( n \) agents:

\[
x_i(t) = \sum_{j=1}^{n} a_{ij} (x_i(t) - x_j(t)),
\]

\( i = 1, \ldots, n \), \( x_i(t) \) are characteristics of agent \( i \), \( a_{ij} \geq 0 \) is the weight with which agent \( i \) takes into account the discrepancy with agent \( j \).

In matrix form (9) has the form:

\[
x(t) = -Lx(t),
\]

\[
x(t) = (x_1(t), \ldots, x_n(t))^T,
\]

\[
L = [l_{ij}]_{n \times n},
\]

\[
l_{ij}(t) = \begin{cases} 
-a_{ij}, & j \neq i, \\
esum_{k \neq j} a_{ik}, & j = i 
\end{cases},
\]

The multiplicity of 0 as an eigenvalue of \( L \) is equal to:
- the number of outgoing trees in the maximum outgoing forest of the communications digraph;
- the number of strong (which do not include arcs from the outside) components of the digraph.

Let’s install this program into the Raspberry Pi single-board computer. To the Raspberry Pi itself, to control the motors, we connect the Arduino Mega via a USB-MicroUSB cable. We will also combine the remaining components in the wiring diagram (see Figure 5): motors, drivers, converter \( 12V \to 5V \) and power supply. Remote control is carried out using the Wi-Fi module built into the Raspberry Pi.

\[\text{Figure 5. Interaction diagram of the tug model components}\]
The performance and quality of architectural elements at the design stage are assessed at five levels:
- level of a physical implementation of interfaces. For example, connector compatibility: that an RJ-45 connector cannot be physically connected to a MOLEX connector.
- level of the power supply interfaces. For example, both checking the voltages and currents transmitted through a specific connection of the system elements, and the sufficiency of power supply for all elements of the system.
- protocol layer, includes the physical layer of the OSI network model. For example, detecting that the sensor interface, implemented using Ethernet technology, transmits an optical signal, and the expansion board, also implemented using Ethernet technology, to which they are trying to connect it, only receives signals in electromagnetic form.
- information layer, which includes the rest of the layers of the OSI network model. Answers the question: can an information message sent by one device be received and "understood" by an adjacent device connected via a hardware interface.
- level of throughput. Is there enough bandwidth of the data transmission channel of the receiving device to receive and not lose data from all transmitting devices connected to it?

The modern development of approaches to the development of control systems, which must be applied to the design of control systems and the design of unmanned ships, are:
- end-to-end design - a process that combines the interdisciplinary preparation of data on the control system (including the system integration of all components of an unmanned vessel, a description of the hardware architecture and characteristics of each unit, a model for managing data flows in the information system, program codes and algorithms for each element);
- digital twin of the control system, which is the result of end-to-end design and includes a description within a single digital model of all components of the control system, which allows automatic testing of all modes of its operation by the method of simulation modeling of the performance of typical tasks of an unmanned vessel. Figure 6 shows the main window of the interface prototype editor.

![Figure 6. Main window of the interface prototype editor](image-url)

### 4. Results
The research resulted in an interface prototype of a remotely controlled ship model. An algorithm for a method for identifying hazards based on navigation tasks has been obtained, thanks to which it is
possible to obtain data on the hazard, as well as prevent a collision. A model of the azimuth tug of the automaton was created according to the scheme of interactions of its components (see Figure 5). After determining the danger of collision, it will be necessary to form a list of goals and a system of performance criteria for assessing the problem and its subsequent resolution.

5. Conclusion
Hazard identification will assist in performing autonomous solutions to basic control processes such as departures, reversals, trajectory, etc. All this is since in any maneuver there are points of coordinates of the vessel and any object that should never intersect. In this case, an example of the identification of a stationary hazard is given. Further research will focus on the ability to identify a dynamic hazard.

The research laboratory "Automation of navigation" of the Federal State Budgetary Institution of Higher Education State Maritime University named after Admiral F. F. Ushakov continues work on the implementation of modern technical solutions for unmanned navigation systems in the modern port. The results of modeling the control system of the ABA group can form the basis for the creation of an autonomous navigation system in the port water area for unmanned navigation.

References
[1] Zelenkov G, Ustinov V and Lopatin M 2019 Problems of creating unmanned harbor tugs and conceptual solutions Marine and intelligent technologies 4 111-119
[2] Senchenko V and Boran-Keshishyan A 2015 Automated navigation complex (Novorossiysk: Admiral Ushakov Maritime University)
[3] Astrein V 2017 Methodology for the analysis and synthesis of complex active technical systems and its implementation in the navigation safety system (Krasnodar: Kuban State Technological University)
[4] Astrein V 2014 Fundamentals of Intelligent Ship Collision Avoidance Systems: (Lambert Academic Publishing, Saarbrucken)
[5] Senchenko V 2015 Technical means for ensuring high-precision ship guidance in cramped conditions with limited visibility Fertoing (St. Petersburg)
[6] Studenikin D 2007 Equations of motion of a large-tonnage vessel in autonomous navigation mode when performing mooring operations Collection of scientific papers Admiral Ushakov Maritime University 12, 57-59 (Novorossiysk: Admiral Ushakov Maritime University) p.