A method for constructing a small-sized unmanned vessel and its automatic wiring

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Abstract. In the article, the author proposes a method for constructing a small-sized unmanned vessel with a communication system with its operator, receiving data on control actions for the purpose of navigating the vessel in automatic and manual modes along a given trajectory, transmitting the necessary kinematic and navigation data for identifying mathematical models of the movement of sea-surface vessels, setting up the automatic steering in real time, as well as entering proofreading into sensor readings via the data transmission protocol via TCP-IP stack on public Wi-Fi radio frequencies. The method of constructing a small-sized unmanned vessel and its automatic wiring allows us to work out the principles of creating full-scale, fully functional unmanned cargo, passenger and military vessels. It allows you to work out the principles of creating automatic control systems for a given trajectory for fully functional crewed and unmanned vessels for various purposes. This method can be used to study the principles of construction and identification of mathematical models of vessel movement. The method proposed in the article was implemented at the competition "Talent and Success" of the "Sirius" educational center, where it successfully won the championship in the category "Marine Intelligence".

1. Introduction

Modern technical means of vessel control, navigation, radio communication and navigation automation are in the process of continuous improvement. Despite significant progress in the accuracy of determining the coordinates of the vessel's position and its kinematic parameters, the processes of controlling the movement of the vessel, including automatic, require further research and improvement. The concept of e-Navigation, declared by IMO, requires research of intelligent systems for automatic control of the vessel's movement and indication of the navigation parameters of the vessel, its surrounding environment and objects, aimed at gradually strengthening the intellectual support for the actions of a human operator in the process of navigation wiring [1]. In this regard, a small-sized experimental vessel was created, equipped with a communication system, receiving control data, collecting and transmitting navigation and kinematic data of the vessel in order to develop its mathematical models of movement, based on an Arduino microcontroller, capable of solving navigation problems of automatic trajectory wiring.
2. Method of constructing a small-sized unmanned vessel

The schematic diagram of the vessel construction is shown in Figure 1, which includes the main technical elements:

- **The Arduino ATmega2560** microcontroller is designed for controlling the operation of sensors and the communication module, collecting data from sensors, processing data from sensors and transmitting them to the communication module, receiving data on control actions through the communication module, transmitting data on control actions to MotorShield;
- **The ESP8266 Wi-Fi transceiver** is designed for remote data exchange between the operator and the ship and operates in the network server mode, in turn, the ship operator module operates as a client. It provides access to clients through authentication in the network;
- **MotorShield L298P**, is designed to control the main propulsion motors and servos of the rudder pen of the vessel. It protects the electronics of the microprocessor from the flow of large currents through its power supply nodes. It is able to control simultaneously four electric motors and two servos, which makes it possible to create a vessel with two propulsion and steering systems and two maneuvering devices with the help of one device;
- **The JGA25-370 electric motor with a 1000 rpm gearbox** is designed to supply torque to the vessel's propeller shaft. With a four-bladed propeller diameter of 4.5 centimeters, it allows the vessel to develop a speed of 1 m/s;
- **The MG996R servo** is designed to supply torque to the rudder pen baller and provides a rudder pen stroke of up to 35 degrees on each side of the vessel;
- **Lithium-polymer batteries** to provide power to the system. The 7.4 volt battery is designed to power the microcontroller, sensors, and steering servo, while the 11.1 volt battery is designed to power the electric motor via MotorShield. The vessel is additionally provided with a device for measuring the remaining battery charge;
- **The screw shaft speed sensor RPMmeter F249**, is designed to measure the number of revolutions of the screw shaft per minute;

![Figure 1. Schematic diagram of the vessel](image-url)
• Gyroscopic, inertial, magnetic sensor **BNO080**, is designed to measure the longitudinal and angular accelerations along the 3 coordinate axes and the components of the Earth's magnetic field along the coordinate axes, it generates the values of the angular velocities of the vessel along the coordinate axes, the values of the real coefficients of the quaternion of the vessel's orientation;

• The **GPSGY-NEO6MV2** sensor is designed to receive the current geographical coordinates of the vessel's location, the HDOP indicator, the number of visible navigation satellites, the course and speed of the vessel relative to the ground.

3. Method for automatically navigating a vessel along a given trajectory

In general, the law of control of a built small-sized unmanned vessel is proposed to be considered in the form of a hierarchically organized PID controller along the course and PI controller along the trajectory:

\[
\begin{align*}
\delta_p &= a_{pr} (K_p + \Delta K_x - K) + a_m \int (K_p + \Delta K_x - K) dt + a_d \omega; \\
\Delta K_x &= b_{pr} \chi + b_m \int \chi dt,
\end{align*}
\]

where \(K, K_p\) are the courses executed and set; \(\Delta K_x\) is the correction to the set course for deviation from the trajectory; \(a_{pr}, a_m, a_d, b_{pr}, b_m\) are the coefficients of the controller; \(\delta_p\) is the the set angle of the rudder tip; \(\omega, \chi\) are the angular velocity and deviation from the trajectory.

The hierarchical organization of the controller consists in the fact that the correction to a given course for deviation from the trajectory, produced by the PI-controller along the trajectory, is the argument of the PID-controller along the course, which produces a control effect on the rudder pen of the vessel. Due to the usually slow change in the transverse deviation of the vessel from the trajectory, the differential channel of the controller along the trajectory is assumed to have little effect on the quality of control and is excluded from the automatic steering [2].

The current course of the vessel relative to the ground, obtained from the GPS sensor, is selected as the data that are the arguments of the automatic steering, the current angular velocity is obtained by integrating the angular acceleration obtained from the gyroscopic sensor.

![Figure 2. Maneuverable elements](image-url)
The deviations of the vessel from the trajectory according to Figure 2 are from the triangles $OWP_i WP_i$ and $OWP_i WP_{i+1}$ according to the Heron formula for Euclidean geometry, which is acceptable, since the deviations usually do not exceed ten meters:

$$S = \sqrt{p(p-a)(p-b)(p-c)}; \quad p = \frac{1}{2}(a+b+c); \quad \chi = \frac{2S}{a},$$

(2)

where $a, b, c$ are the sides of the triangles $OWP_i WP_i$ and $OWP_i WP_{i+1}$, and side $a$ corresponds to the bases $WP_i WP_i$ and $WP_i WP_{i+1}$ of these triangles, respectively.

The lengths of the sides of the $OWP_i WP_i$ and $OWP_i WP_{i+1}$ triangles are calculated as the lengths of the orthodromies between their vertices using a formula that provides maximum accuracy for computer floating-point operations [3]:

$$\Delta \sigma = 2 \arcsin \left( \sin \left( \frac{\phi_2 - \phi_1}{2} \right) \cos \phi_1 \cos \phi_2 \sin \left( \frac{\lambda_2 - \lambda_1}{2} \right) \right),$$

(3)

where $\Delta \sigma$ is the distance in DBK between the vertices of the triangles; $\phi_i, \lambda_i$ are the latitude and longitude points, the location of the vessel.

The given courses between waypoints are calculated using the following formulas:

$$K_p = \arctan \left( \Delta \lambda \ln \left( \frac{1 + e \sin \phi_2}{1 - e \sin \phi_2} \right) - \ln \left( \frac{1 + e \sin \phi_1}{1 - e \sin \phi_1} \right) \right)^{-1};$$

(4)

$$\Delta \lambda = \begin{cases} \lambda_2 - \lambda_1, & |\lambda_2 - \lambda_1| \leq \pi; \\ 2\pi + \lambda_2 - \lambda_1, & \lambda_2 - \lambda_1 < -\pi; \\ \lambda_2 - \lambda_1 - 2\pi, & \lambda_2 - \lambda_1 > \pi; \end{cases}$$

where $a, b$ are the lengths of the major and minor semimajor axes of the earth ellipsoid.

The orientation of the vessel in space is determined by the quaternion $Q$, obtained from the gyroscopic sensor installed on the vessel in the form of its real coefficients. The conversion of the quaternion to Euler angles to determine the yaw, roll, and trim angles is performed using the formulas:

$$\begin{align*}
Q &= q_0 + q_1 i + q_2 j + q_3 k; \\
\gamma &= \arctg \left( \frac{-2q_1 q_3 - 2q_0 q_2}{2q_1^2 + 2q_3^2 - 1} \right); \\
\theta &= \arcsin(2q_1 q_3 + 2q_0 q_2) k; \\
\psi &= \arctg \left( \frac{-2q_2 q_3 - 2q_0 q_1}{2q_1^2 + 2q_3^2 - 1} \right),
\end{align*}$$

(5)

where $q_0, q_1, q_2, q_3$ are the real coefficients of the quaternion; $i, j, k$ are the imaginary units of the quaternion; $\gamma, \theta, \psi$ are the yaw, trim, and roll angles.

The key moment of control over a given trajectory is the time of the start of the maneuver to transfer control from the current shoulder of the trajectory to the next one when setting the trajectory as a broken line [4]. On the basis of Table 2.21 MT-2000 for this vessel, the dependence was determined empirically, which showed good results in maneuvering tests.
\[ \chi_{i+1} \leq e^{\Delta K/36 - 2.3}, \]  

where \( \Delta K \) is the angle of rotation; \( X_{i+1} \) is the deviation from the next shoulder of the trajectory; \( i \) is the index of the current shoulder of the trajectory.

Thus, when the vessel reaches a deviation from the next shoulder of the trajectory (6), control begins on the next shoulder of the trajectory, regardless of the current deviation from the course or the current shoulder of the trajectory, Figure 2. Another circumstance that determines the expediency of switching to control over the next shoulder of the trajectory is the fulfillment of the condition when the deviation from the current shoulder of the trajectory is greater than the deviation from the next shoulder of the trajectory:

\[ \chi_i > \chi_{i+1}, \]  

This will ensure an automatic transition to the next shoulder of the trajectory, even when condition (5) is unattainable due to strong deviations from the trajectory and it is not advisable to go back to the current shoulder of the trajectory. Figure 2 shows that the vessel, according to conditions (6), (7), when leaving the shaded area, begins to be controlled along the next shoulder of the trajectory.

Figure 3. Automatic navigation of the vessel along a given trajectory

Figure 3 shows the automatic wiring of the vessel under the control of the automatic steering (1) along a given trajectory from point 1 to point 2. As can be seen from Figure 3, the proposed controller (1) successfully coped with the given trajectory, despite the significant (up to 108 degrees) rotation angles. Minor unsystematic over-regulation and maneuver lag are observed, which indicates local disturbances of the water environment at the turning points, which are not taken into account by the
regulator [5]. There is a need for further experiments to adjust the coefficients of the controller (1), to adapt the filter to the moving average depending on the nature of the movement, to equip the vessel with a maneuvering device for dynamically holding the position when reaching the final or intermediate point of the trajectory, to refine the mathematical model of the vessel's movement.

4. Conclusion
The proposed method of constructing a small-sized unmanned vessel and its automatic wiring allows us to work out the principles of creating full-scale, fully functional unmanned cargo, passenger and military vessels. It allows you to work out the principles of creating automatic control systems for a given trajectory for fully functional crewed and unmanned vessels for various purposes. The method can be used to study the principles of construction and identification of mathematical models of vessel movement. The proposed method was implemented at the competition "Talent and Success" of the "Sirius" educational center, where it won the championship in the category "Marine Intelligence".

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