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Statement of the Problem of Control of an Autonomous Surface Vessel for Inland Waterways

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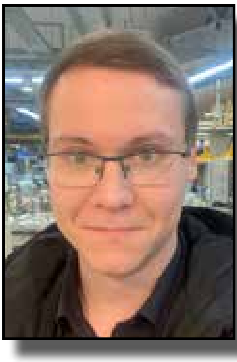

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ABSTRACT

Development of autonomous (uncrewed) surface vessels for commercial, industrial, and auxiliary fleet is currently one of the most rapidly advancing transport technologies. The key issue of its implementation is creation of an integrated control system (ICS) of safe navigation of uncrewed surface vehicles (USV) in automatic mode along the route. Then, it is necessary to keep in mind the features of maritime navigation and inland navigation.

A performed analytical review of basic heading and speed control algorithms allowed revealing the main problems referring to development of an integrated control system for an USV. The statement of the control problem is followed by enlisting directions for further research.

Keywords: *water transport, automated control system, uncrewed navigation, navigation.*

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INTRODUCTION

Currently, development of uncrewed surface vessels (USV) for commercial marine industry, industrial and auxiliary fleets is in the focus of attention of leading maritime powers since it will improve safety and efficiency of navigation. The key issue of its implementation is creation of an integrated control system (ICS) of safe navigation of uncrewed surface vehicles (USV) in automatic mode along the route.

Adaptive motion control systems (AMCS) are an advanced class of automated ship control systems. As noted by G. E. Ostretsov and L. M. Klyachko, the authors of several works (including [1; 2]) to which we will refer repeatedly, AMCS can evaluate motion parameters and change control coefficients depending on operating conditions. However, even modern AMCS are used mainly on the open sea, where there are no constraints on manoeuvring and deviating from the course. The problem of automatically controlling a vessel in river waters and when diverging from other vessels under the conditions of waves, currents and wind has not yet been completely solved.

The objective of the study is to formulate basic tasks related to increasing the degree of control automation for development of uncrewed vessels, including those operating on inland waterways, and to determine further directions for research in this area.

RESULTS

Analytical Review of Control Algorithms

Automatic navigation of a vessel from one point to another is a complex control problem which has been stated earlier (for example: [3]) but has now acquired high relevance regarding development of autonomous navigation (for example: [4–7]).

A widely known approach of simplifying this problem is to divide it into two main tasks, which can be considered separately:

– Control of the trajectory and course of the vessel, not considering changes in speed.

– Speed control, which is achieved by changing the operating mode of the main propulsion system.

Proceeding with the described separation, it is possible to reduce the order of the considered system of equations of motion and simplify the procedure for synthesising algorithms.

Course control algorithms

The first autopilot systems operated based on proportional (P) control laws, the formulas of which are presented, for example, in the above-mentioned work [1]. At the same time, as noted in it, the linear control P-law did not ensure stability of a closed-loop system of automatic course control on medium-tonnage vessels, and the ship could not maintain a given course without yaw with an angle amplitude of up to two degrees. The use of such autopilot systems on large-tonnage vessels was impossible [1].

In this regard, autosteering systems with a proportional-derivative (PD) control law were developed. These systems proved to be more effective when sea is heavy and were equipped with angular velocity sensors, as well as reliable analogue elements. The control law still used the gain k, but also used an additional differential term that allowed more precise control of the ship's heading. The formula for such a control law is as follows [2]:

$$\frac{d\delta}{dt} = k_1 \bullet \Delta\varphi + k_2 \bullet \frac{d\varphi}{dt}.$$

Autopilot developments had the ultimate goal of stabilising the ship's course. For this purpose, an autopilot was developed that uses proportional-integral-derivative control laws (PID), the formulation of which is also contained in [1].

When the steering gear is manually controlled, the rudder is put over no more than 100 times per hour, but in rough seas this number can reach 1400 per hour, which is extremely undesirable.

To reduce overload and cut off high-frequency components of sea waves, a proportional derivative filtered (PDF) control law was developed, which cuts off high-frequency components of sea waves [1; 2].

Then an adaptive motion control system (AMCS) was created with a unit for estimating measured parameters and a «unit for adjusting control coefficients when operating conditions change. Such self-adjusting automatic control systems with autonomous adaptive adjustment of parameters or using information about navigation conditions to rearrange the control law, as well as with a unit for predicting the phase state of the vessel and a diagnostics subsystem, began to be produced all over the world» [1; 2].

The authors of [2], with reference to foreign sources of seaworthiness test results, indicate that «adjusting the gear ratio k_1 reduces fuel consumption by 2 %, and the use of estimates in formation of control laws reduces voyage time by 2 %» [2].

Route-following control

In general, the route of a vessel's movement consists of a sequence of straight and curved segments. The requirement for moving through each segment is usually established by the amount of permissible lateral deviation from it. It may be necessary to adjust the selected route, for example, to diverge from other vessels or due to unfavourable conditions in the navigation area.

Automatic vessel motion control is especially widely used in open water, where active manoeuvring is not required. However, even with automatic control, there is a need to ensure that the vessel reaches the specified points on the route, especially in the presence of external disturbances such as wind and waves, and is not guaranteed by existing automatic control systems even when using the PID control law (see, for example, [1]).

With emergence of satellite navigation systems, it became possible to determine the coordinates of a vessel at any time, and, consequently, to automate the movement of a vessel along a route consisting of a set of points with known coordinates.

Technologies for using AMCSs with a satellite navigation receiver are discussed in detail in several sources [1; 2; 8].

In view of the tasks under consideration and the experience of AMCS operation, one can conclude that the control system should automatically adjust the coefficients when sailing at low speeds and depths, changing the load, as well as in strong waves.

Variants of trajectory tracking control algorithms

Trajectory tracking control has found wide application in various fields, including robotics [9; 10], aviation, including unmanned [11], this issue was also analysed in relation to maritime transport and in several other works, in addition to the above mentioned [12].

Navigation algorithms constitute an implementation of a dual task of determining one's own position in space, i. e. determination at each current moment of time of the spatial angular position (orientation algorithms) and determination at each current moment of time of projections of speed and coordinates (reckoning of speed and coordinates) on the axis of the inertial coordinate system.

Control algorithms are used to calculate such control commands to arrive at a point of interest, that is, to develop trajectories in which the relative coordinates of the vehicle and the end point of its movement would simultaneously turn to zero at some terminal (final) moment in time.

Stabilisation algorithms serve to convert control commands calculated during guidance into signals that cause steering wheel or rudder turns or changes in the position of other controls, that is, in other words, so that the rudder at each moment in time deflects so that at the final moment in time the ship reaches the end point (e. g.: [13–15]).

Transverse acceleration guidance method

A motion trajectory is such a continuous curve, at each point of which the vehicle's speed vector is directed tangentially to it.

To change the trajectory, that is, change the direction of movement of the vehicle, it is necessary to rotate the speed vector. It is possible to rotate the speed vector in different ways.

For example, it is possible to create an increment of the speed vector in the transverse direction, that is, in other words, to create an acceleration orthogonal to the speed vector.

Instantaneous zero miss and proportional guidance methods are also used (mainly for aircraft).

A significant difficulty in implementing the heading angle PID-controller is the presence of noise in the measured heading angle signal due to sea surface roughness. In addition, in the course angle regulator it is also necessary to know the yaw rate; if its value is obtained by simply differentiating the heading angle signal, then the noisiness of the signal will increase.

If the instantaneous zero miss control method is applied to vessels, the total acceleration vector will have one zero component. Controlling a vessel by lateral acceleration is difficult to implement in practice due to the specific features of the controls, but it is possible to convert the acceleration into the corresponding angular yaw rate and control it through this parameter.

Control algorithms in the speed channel

The issues of building vessel speed control algorithms have not been considered in sufficient detail in the domestic literature. Traditionally, the control algorithm for a generalised parameter, the traction equivalent, is built based on a PID or PI speed controller. The speed channel does not appear to be difficult to be controlled.

In view of this, it is advisable to use traction equivalent control algorithms.

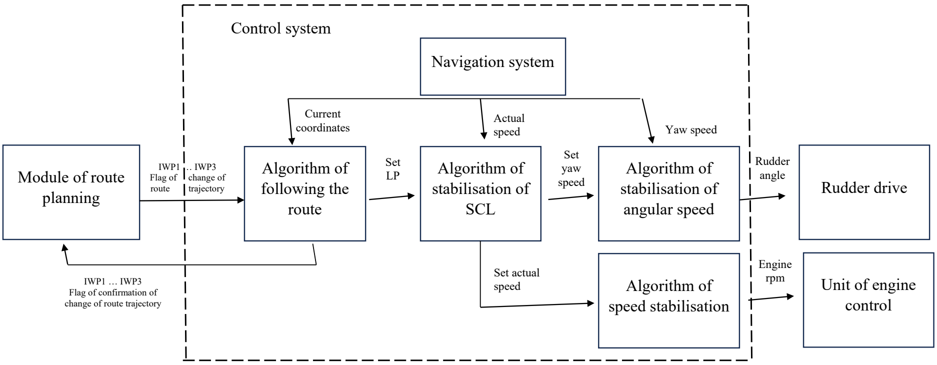
Let the current speed of the vessel V and the set speed V_g be known. Then it is possible to get a set change in speed $\dot{V}_g = R(p)(V_g - V)$, where $R(p)$ is some control operator, $\dot{V}_{gmin} \le \dot{V}_g \le \dot{V}_{gmax}$.

Then a traction equivalent control signal is generated:

$$E_{tg} = K_1 \dot{V}_g + \frac{K_2}{p}\left(\dot{V}_g - \dot{V}\right),$$

$$E_t^{min} \le E_{tg} \le E_t^{max},$$

where E_t^{min} and E_t^{max} correspond to the «low speed» and «full speed» modes. The traction equivalent is



Pic. 1. A schematic diagram of the control algorithm operation [performed by the authors].

used to obtain a linear system. Next, it needs to be converted into real traction. Coefficients K_1 and K_2 can be functions of actual speed or other parameters.

There are several possible ways to increase stability:

– introduction of a «heavy» filter into control algorithms for the control action coming to the drive;

– use of alternating on/off switching of the drive, similar to PWM control (pulse-width modulation).

Both methods will reduce system performance and their necessity must be assessed before implementation.

The given basic algorithm for controlling the speed of a vessel can be used as a first approximation when synthesising control algorithms in the speed channel.

Setting Task of Trajectory Control

The algorithm must ensure the generation of control commands to actuating units for following the route specified by three intermediate waypoints (IWP). The consequence of IWP is developed in accordance with the route and considering navigation rules and environment. Algorithm should provide for minimum vessel's deviation from the legs of route linking IWP.

The tasks are as follows:

– Control of rudders, engines and thruster.

– Control of dimensionless yaw rate $\overline{\omega} = \frac{\omega L}{V} = R^{-1}$.

– Stabilisation of a set course line (SCL).

– Switching between SCL with lateral lead turn (LLT).

At each cycle of operation, the control system receives the following parameters as input:

– Vectors of coordinates of three IWP x1, x2 and x3, forming two given course lines (x1, x2) and (x2, x3) (from the route planning module).

– Vector of vessel coordinates x [m] (from the measurement system); yaw rate ω_y [rad/s]; actual speed vector V_k [m/s] (from the navigation system).

The output parameters are:

– Specified rudder position δ_s [deg] (to the rudder drive).

– Signals specifying speed of thruster n [r/s] (to the thruster control unit, in the mooring mode).

– Signals specifying engine speed n [r/s] (to the electronic engine control unit).

A schematic diagram of the route-following algorithm is shown in Pic. 1. The algorithm receives from the route planning module of the control system triplets of intermediate waypoints and the ext_reset flag, which signals the route-following algorithm about a new triple of IWP. In turn, the algorithm for following the route transmits the PL_flag of confirmation to the route planning module when moving to the second line of the route.

Directions of Further Research

The directions of further research include:

– Development of adaptive mathematical model of the dynamics of ship's motion for adjustment of control system for different vessels and different load.

– Implementation of control modes for low speed for mooring using thrusters, also for dynamic positioning and manoeuvring in the port.

– Course and speed simultaneous control to increase the accuracy of solution of control problem.

– Evaluation of speed and direction using Doppler lag relative to seabed to compensate for noise regarding speed and course.

– Evaluation of current and wind speed and direction using weather station sensors to preventively compensate for disturbance.

– Application of external quality control controllers to detect failures, optimise resources of control drives, and raise the stability of solutions.

– Common optimisation of features of control drives regarding resources and of control system regarding accuracy of following the route (number of drive activation).

CONCLUSION

An analytical review of the methods and algorithms of vessel's speed and course control was performed that also allowed highlighting key constraints on existing solutions.

Based on analytical review, the statement of the problem of trajectory tracking control of autonomous ship was formulated.

Directions of further research were identified that include development of adaptive control system that could be operated on different vessels, navigation at lower speed, simultaneous control of speed and course, application of a priori data from sensors, system stability, filtering and correcting the signals, failure recognition.

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