Vessel Dynamic Positioning System Mathematical Model

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Abstract: - This study aims to examine two potential approaches for addressing the challenge of synthesizing control laws in the Dynamic Positioning (DP) system. Both approaches pertain to the same ship model but are rooted in distinct ideologies concerning how to account for the influence of external disturbances on a closed system. The findings of this investigation could offer valuable insights for enhancing DP systems and formulating more efficient management strategies in maritime conditions. The research delves into the structure and principles of the DP system as a sophisticated control complex, identifying associated challenges in its application. Despite numerous implemented projects and considerable developer efforts, sustaining a ship in a specified position during rough seas remains a formidable task, partly due to the ship's lack of energy armament. Exploration in the realm of regulatory system development has yet to yield the anticipated results. The present study constructs a mathematical model depicting the dynamics of a ship during positioning, considering two versions of automatic control laws aimed at stabilizing the ship's position. The second model demonstrates superior efficiency in the control system, surpassing the first by at least 14%. A comparative analysis of two control system options with filtering properties in dynamic positioning mode for the vessel was conducted. For better results, it is recommended to implement filtering on the relevant data source before this procedure on a specific data consumer. This preliminary testing helps to remove duplicate and inaccurate data, reducing the load on the data link. Final filtering should be performed on high-performance systems. In summary, the originality and novelty of this article stem from its comparative analysis of control laws, exploration of DP system dynamics, acknowledgment of existing challenges, and practical recommendations for data filtering in dynamic positioning. The study brings a tangible contribution to the field, paving the way for advancements in the development of DP systems management and control methods.

Key-Words: - dynamic positioning system, offshore vessel, automatic control, modeling, power system, Kalman filter, DPS operation control, thrusters.

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1 Introduction

In today's context, maritime transport plays a crucial role in the global transportation system, and the offshore fleet is undergoing rapid development. Depending on their type and specialization, offshore vessels are equipped with specific equipment not generally found on conventional merchant vessels.

The nature of work on offshore vessels differs significantly from that on merchant ships. The offshore fleet includes special-purpose vessels designed to perform specialized tasks, unlike the merchant fleet, which primarily focused on transporting cargo between destinations.

Specialized offshore vessels are required for various offshore activities, including offshore oil and gas exploration, drilling oil wells, developing subsea infrastructure, installing fixed platforms, deploying wind turbines, laying transcontinental cables and pipelines, and providing comprehensive maintenance of the above infrastructure. These complex processes include low-level construction and installation activities in the high seas.

Offshore operations require vessels with a specific design and specialized equipment. Anchor handling vessels tow drilling rigs and set/moor anchors in the correct position. Cable layers are specially designed for laying subsea cable networks.

Diving support vessels serve as a floating base for deepwater operations. Two types of vessels are involved in monitoring and maintaining pipelines and drilling rigs: pipe-laying vessels that lay pipelines and drilling vessels that specialize in drilling exploration wells. These vessels are equipped with systems for securing the vessel to the wellhead, drill pipe storage racks, and drilling fluid tanks, [1].

As the electrical equipment and control systems on these vessels become increasingly complex, the competence of personnel, especially in the support fleet, is crucial. The reliable operation of shipboard electrical equipment relies on obtaining and processing accurate measurement data, making research in this area relevant.

Dynamic Positioning (DP) systems are extensively used to meet safety requirements for performing various special tasks at sea and to ensure proper control of the course and positioning of offshore vessels. From an economic standpoint, the use of DP systems on offshore vessels is preferred, as it eliminates additional costs associated with ensuring effective control of the vessel's location and course during operations.

The application of DP systems extends beyond offshore activities, encompassing support for diving operations, subsea pipe and cable laying, transportation, research tasks, and more. This technology addresses crucial challenges in modern shipping, especially with the growing interest in exploring natural resources in the world's oceans.

Given their specific function, offshore vessels are equipped with a substantial amount of electrical and electronic apparatus overseen by an electrical-technical officer, [2]. Reliable data from measuring instruments and their timely and correct interpretation are crucial for ensuring the reliable operation of electrical equipment on ships, which ensures the relevance of this study.

1.1 Problem Statement

Modern ship control systems and power plants are highly complex automated technical complexes designed to efficiently perform operations determined by the purpose and specifics of the ship's operation in different conditions. The main method of studying automatic systems is their mathematical modeling. Mathematical models of real systems must reflect their characteristics with the required accuracy, which leads to complex nonlinear dependencies.

1.2 Analyses of Recent Sources

The wealth of published papers in the field of ship modeling is vast. To illustrate, [3], presents ship dynamics models showcasing the ship's response to rudder shifting and fixed pitch propeller (FP) speed, while a nonlinear model with 6 degrees of freedom is displayed, [4]. Numerous publications, including, [5] and [6], provide an overview of ship models and experimental methods for identifying ship dynamics. Addressing the Dynamic Positioning (DP) control problem, a publication details a nonlinear multivariable simulation model for a floating production, storage, and offloading (FPSO) vessel, as analyzed in [7], where the system's cascade models are also presented, [8].

Dynamic positioning (DP) has two main categories: absolute and relative. Absolute positioning records the position of a vessel at a specific point, while relative positioning records the vessel to a moving object, such as another vessel. As explained above, a vessel can also be strategically positioned to take advantage of wind, waves, or currents - a principle called weathervane, [9].

2 Theoretical Basis

DP systems autonomously manage the vessel's position and heading through the continuous operation of thrusters, effectively balancing environmental forces such as wind, waves, and current. These environmental forces naturally attempt to displace the vessel from its intended position. However, the automatically controlled thrust strategically counteracts these forces, ensuring the vessel remains steadfast in the desired position.

Dynamic positioning systems can be described as the integration of several shipboard systems to achieve precision maneuverability (Figure 1). Support and maintenance vessels in the offshore industry, for example, need the ability to hold positions within a centimeter as they may have to move dangerously close to drilling rigs, [9].

The DP system allows vessels to:

- follow a predefined trajectory for precise maneuvering or staying on course within the pipeline laying area;
- move at a predetermined speed;
- stay at a predetermined drilling point.
- The DP system is used by:
- drilling vessels and semi-submersible drilling rigs to stay on point while drilling in deep water;
- offshore platform supply vessels to maintain a position in the open sea, unloading supplies or loading extracted resources or waste materials;
- pipe-laying and offshore construction vessels to maintain position.

This is becoming increasingly important in the development of offshore fields. As oil and gas exploration moves into deeper waters, the demand for DP systems increases, reducing the risk of emergencies during exploration and production.

The main components of any DP system are:

- a positioning system, usually GPS;
- DP computer;
- engines/thrusters.

The positioning system monitors the vessel's position, the DP computer calculates the required thrust, and the thrusters apply the calculated thrust to maintain the vessel's position.

Figure 1 shows the vessel's dynamic positioning system schematic diagram.

Advantages of the DP system include:

- efficient & easy vessel positioning and maneuverability without the need for moorings, tugs, or labor-intensive anchor operations;
- capability to operate in ultra-deep waters where establishing mooring lines is challenging;
- flexibility to change location or direction swiftly to avoid adverse weather effects;
- quick disconnection and the ability to sail away if necessary;
- safety, when working on congested seabeds with numerous pipelines, buried munitions, mooring ends, or underwater structures.

The disadvantages of a dynamic positioning (DP) system include:

- Designing and installing DP requires significant capital investment.
- Dynamic positioning systems are associated with increased fuel consumption and maintenance costs, increasing overall operating expenses.
- In shallow water, DP systems may be less cost-effective than traditional mooring systems.
- There is a risk of severe consequences in the event of equipment failure, especially during critical operations such as pipe-laying or near fixed offshore platforms.

Given the above factors, when using DPs for fixed positioning of a vessel, it is essential to consider the vessel's course and all the opposing forces acting on it. One method often used to assess the impact of these risks is mathematical modeling.

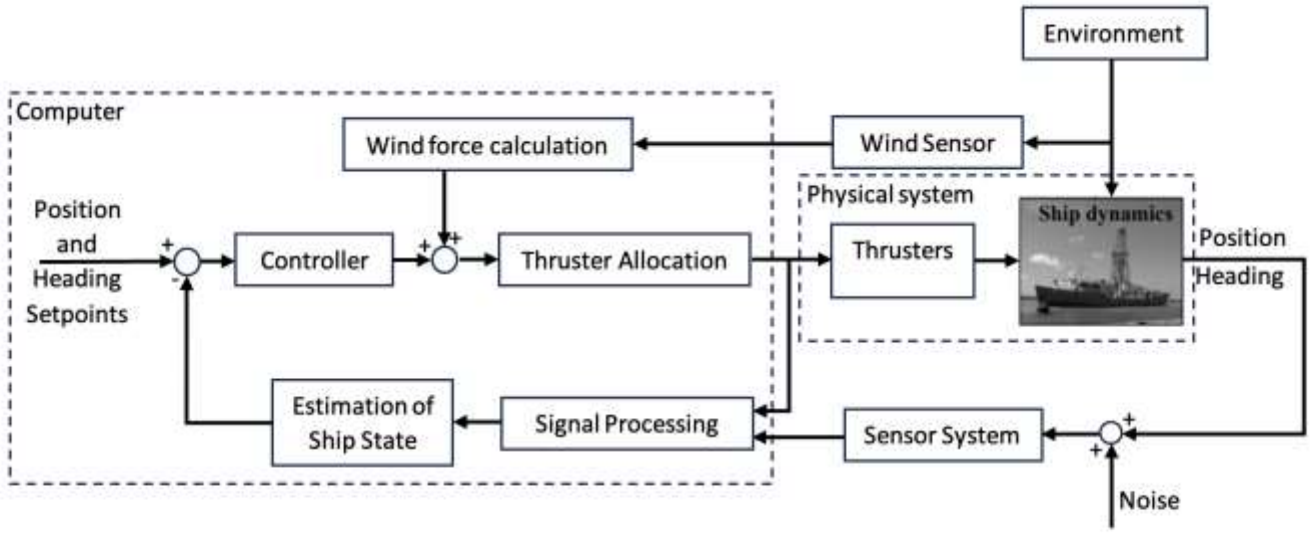

Fig. 1: Schematic diagram of the dynamic positioning system, [9]

The DP task involves keeping a ship at a specific point in the horizontal plane with a given heading angle. Controlling forces and torque generated by onboard actuators are employed for this purpose.

Using various hardware and software, the Dynamic Positioning System (DPS) automatically maintains a vessel or offshore structure in a fixed position, with or without propeller or thruster thrust, [11].

The ship's current heading position is determined by an estimation process based on the ship's model, position, and previous heading measurements, as well as consideration of the forces at work. The engines are provided with an appropriate compensating load to counteract the external forces and moments, while the thrusters generate the necessary forces to maintain the desired position.

The evaluation module processes all signals. This process includes tests to detect high scatter, peaks, and signal drift. False signals are ignored and compensated for by considering the ship's tilt. The estimation module's main goal is to provide accurate position, heading, and speed data. The estimation system filters out fast, purely oscillatory movements caused by pitching.

The Dynamic Positioning System (DPS) uses information from the sensor system or position reference system in the ship model to estimate the ship's position. A typical control strategy is the proportional-integral-derivative (PID) controller, which uses the position and heading estimates. The integral action is necessary to compensate for static environmental disturbances, and the controller feedback includes reference and forward feedback. The thruster distribution unit displays the parameters at the controller outputs at a given point. The hydrodynamic and derivative coefficients, critical components of the equations of motion, are determined by experimental testing on a physical model.

The ship's behavior during dynamic positioning is nonlinear, and accurate prediction for ship control is achievable primarily with the use of a nonlinear mathematical model. System identification methods are increasingly used to determine ship dynamics, identifying various input signals.

2.1 The Purpose of the Study

The article analyses the structure and principles of operating a dynamic positioning system (DPS) as a complex control system. It also discusses the problems associated with these systems. Despite the considerable efforts of developers and many implemented projects, it is impossible to achieve long-term maintenance of a ship in a given position undersea heave. This is because of the lack of energy armament of the vessels in use. Numerous studies in the field of regulation systems development have not yet yielded the expected result.

This paper aims to analyze two possible approaches to solving the problem of synthesizing control laws in the DP system. Both methods can be applied to the same ship model, but they are based on different ideologies of accounting for the effect of external disturbances on a closed system.

3 Methods

A ship model comprises a set of motion equations employed for forecasting the movement of a vessel under the influence of specified forces and moments. For optimal Dynamic Positioning System performance, it is crucial to maximize the level of detail in the model. Validation of model parameters is essential through sea trials. Nevertheless, it's important to note that the model offers only an approximation of certain aspects of the ship's behavior and is not flawless. The ship model implements a mathematical model of flat, parallel ship motion that takes into account the hydrodynamic characteristics of the ship's hull, pitching and wind drift forces, and moments, which allows to simulation of the movement of a given design ship under external environment influence, [12].

The ship model encompasses representations of the hull, propulsion system, and active control components such as propeller columns (PCs) and thrusters (TPs), which initiate the ship's movement and dictate its course.

Similar to an actual vessel, the ship model is furnished with various sensors:

- position and heading sensors are utilized to ascertain the ship's spatial coordinates (X and Y) and heading angle;
- motion sensors provide data on the ship's velocity, along with projections of the speed vector on the X and Y axes, as well as the circular speed;
- rotational speed sensors monitor the propellers of rudder columns (RC) and thrusters (TP), along with the rotation angle of RC and TP;
- accounting external influences, including wind (which determines wind speed and direction, denoted as *u* and *v*) and pitching

(which determines the pitching score and wave direction).

In motion, the ship is exposed to environmental forces - wind, pitching, and current (Figure 2).

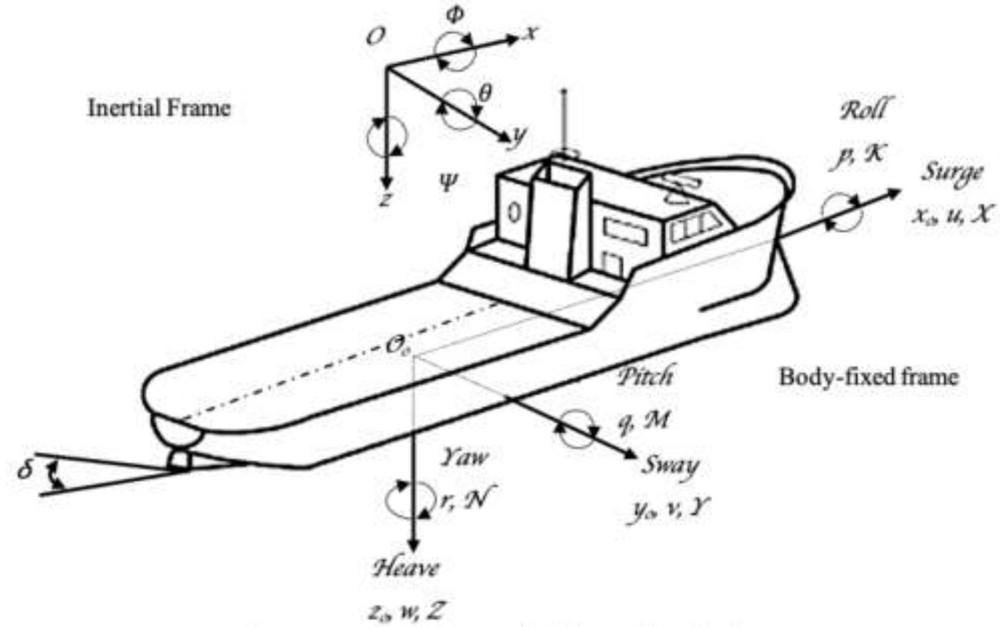

Fig. 2: Forces acting on the ship and its displacement, [12]

The external influences model simulates environmental factors that disrupt the ship's position, encompassing various disturbances such as waves of different intensities and directions, as well as wind exerting force on the ship with specific strength and direction, [13]. Relevant sensors on the ship model capture these parameters, serving as input data for calculating the forces responsible for the ship's longitudinal and transverse movements. The resultant forces are then transmitted to the calculation blocks within the ship's DPS model for further consideration and compensation.

A sea vessel contends with forces from wind, waves, currents, and the propulsion system. The vessel's reactions, manifesting as position, heading, and speed alterations, are gauged by position reference systems, a gyrocompass, and vertical reference sensors. Data from the vertical reference sensors are used to correct for roll and pitch in the reference system readings. Wind sensors measure wind speed and direction.

The DPS control system computes the forces required for the engines to manage the ship's motion across three degrees of freedom in the horizontal plane—wave, oscillation, and pitch.

In describing the dynamics of a surface vessel, a horizontal motion-based model with variable parameters such as wave, oscillation, and pitch is employed. Several main forces influence the movement of a vessel: hydrodynamic forces and torques. The main input variables for calculating the current course are the shaft angular velocity related to the propeller thrust and the rudder deflection angle. This model assumes negligible changes in roll and pitch, allowing their omission from the equations. Consequently, the ship is considered a solid body moving in a plane, possessing three degrees of freedom, as outlined in Equations 1-3, [12].

$$m\left(\frac{du}{dt} - vr - x_G r^2\right) = X\left(u, v, r, \frac{du}{dt}, \delta, n\right) \tag{1}$$

$$m\left(\frac{du}{dt} + ur + x_G\frac{dr}{dt}\right) = Y\left(v, r, \frac{dv}{dt}, \frac{dr}{dt}, \delta\right) \tag{2}$$

$$I_Z\frac{dr}{dt} + mx_G\left(\frac{dv}{dt} + ur\right) = N\left(v, r, \frac{dv}{dt}, \frac{dr}{dt}, \delta\right) \tag{3}$$

In the given expression

t is the time index,

u, v - wind speed and direction,

r is the angular velocity,

m and Iz are the mass of the vessel and the moment of inertia relative to the axis of normal to the X0Y0 plane, xG - Cartesian coordinates of the centre of gravity along the X0 axis,

δ is the deviation of the rudder angle,

n - shaft rotation frequency,

X(...), Y(...) and N(...) correspond to external forces (longitudinal waves X0, oscillation axis Y0) and moment (for X0-Y0 rotation). Accurate, dependable, and continuous location data plays a crucial role in dynamic positioning, with a requisite data rate of once per second to attain high precision.

The dynamic positioning of a vessel depends on a particular coordinate system that differs from a conventional navigation system. In DPS mode, the model provides automated steering from the current position to a predetermined point, calculating the basic parameters for the active steering mechanisms. Built-in algorithms in the DPS model dynamically determine the necessary adjustments through the remote pilot unit (RPU) and power plant (PP), compensating for counteracting forces and guiding the vessel on a predetermined course. Within the DPS model, various calculation modules handle distance and heading correction, speed correction, torque correction, compensation for forces, optimal distribution of thrusts, conversion of thrusts to angles, and propeller speed calculation.

Implementations of modern DPS control systems often require velocity estimation from position and direction measurements and filtering out the oscillatory components of motion due to waves. This type of filtering, known as wave filtering, is a key aspect in the motion control of marine surface vessels.

It is recommended that the ship model be improved by considering the oscillatory wave motion model to estimate the wave velocity and filtering. The states of the various components of the model can be accurately estimated using a Kalman filter. This methodology integrates ship velocity estimation with effective wave motion filtering, resulting in significantly improved accuracy and reliability of dynamic positioning systems.

This model is directly used in one of the approaches to construct the control law and is also used in simulation modeling in numerous experiments.

A first-order Markov process is used to describe the slowly changing forces acting on the ship, so we write:

$$\dot{b} = -T^{-1}b + \Psi n \tag{4}$$

In Equation 4, $b \in R^3$ is a vector of slowly varying forces and moments, $n \in R^3$ is white noise, $T \in R^{3+3}$ is a diagonally positive definite matrix, and $\Psi \in R^{3+3}$ is a matrix that scales the disturbance by components.

The sea disturbance model will be:

$$\begin{aligned} \xi &= \Omega\dot{\xi} + \sum w, \\ \eta_w &= \Gamma\xi. \end{aligned} \tag{5}$$

Here, $\xi \in R^6$ is the model state vector, $w \in R^3$ is white noise, and $\eta_w \in R^3$ is the component of the measurement signal that arises due to the wave.

The matrices in the equation are as follows:

$$\begin{gathered} \mathbf{\Omega} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -\omega_{01}^2 & 0 & 0 & -2\varsigma_1\omega_{01} & 0 & 0 \\ 0 & -\omega_{02}^2 & 0 & 0 & -2\varsigma_2\omega_{02} & 0 \\ 0 & 0 & -\omega_{03}^2 & 0 & 0 & -2\varsigma_3\omega_{03} \end{bmatrix}, \\ \mathbf{\Sigma} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}, \mathbf{\Gamma} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \end{gathered} \tag{6}$$

The parameters ω_{01} $(i = 1..3)$ are the central frequencies of the disturbance, ζ_{01} $(i = 1..3)$ are the attenuation coefficients, and σ_{01} $(i = 1..3)$ are the intensity of the disturbance for each component.

As noted above, the measured signal is affected by measurement errors. These errors are represented as a sum:

$$y = \eta + v \tag{7}$$

where, η – ship's position; v – white noise.

Data obtained from a positioning system introduces undesirable negative white noise, a factor influenced by the sensor type and the measurement method employed to gauge the ship's position. The ensuing challenge revolves around accurately estimating the vessel's position when confronted with imprecise knowledge of its dynamics and measurements affected by noise. The solution to this quandary lies in applying Kalman filtering, [13]. In the context of a dynamic positioning program, the Kalman filter estimates the vessel's state, leverages a previously established dynamic model, and relies on noise-influenced measurements from the reference system and sensors.

The Kalman filter is a mathematical algorithm for solving the problem of linear optimal filtering of discrete random nonstationary processes. It has proven itself very well in solving digital signal processing problems. No GPS navigator can do without a software implementation of the Kalman algorithm, and the algorithm is successfully used in sensor readings processors to implement control systems.

The relevance of using mathematical filters in signal processing is caused by the invariably present error in the readings of various sensors and devices caused by the finite accuracy of the device itself and the influence of random influences. The situation is aggravated by the inability to directly measure the parameters of processes inside certain devices without disrupting the operation of these devices in a large number of cases.

The use of filtering methods, in particular the Kalman method, minimizes the error in observations and sensor readings. To a first approximation, we can say that the task of the filter is to find a good approximation for the true data, knowing the incorrect sensor readings (sensor, meter, or just observations) and knowing the mathematical model of the process under study.

The Kalman filter employs a feedback control mechanism to estimate the process; it gauges the state of the process at a specific time and then incorporates feedback through (noisy) measurements.

The Kalman filter equations consist of time update equations and measurement update equations. Time update equations project the current state and error variation estimates forward in time, generating a priori estimates for the next time step. Measurement update equations incorporate new measurements into the a priori estimate to produce an improved a posteriori estimate.

Time update equations can be considered forecasting equations that project forward state estimates and error variations. The measurement equations can be thought of as correction equations that integrate new measurements to improve the a priori estimate. The final estimate produced by the algorithm resembles a predictor-corrector algorithm commonly used to solve numerical problems. The equations for updating time and measurements are as follows, [12]:

Time update, Eqs. 8-9:

$$\dot{\widehat{x_k}} = A\widehat{x_{k-1}} + Bu_{k-1} \tag{8}$$

$$P_k^- = AP_{k-1}A^T + Q \tag{9}$$

Update measurements, formulas 10-12:

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{10}$$

$$\widehat{x_k} = \widehat{x_k^-} + K_k(z_k - H\widehat{x_k^-}) \tag{11}$$

$$P_k = (I - K_k H)P_k^- \tag{12}$$

After each pair of time and measurement updates, the process repeats and compares the current iteration with the previous one. The a posteriori estimates obtained from the measurement updates are then confidently used to formulate new a priori estimates during the time update, creating a robust recursive loop. The iterative nature of the Kalman filter allows it to continuously refine and improve its estimates as new measurements become available, increasing the accuracy and reliability of the overall estimation process with each iteration. This recursive nature stands out as a highly appealing characteristic of the Kalman filter, making practical implementations more manageable than, for instance, implementing a Wiener filter. Unlike the Wiener filter, which processes all data directly for each estimate, the Kalman filter conditions the current estimate recursively on all past measurements.

The main task of the positioning control system is to maintain a given position and compass heading, regardless of external disturbances. This system effectively counteracts external forces and factors, ensuring accurate and stable positioning of the vessel. The challenge lies in mitigating these disturbances by applying appropriate counteracting forces.

Computer and simulation modeling are important ways to study control systems. The approaches based on them, allow conducting experiments using computer systems, resorting to the construction of physical models and without conducting expensive field tests. Such experiments are designed to reveal the properties of dynamic systems, which helps to choose control laws.

For computer modeling of dynamic objects, [14], the MATLAB environment with the Simulink software subsystem is used, [15].

This tool allows create computer models of dynamic systems in a visual mode using a set of standard elements. Simulink runs under the MATLAB application package and has access to a wide range of features, such as efficient numerical methods, powerful data processing tools, and scientific visualization. The computer model can be used to simulate dynamic processes. The system gives the opportunity to display the data obtained during the simulation in special blocks or transfer them to the MATLAB working environment for further processing.

The structures of analyzed control systems computer models are shown in Figure 3 and Figure 4. They consist of five main blocks: External disturbances, Measurement noise, Vessel model, Observer, and Controller.

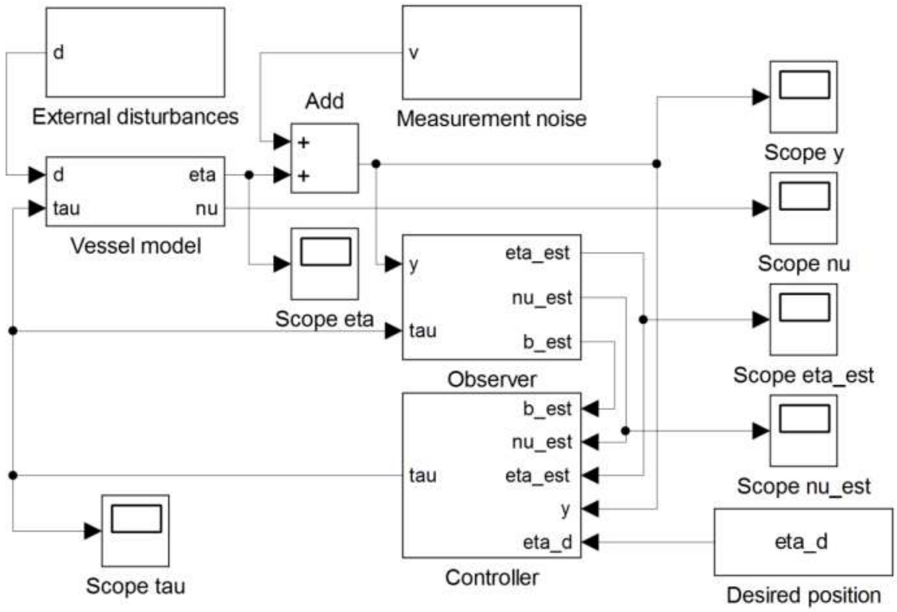

Fig. 3: Simulink model of the first control law (author's development)

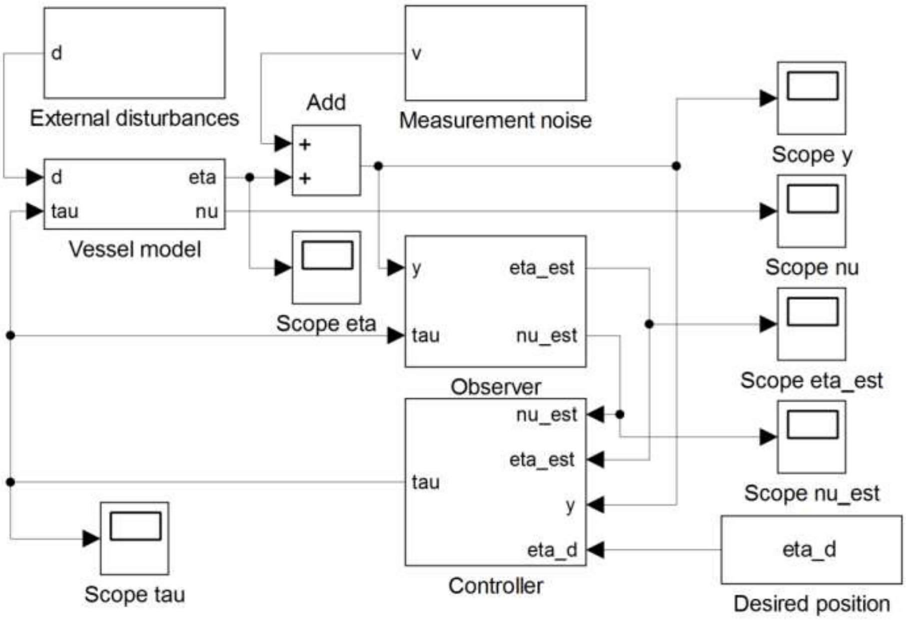

Fig. 4: Simulink model of the second control law (author's development)

The computer model of external disturbances is represented by the External disturbances block, which consists of slowly changing components that arise under the influence of wind, currents, and harmonic oscillations caused by sea waves.

The vessel model represented by equations (1-3) is implemented using the Vessel model block. The model contains two input signals: sea disturbance and control, which originate from the External disturbances and Controller blocks, respectively. The output of this model is the components of the ship's state vector. To obtain a model of the measured signal y, it is necessary, according to equation (7), to add the output η of the ship model with a component that realizes measurement errors. This component is the output v of the Measurement noise block. The noise range is determined by the accuracy of the measuring instruments. The arrangement of the External disturbances, Measurement noise, and Vessel blocks are completely the same in both computer models.

The speed and position of the vessel, as well as the control signal, are transmitted to the Scope visualization blocks. This data can be conveniently used in MATLAB to compare the performance of the systems under consideration.

Figure 3 shows the Simulink model of the first control law. It shows that the output signals of the Observer block are position and velocity estimates, as well as an estimate of external disturbances. The structure of the second computer model (Figure 4) differs only in the output signals of the asymptotic observer. There are no estimates of the external disturbance vector.

Let us consider the results of the computer models presented above. Figure 5 shows the combined transients of the control systems, with the blue color indicating the model of the first control law (Figure 3) and the green color indicating the second computer control model (Figure 4). Since they have the same basic controller, it takes some time to reach the neighborhood of the equilibrium point.

Figure 6 shows the joint graphs of the systems at the equilibrium point under the influence of external perturbations to the ship. It can be seen from the figures that the control systems keep the ship in the vicinity of the set position. The ship has similar behavior in both cases.

From the results presented in Figure 6, slightly smaller deviations can be seen, given by the second system in the value of the ship’s heading angle.

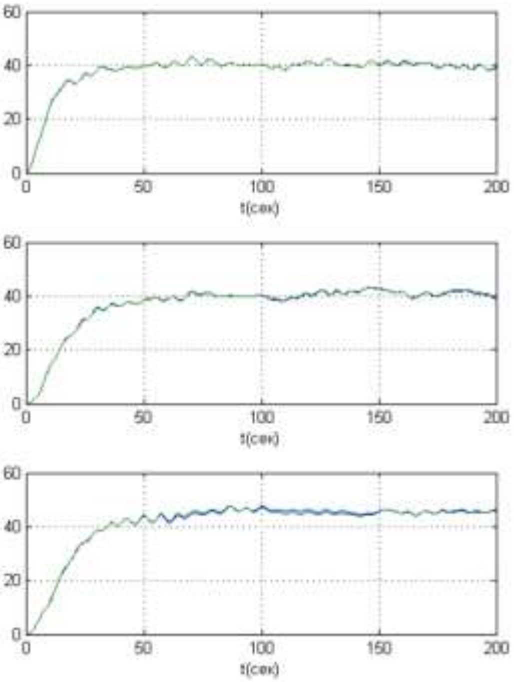

Fig. 5: Control system transients (author's development)

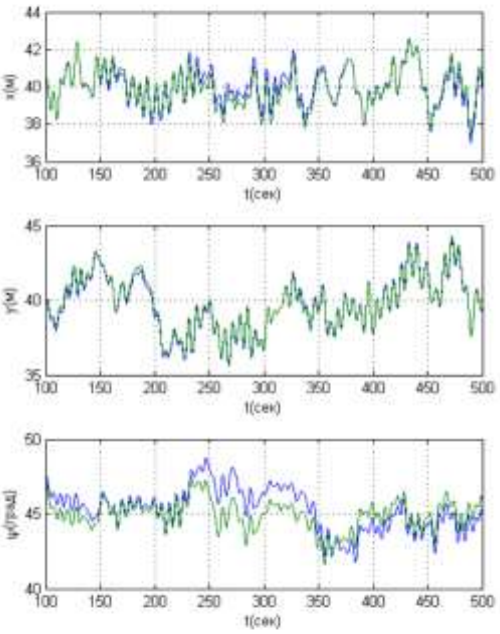

Fig. 6: System dynamics at the equilibrium point η=(40m, 40m, 45°) (author's development)

Values of both control signals are presented in Figure 7. Control systems of both types produce similar signals, which can be seen from the figures.

It should be noted that the control system of the second computer model has a special feature, i.e., its ability to switch between different correctors easily. Thus, with a small amplitude of disturbance, a simple version of the corrector can be used, and if necessary, switch to a more modern version.

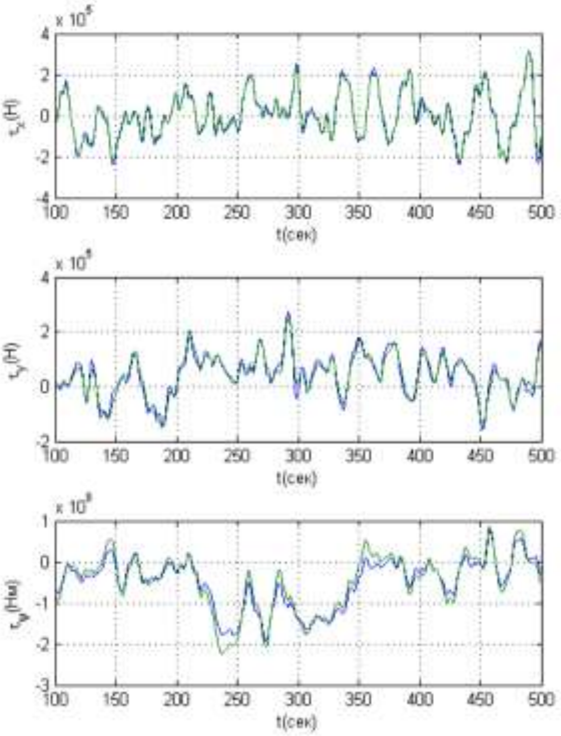

Fig. 7: Control signals of the control systems (author's development)

Such an operation is not provided in the first system since the harmonic component of the ship's position is included in the state vector of the asymptotic observer.

Figure 8 demonstrates this switching. For the first 300 seconds, the simple version of the corrector is running, and the rest of the time, the complex version of the control law is running. This figure also demonstrates the advantages of control laws that have a filtering property using the Kalman filter.

As the comparative analysis shows, the analyzed approaches give similar results, despite significant differences in the ideology of building control laws.

The control law with dynamic correction gives good results. Its efficiency is higher because it requires solving a system of differential equations of a lower order. Although the procedure for setting up the dynamic corrector is more complicated for this approach than for the first option, there is a possibility of further improving the dynamic corrector to obtain new properties of the control system, for example, setting up additional filtering frequencies.

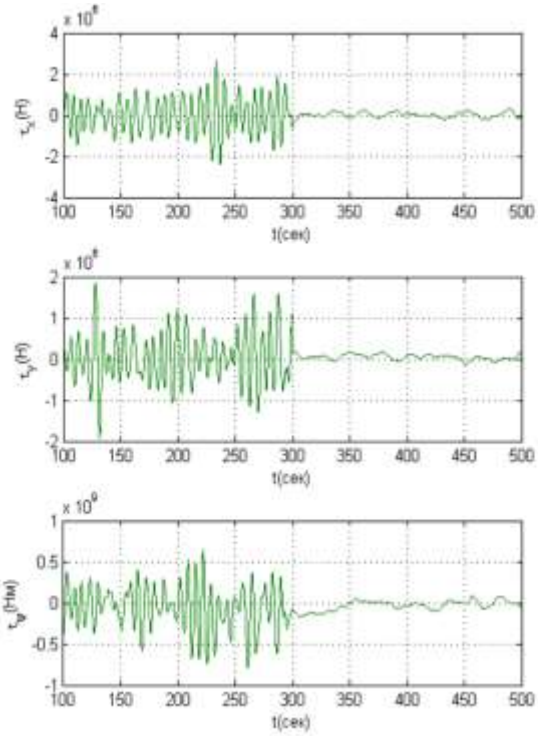

Fig. 8: Switching between correctors in the control system of the second computer model (author's development)

One of the main advantages of the control law with correction is the flexibility of its use. The control law makes it possible to change the dynamic corrector during operation, which allows to selection the control mode by changing conditions. For example, in the absence of any disturbances, control low can be limited by basic part, and if necessary, a switch-over to more advanced options is available.

The advancement in computing power has opened up possibilities for implementing more sophisticated control algorithms. This has led to commercialising demanding control strategies like predictive model control and online numerical optimization methods.

The literature explores numerous controllers, [16], [17], [18], [19], [20], with some successfully integrated into various commercial Dynamic Positioning (DP) systems.

Many DP systems leverage multivariate Proportional-Integral-Derivative (PID) controller algorithms in conjunction with an observer, [21]. The PID generates thrust that is proportional to the three-dimensional position of the vessel and the deviation vector from the desired setpoint (proportional component), the speed deviation vector (differential component), and the accumulated deviation vector (integral component). All of these vectors are time-dependent. The system determines the required motor force vector as the sum of the three components responsible for proportional, differential, and integral actions.

4 Results

The approach to designing new systems marks a significant advancement in dynamic vessel positioning system technology, comparable in importance to the integration of Kalman filtering into optimal control schemes. The evident advantages of the latter led to the widespread adoption and practical application of the Kalman filtering system.

Upon conducting a thorough analysis of navigation safety challenges in various sea surface conditions, it becomes apparent that employing a mathematical model facilitates numerous computational studies on ship control modes with Dynamic Positioning Systems (DPS). These studies contribute to the formulation and refinement of algorithms governing ship movement during positioning, with due consideration for the optimal utilization of electric power system resources. This approach simplifies the complexity associated with the development and adjustment of control algorithms.

A mathematical model of the ship's dynamics in the process of its dynamic positioning is built in the study and two versions of the automatic control laws that stabilize the ship's position are considered, while the second model shows a greater efficiency of the control system, at least by 14% compared to the first.

Considering the variable values of external disturbances that affect the quality of object management, the accuracy of forecasts and the speed of model updating play a significant role in the management of the DP system. The simulation results allow us to describe the offshore vessel as a rigid body that moves in a plane, considering three degrees of freedom, which is used to analyze the course control of the DP system.

A comparative assessment was conducted on two control system variants with filtering properties applied to a vessel under dynamic positioning mode. The study concluded that it is preferable to conduct filtering initially on the data source and subsequently on the information consumer. Implementing pre-filtering enables the elimination of redundant and erroneous data, consequently lessening the burden on the data transmission channel. Additionally, it was determined that the ultimate filtration should be carried out on high-performance systems to achieve the most effective filtration results.

5 Discussion

In aligning the simulation results with prevailing research trends in ship dynamic positioning, it becomes evident that various researchers similarly underscore the significance of advancing systems for dynamic positioning on ships. This collective emphasis signifies a progressive stride in technological innovation. Much like the present study, the integration of Kalman filtering into optimal control schemes is recognized as a pivotal step by other researchers, emphasizing its role in determining system efficiency.

For instance, practical implementations of Kalman filtering have been successfully employed in real-world maritime scenarios, showcasing its efficacy in enhancing the precision of navigation systems during dynamic positioning maneuvers. The integration of such filtering techniques aligns with the broader industry push towards more robust and efficient dynamic positioning systems for ships.

Moreover, beyond the theoretical framework of research, the identified effectiveness of specific automatic control laws for stabilizing ship positions can be directly applied in the development and optimization of shipboard control systems. This could lead to the implementation of more reliable and responsive control strategies, thereby improving the overall safety and operational efficiency of dynamic positioning systems in practical maritime applications.

Extending beyond the realm of the research, comprehensive analyses of navigation safety problems in diverse sea surface conditions are found in other studies, contributing valuable insights. These broader investigations, although exceeding the chosen topic's scope, serve to reinforce the overarching importance of mathematical models for studying and analyzing dynamic positioning system (DPS) management modes.

In the context of processing externalities and data filtering, the research conducted by contemporary scholars lends support to the concept of a staged approach to filtering at both the data source and information consumers. For example, recent applications in maritime data processing have demonstrated the benefits of implementing pre-filtering at the data source to eliminate redundant and erroneous data, followed by a final filtration stage on high-performance systems. These practical examples substantiate the broader implications and applications of the research outcomes in the context of dynamic positioning systems for ships.

6 Conclusions

Although the research poses a significant value, it is important to recognize its inherent limitations and imperfections. It stands to reason that the fixation on the implementation of Kalman filtering and mathematical models may unintentionally distract from other technologies that may offer alternative or complementary solutions. It is also possible that the research's particular circumstances may not fully reflect the varied and sophisticated real-world maritime environments.

The effectiveness of control algorithms and filtration methods depends on the environment. Therefore, determining the specifics of their use by different vessel types and service conditions required further detailed studies.

The rigid body model for sea-going vessels proposed in this study resulted in a significant breakthrough. Nevertheless, it does not take into account the peculiarities of the dynamic marine environment or the structural features of more complex vessels.

The above limitations demonstrate the importance of a multi-vector approach to dynamic positioning system (DPS) design. The obtained results achieved through the use of the Kalman filter and mathematical models may be further applied with due regard to the alternative technologies and uncertain marine environment. The actual service adaptability and reliability of DPS can be increased by conducting a comprehensive study of AI-based control systems, improved sensors, and other alternative technologies.

Control algorithms and filtering techniques might need to undergo adjustment for specific vessels, conditions, and operational requirements for practical implementation. The implementation and design of DPS must be performed adaptively to obtain more reliable and impactful outcomes in different maritime conditions.

The research constitutes a substantial development in dynamic vessel positioning, although practical application requires addressing the identified limitations. The outlined development approaches should be refined and adapted for their effective and varied employment in real-world maritime environments. Researchers, industry specialists, and technology developers should continuously collaborate to bridge the gap between theory and practice. This collaboration is crucial for the further advancement of dynamic vessel positioning technologies.

References:

[1] Z. Shan, Research on ship management ERP integrated platform system of offshore engineering exploration and scientific research enterprise, *Journal of Physics: Conference Series*, Vol. 1549, No. 4, 2020, paper 042082. DOI: 10.1088/1742-6596/1549/4/042082.

[2] International Maritime Organization. *Model Course 7.08 Electro-Technical Officer*. London: IMO, 2014.

[3] O. Daki, V. Kolesnyk, Z. Dorofieieva, V. Tryshyn, Model and scenarios of automatic control of ship power plant, *Systems of Arms and Military Equipment*, Vol. 4, No. 68, 2021, pp. 70-76. DOI: 10.30748/soivt.2021.68.10

[4] R. H. Rogne, T. H. Bryne, T. I. Fossen, T. A. Johansen, On the usage of low-cost MEMS sensors, strapdown inertial navigation and nonlinear estimation techniques in dynamic positioning, *IEEE Journal of Ocean Engineering*, Vol. 46, No. 1, 2020, pp. 24-39. DOI: 10.1109/JOE.2020.2967094.

[5] T. I. Fossen, Line of sight path following control utilizing an extended Kalman filter for estimation of speed and course over ground from GNSS positions, *Journal of Marine Science and Technology*, Vol. 27, 2022, pp. 806–813. DOI: 10.1007/s00773-022-00872-y.

[6] H. S. Halvorsen, H. Øveraas, O. Landstad, V. Smines, T.I. Fossen, T.A. Johansen, Wave motion compensation in dynamic positioning of small autonomous vessels, *Journal of Marine Science and Technology*, Vol. 26, 2021, pp. 693–712. DOI: 10.1007/s00773-020-00765-y.

[7] P. Durdevic, Z. Yang, Application of H – Robust control of a scaled offshore oil and gas de-oiling facility. *Energies*, Vol. 11, No. 2, 2018, Article 287. DOI: 10.3390/en11020287.

[8] H. Wang, Y. Wang, Z. Chen, X. Wang, Cascade-based tracking control for dynamic positioning vessels under unknown sea loads, *International Journal of Control*, Vol. 96, No. 7, 2023, pp. 1846-1858. DOI: 10.1080/00207179.2022.2073474.

[9] T. I. Fossen, *Hanbook of Marine Craft Hydrodynamics and Motion Control*, 2nd ed. New York, NY:Willey, 2021.

[10] F. Wang, M, Lv, Y, Bai, F. Xu, Software implemented fault tolerance of triple-redundant dynamic positioning (DP) control system, *Ships and Offshore Structures*, Vol. 12, No. 4, 2017, pp. 545-552. DOI: 10.1080/17445302.2016.1186331.

[11] S. Wen, D. Zhang, B. Zhang, H. K. Lam, H. Wang, Y. Zhao, Two-degree-of-freedom internal model position control and fuzzy fractional force control of nonlinear parallel robot, *International Journal of Systems Science*, Vol. 50, No. 12, 2019, 2261-2279. DOI: 10.1080/00207721.2019.1654006.

[12] Mathematical model, *Encyclopaedia Britannica*, 2018, [Online]. https://www.britannica.com/science/mathematical-model (Accessed Date: 1 March 2024).

[13] C. Urrea, R. Agramonte, K. Filter, Historical overview and review of its use in robotics 60 years after its creation, *Hindawi Journal of Sensors*, Vol. 2021, 2021, Article 9674015, DOI: 10.1155/2021/9674015.

[14] M. Liao, G. Wang, Z. Gao, Y. Zhao, R. Li, Mathematical modelling and dynamic analysis of an offshore drilling riser. *Shock and Vibration*, Vol. 2020, 2020, paper 8834011. DOI: 10.1155/2020/8834011.

[15] S. Eshkabilov, *Beginning MATLAB and Simulink: From Beginner to Pro*, Second Edition. Fargo, ND: Agricultural and

Biosystems Engineering Department, North Dakota State University, 2022.

[16] C.V. Amaechi, C. Chesterton, H. O. Butler, N. Gillet, C. Wang, I. A. Ja'E, A. Reda, A. C. Odijie, Review of composite marine risers for deep-water applications: Design, development and mechanics. *Journal of Composites Science*, Vol. 6, No. 3, 2022, paper 96. DOI: 10.3390/jcs6030096.

[17] E. A. Basso, H. M. Schmidt-Didlaukis, K. Y. Pettersen, A. J. Sørensen, Global asymptotic tracking of marine surface vehicles using hybrid feedback in the presence of parametric uncertainties. In *2021 American Control Conference (ACC)*. New Orleans, LA: IEEE, 2021, pp. 1432–1437. DOI: 10.23919/ACC50511.2021.9483419.

[18] M. A. Jaculli, B. J. Leira, S. Sangesland, C. K. Morooka, P. O. Kiryu, Dynamic response of a novel heave-compensated floating platform: Design considerations and the effect of mooring. *Ships and Offshore Structures*, Vol. 18, No. 5, 2022, pp. 1-11. DOI: 10.1080/17445302.2022.2075647.

[19] M. Wan, J. Du, H. Yi, Dynamic positioning for semi-submersable platform using stable fuzzy model predictive control. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, Vol. 238, No. 1, 2024, pp. 73-86. DOI: 10.1177/09596518231182280.

[20] D. Zhang, X. Chu, C. Liu, Z. He, P. Zhang, W. Wu, Review on motion prediction for intelligent ship navigation. *Journal of Marine Science and Engineering*, Vol. 12, No. 1, 2024, paper 107. DOI: 10.3390/jmse12010107.

[21] D. A. Nahovskyi, H.G. Doshchenko, Mathematical model of the observer for the vessel position maintenance control system, *Applied Questions of Mathematical Modelling*, Vol. 5, No. 1, 2022, pp. 58–63. DOI: 10.32782/mathematical-modelling/2022-5-1-7.

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