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Abstract	This paper addresses the issues of automatic beam aiming of the laser optical reference system (LORS) at the center of reflector in conditions of strong pitching and rolling. Practical observations show that LORS does not receive a stable or high-quality reflection and sometimes even complete loss of the reflection is observed in conditions of strong waves. The authors have conducted full-scale experiments with the CyScan LORS, installed on a supply vessel “ESNAAD 225”, which confirmed instability and reflection loss under conditions of strong pitching and rolling. A method and algorithm were proposed for automatic aiming of the LORS beam into the center of reflector, which ensures a high reflection quality under conditions of strong pitching and rolling as well. The efficiency of automatic beam aiming under conditions of strong pitching and rolling was verified by mathematical modeling in MATLAB. The practical value of the obtained results lies in opportunity to improve the quality of the reflected signal and, therefore, to increase the accuracy and reliability of dynamic positioning in general, which is especially important when operating near hazardous objects such as oil and gas platforms.

Keywords (separated by '-')	Automatic beam aiming - Laser optical reference system - Offshore vessel - Reflector - Coordinate system

Author Proof

Automatic Beam Aiming of the Laser Optical Reference System at the Center of Reflector to Improve the Accuracy and Reliability of Dynamic Positioning

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Abstract. This paper addresses the issues of automatic beam aiming of the laser optical reference system (LORS) at the center of reflector in conditions of strong pitching and rolling. Practical observations show that LORS does not receive a stable or high-quality reflection and sometimes even complete loss of the reflection AQ1 is observed in conditions of strong waves. The authors have conducted full-scale experiments with the CyScan LORS, installed on a supply vessel "ESNAAD 225", which confirmed instability and reflection loss under conditions of strong AQ2 pitching and rolling. A method and algorithm were proposed for automatic aiming of the LORS beam into the center of reflector, which ensures a high reflection quality under conditions of strong pitching and rolling as well. The efficiency of automatic beam aiming under conditions of strong pitching and rolling was verified by mathematical modeling in MATLAB. The practical value of the obtained results lies in opportunity to improve the quality of the reflected signal and, therefore, to increase the accuracy and reliability of dynamic positioning in general, which is especially important when operating near hazardous objects such as oil and gas platforms.

Keywords: Automatic beam aiming · Laser optical reference system · Offshore vessel · Reflector · Coordinate system

1 Introduction

The dynamic position (DP) system is an automated onboard computer-controlled system that automatically maintains the required position and course of the vessel in order to reduce human error and risk of an accident during manual maneuvering [1–3]. DP system can work with both global (GPS) and LORS systems. GPS provides information about the geographical coordinates of the vessel's location while LORS provides information about the vessel's position relative to the landmark by measuring the bearing and distance to the landmark [4, 5].

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The LORS occupies the second place in the list of installed reference systems, because it is characterized by accuracy, low cost, reliability, and ease of use, thus meeting the requirements of the International Maritime Organization, International Association of Marine Contractor and Det Norske Veritas Germanischer Lloyd [6–8].

The laser optical reference system is a measuring system and integral part of the DP system. It consists of a laser unit, integrated controller, and intelligent software [9, 10]. The laser unit rotates or scans in a horizontal plane and emits high-frequency pulses. The pulses are reflected from the reflectors attached to moving or stationary objects (platforms or vessels) and returned back to the laser unit. The distance to the object is measured by the difference in the time of emission and return of pulses [11]. Laser optical reference system, as any other positioning system, has its own risks of losing position. One of the reasons for signal loss is shading of the reflector by objects or contamination of the lens. Such problems are easily solved by correct installing the reflector (in the line of sight), cleaning the lens of dirt, etc. [12, 13]. However, deviation of the optical axis outside the reflector, especially in conditions of strong pitching and rolling, due to the limited beam width (12–18°) in the vertical plane [14–16] appears to be more significant reason of losing position, which leads to the weakening and even disappearance of the signal.

The risk of collision is associated with the human factor as well. The influence of the human factor on safety has been considered by authors, in particular [17, 18]. Reducing the influence of the human factor can also be achieved through the creation of automated [19, 20] or automatic [21] ship traffic control systems. The works [22–26] consider the issues of creating such systems for other modes of transport too.

2 Review of Literature Sources Focused on Improving the Accuracy and Reliability of Dynamic Positioning

The issues of increasing the accuracy and reliability of automatic control systems, including DP systems, were considered in many research works, for example, [27–31]. Thus, the article [27] explored a new method for determining location in visible light using a dynamic positioning and tracking algorithm based on optical flow detection and Bayesian prediction. Experiments showed that the proposed dynamic positioning and tracking algorithm could provide a high positioning accuracy and reduce the risk of accident.

The article [28] studied the accuracy of smartphones when maneuvering a vessel in the dynamic positioning system. The researcher's results showed that in this case the positioning accuracy of 2–3 cm was provided with a probability of 95%.

The article [29] considered a reliable nonlinear control law for the dynamic positioning system using a perturbation observer, an auxiliary dynamic system, and a dynamic surface control method. The developed law of reliable nonlinear DP control proved the ability to maintain the position of the vessel and to reduce risk of collision, while guaranteeing a uniform limitation of all signals in a closed DP control system.

The article [30] studied a nonlinear adaptive fuzzy feedback controller for dynamic positioning system in order to reduce the risk of losing position. The proposed nonlinear adaptive feedback controller with fuzzy output showed improvement of stability of positioning under various environment conditions.

The user manual [31] describes three DP systems: Navis Engineering OY, Marine Technologies LLC and Rolls Royce Marine. Each of these DP systems works with LORS. At the same time, before starting operations with LORS, the angle of elevation of the LORS beam above the horizon is manually set up in each of these systems, so that the beam hits the reflector while the laser direction unit is passing the reflector during circular or sector scanning.

As follows from the above review, the solutions do not consider the possibility of increasing the accuracy and reliability of the DP system by automatically aiming the LORS beam at the center of the reflector. The closest solutions [31] involve only the initial manual setting of the beam elevation, which is insufficient during strong pitching or rolling. Therefore, the development of method, algorithm and software for the system of automatic aiming of the beam at the center of the reflector, considering the angular deviations of the vessel from the initial position during rolling and pitching, is an urgent scientific and technical problem.

The object of research is the processes of automatic aiming of the LORS beam at the center of the reflector under conditions of strong rolling and pitching.

The subject of research is method, algorithm and software for the control system of aiming in conditions of strong pitching and rolling.

The purpose of the research is to improve the accuracy and reliability of the dynamic positioning system in conditions of strong pitching and rolling.

This is achieved by automatically aiming the LORS beam at the center of the reflector in conditions of strong pitching and rolling, namely: LORS measurements of bearing $B_m(n)$ and distance $D_m(n)$ to the reflector at the moment the beam is passing the reflector; according to the measured bearing $B_m(n)$, distance $D_m(n)$ and the elevation $h_2 - h_1$ of the reflector center above the laser tube, the elevation angle θ^* is determined; measured roll $\varphi_m(n)$ and pitch $\vartheta_m(n)$ angles of the vessel, together with the elevation angle θ^*, are used to calculate the required optical axis position angle $\theta_m^0(n)$ in vertical plane; the current position of the optical axis $\theta_m(n)$ is brought to the required position $\theta_m^0(n)$.

3 Method and Algorithms for Automatic Aiming of the LORS

In the process of our research, were applied the following methods: analysis and synthesis, methods of theory of automatic control systems, linear algebra methods, matrix calculus and transformation of coordinate systems, methods of numerical integration, mathematical modeling methods, and full-scale experiment methods.

The linked coordinate system (LCS) $X_L Y_L Z_L$ associated with the platform is located in the center of rotation of the vessel, the axis OX_L lies in the plane of the local horizon and is directed towards the reflector, the axis OY_L lies in the plane of the local horizon being perpendicular to the axis OX_L and directed to the right. The axis OZ_L complements the system to the "right".

The base coordinate system (BCS) $X_B Y_B Z_B$, associated with the vessel, is located in the center of rotation of the vessel, the axis OX_B lies in the diametrical plane and is directed towards the stern of the vessel, the axis OY_B is perpendicular to the axis OX_B and directed to the port side, the axis OZ_B complements the system to the "right".

The measuring coordinate system (MCS) $X_M Y_M Z_M$ is located in the center of rotation of the vessel, the axis OX_M is directed along the optical axis, the axis OY_M is perpendicular to the axis OX_M and directed to the right, the axis OZ_M complements the system to the "right". Figure 1 shows the coordinate systems used in the calculations.

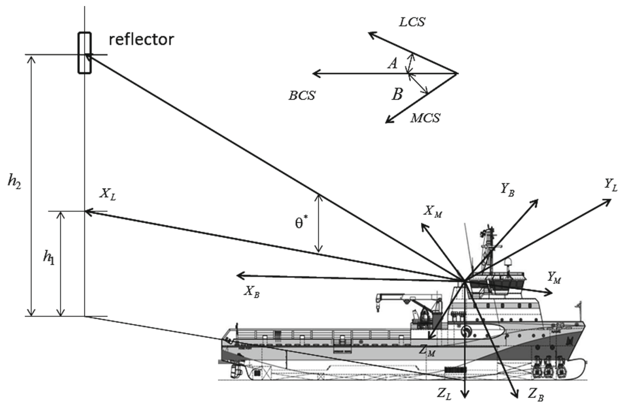


Fig. 1. Coordinate systems

The transition matrix A between LCS and BCS for the sequence of turns $Z - Y - X$ is presented in Table 1, where φ, ψ, ϑ are the angles of roll, yaw and pitch, respectively.

Table 1. Transition matrix A between LCS and BCS

A	X_L	Y_L	Z_L
X_B	$\cos\vartheta \cos\psi$	$\cos\vartheta \sin\psi$	$-\sin\vartheta$
Y_B	$\sin\varphi \sin\vartheta \cos\psi -$ $\cos\varphi \sin\psi$	$\sin\varphi \sin\vartheta \sin\psi +$ $\cos\varphi \cos\psi$	$\sin\varphi \cos\vartheta$
Z_B	$\sin\varphi \sin\psi +$ $\cos\varphi \sin\vartheta \cos\psi$	$\cos\varphi \sin\vartheta \sin\psi -$ $\sin\varphi \cos\psi$	$\cos\varphi \cos\vartheta$

The transition matrix B between the BCS and the MCS for the sequence of turns $Z - Y$ is presented in Table 2, where ψ_m, θ_m are the angles that determine the position of the optical axis in a BCS.

The unit vector, defining the required optical axis direction to the center of the reflector in LCS, is (see Fig. 1).

$$\mathbf{e}^{LCS} = (\cos\theta^*,\ 0,\ -\sin\theta^*),\quad \theta^* = \arcsin(\frac{h_2 - h_1}{D_m}),$$

Table 2. Transition matrix B between BCS and MCS

B	X_B	Y_B	Z_B
X_M	$\cos\theta_m \cos\psi_m$	$\cos\theta_m \sin\psi_m$	$-\sin\theta_m$
Y_M	$-\sin\psi_m$	$\cos\psi_m$	0
Z_M	$\sin\theta_m \cos\psi_m$	$\sin\theta_m \sin\psi_m$	$\cos\theta_m$

where h_1, h_2 are the laser and reflector heights above sea level, D_m is the measured distance to the center of the reflector.

The unit vector, defining the required optical axis direction to the center of the reflector in BCS, taking into account Table 1, has the form

$$\begin{aligned} e_x^{BCS} &= \cos\theta^* \cos\vartheta \cos\psi + \sin\theta^* \sin\vartheta, \\ e_y^{BCS} &= \cos\theta^*(\sin\varphi \sin\vartheta \cos\psi - \cos\varphi \sin\psi) - \sin\theta^*(\sin\varphi \cos\vartheta), \\ e_z^{BCS} &= \cos\theta^*(\sin\varphi \sin\psi + \cos\varphi \sin\vartheta \cos\psi) - \sin\theta^*(\cos\varphi \cos\vartheta). \end{aligned}$$

The unit vector, defining the optical axis direction in BCS, taking into account Table 2, has the form

$$\mathbf{e}^{BCS} = (\cos\theta_m \cos\psi_m, \cos\theta_m \sin\psi_m, -\sin\theta_m).$$

Conditions, that determine the direction of the optical axis to the center of the reflector are written down

$$\begin{aligned} \cos\theta_m^0 \cos\psi_m^0 &= \cos\theta^* \cos\vartheta \cos\psi + \sin\theta^* \sin\vartheta, \\ \cos\theta_m^0 \sin\psi_m^0 &= \cos\theta^*(\sin\varphi \sin\vartheta \cos\psi - \cos\varphi \sin\psi) - \sin\theta^*(\sin\varphi \cos\vartheta), \\ -\sin\theta_m^0 &= \cos\theta^*(\sin\varphi \sin\psi + \cos\varphi \sin\vartheta \cos\psi) - \sin\theta^*(\cos\varphi \cos\vartheta). \end{aligned} \quad (1)$$

3.1 Aiming the LORS Beam in the Laser Rotation or Scan Mode

In the case under consideration, the bearing to the reflector is measured only at the moment when the beam is passing the reflector, the rest of the time the bearing is predicted using the measured yaw rate.

$$\begin{aligned} B_m(n) &= B_m^0(n) + \omega_{zm}(n)\Delta T;\ B(n) \neq B_m(n), \\ B_m(n) &= B_m^0(n);\ B_m(n) = B_m^0(n), \end{aligned}$$

where $B_m(n)$ is the bearing prediction to the reflector at the n - calculation step, $B_m^0(n)$ is the measured bearing to the reflector at the n - calculation step, $\omega_{zm}(n)$ is the measured yaw rate at the n - calculation step, ΔT is the information processing cycle in the onboard controller.

From the last equation of system (1), taking into account for the adopted coordinate systems, that $B_m(n) = -\psi,\ \varphi_m(n) = \varphi,\ \vartheta_m(n) = \vartheta$, is determined the following

$$\begin{aligned} &\theta_m^0(n) = \arcsin(\sin\theta^* \cos\varphi_m(n) \cos\vartheta_m(n) + \cos\theta^*(\sin\varphi_m(n) \sin B_m(n) - \\ &\cos\varphi_m(n) \sin\vartheta_m(n) \cos B_m(n))), \end{aligned} \quad (2)$$

where $\theta_m^0(n)$ is the required optical axis deviation angle in vertical plane at the n - calculation step, $\varphi_m(n)$ is the measured roll angle of the vessel at the n - calculation step, $\vartheta_m(n)$ is the measured pitch angle of the vessel at the n - calculation step.

Equations (2) determine the required angle $\theta_m^0(n)$ of the optical axis deviation in vertical plane at the n - calculation step, at which the optical axis will be directed to the center of the reflector for any measured values of the roll $\varphi_m(n)$ and pitch $\vartheta_m(n)$ angles of the vessel at the n - calculation step.

Reduction of the beam to the required position is performed according to the difference scheme, which is a discrete analogue of the aperiodic link

$$\theta_m(n) = \theta_m(n-1) + \frac{\Delta T}{T}(\theta_m^0(n) - \theta_m(n)), \tag{3}$$

where T is the time constant of aperiodic link.

3.2 Aiming the LORS Beam in the Follow Reflector Mode

In the case under consideration, the laser module is constantly oriented to the reflector by changing the direction of the beam in both the vertical and horizontal planes.

From the last equation of system (1), taking into account, that $B_m(n) = -\psi,\ \varphi_m(n) = \varphi,\ \vartheta_m(n) = \vartheta$, is determined the following

$$\begin{gathered}\theta_m^0(n) = \arcsin\left(\sin\theta^* \cos\varphi_m(n) \cos\vartheta_m(n) + \cos\theta^* (\sin\varphi_m(n) \sin B_m(n) - \right. \\ \left. \cos\varphi_m(n) \sin\vartheta_m(n) \cos B_m(n))\right),\end{gathered} \tag{4}$$

From the first and second equations of system (1), is determined the following

$$\begin{gathered}\psi_m^0(n) = arct\ \left(\frac{\sin\varphi_m(n)\sin\theta_m(n)\cos B_m(n) + \cos\varphi_m(n)\sin B_m(n)}{\cos\theta_m(n)\cos B_m(n) + tg\theta^*\sin\theta_m(n)}\right. \\ \left. - \frac{tg\theta^*\sin\varphi_m(n)\cos\theta_m(n)}{\cos\theta_m(n)\cos B_m(n) + tg\theta^*\sin\theta_m(n)}\right).\end{gathered} \tag{5}$$

Equations (4), (5) determine the required angles $\theta_m^0(n),\ \psi_m^0(n)$ of the optical axis deviation in vertical and horizontal plane at the n - calculation step, at which the optical axis will be directed to the center of the reflector for any measured values of the roll $\varphi_m(n)$ and pitch $\vartheta_m(n)$ angle of the vessel at the n - calculation step.

The reduction of the beam to the required position is performed according to the difference scheme, which is a discrete analogue of the aperiodic link

$$\theta_m(n) = \theta_m(n-1) + \frac{\Delta T}{T}(\theta_m^0(n) - \theta_m(n)), \tag{6}$$

$$\psi_m(n) = \psi_m(n-1) + \frac{\Delta T}{T}(\psi_m^0(n) - \psi_m(n)). \tag{7}$$

4 Experiment

4.1 Full-Scale Experiments with Laser Optical Reference System CyScan on the Vessel "ESNAAD 225"

The authors conducted an experiment with LORS CyScan, installed on the platform supply vessel "ESNAAD 225" and reflector mounted on a Jack-Up type platform.

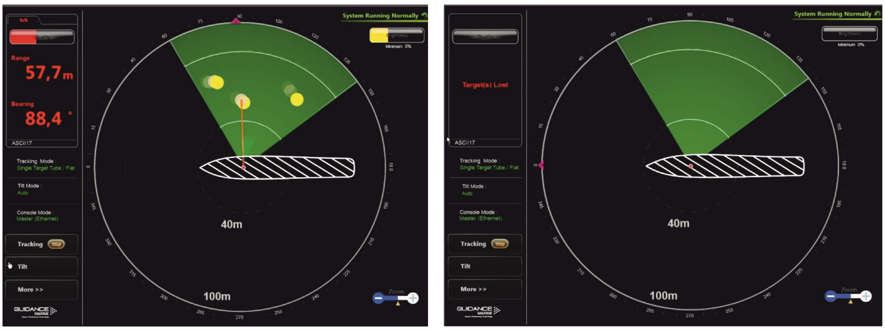
Figure 2 shows the LORS CyScan screen during experiments with pitching and rolling. The LORS CyScan screen are displays the position of the reflector relative to the vessel, the bearing and the distance to the target, the quality of the received data, the brightness of the reflecting rays, and the angle of the beam relative to the horizon.

Experiment with Pitching and Rolling. Distance to the reflector is 68.8 m, bearing to the reflector is 200.9°, tracking mode is a single reflecting tube, beam tilt is in auto mode.

Figure 2a shows the LORS CyScan screen with pitching (pitching amplitude is 6°–9°), pitching period is 3–4 s).

Figure 2b shows the LORS CyScan screen with rolling (rolling amplitude is 11°–14°), rolling period is 1.5–2 s.

The below figure shows, the LORS CyScan reflection during pitching is unstable, the quality and brightness of reflection is low. The LORS CyScan reflection during rolling is also unstable, the quality and brightness of the reflection is minimal, a loss of the reflection from the reflector tube occur.



a b

Fig. 2. Experiment with pitching and rolling

Since the system can be installed on any type of the vessel (DSV, PSV, or Shuttle tanker) [32, 33], an unstable reflection or its complete loss can lead to disruption of the reference positioning system and failure as a whole [34, 35], which is associated with severe risks: environmental pollution, accidents on the oil and gas platform, and even human casualties.

4.2 Simulation of Automatic Beam Aiming at Reflector in MATLAB

The operability and efficiency of the proposed method and algorithms for automatic aiming of the beam at the center of the reflector was tested by mathematical modeling in the MATLAB environment in the follow reflector mode.

Figure 3 and 4 demonstrate the results of mathematical modeling of the processes of dynamic positioning of the vessel in the form of graphs of changes in time longitudinal speed V_x, lateral speed V_y, longitudinal displacement X_g, lateral displacement Y_g, roll rate ω_x(wx), roll angle φ(fi), pitch rate ω_y(wy), pitch angle ϑ(tet), yaw rate ω_z(wz), yaw angle ψ(psi), bearing to the platform P_m, distance to the platform D_m, angles, that determine the current position of the optical axis LORS in BCS θ_m(tetCyScan), ψ_m(psiCyScan) and optical axis deviations from the direction to the center of reflector in vertical plane (dtet) and horizontal plane (dpsi). Figure 3 provides simulation results for pitching parameters (amplitude and frequency), which coincide with the corresponding parameters in a full-scale experiment. Furthermore, in order to create more severe conditions compared to the full-scale experiment, the initial values of the longitudinal (V_x), lateral (V_y) and angular (wz) ship speeds are set.

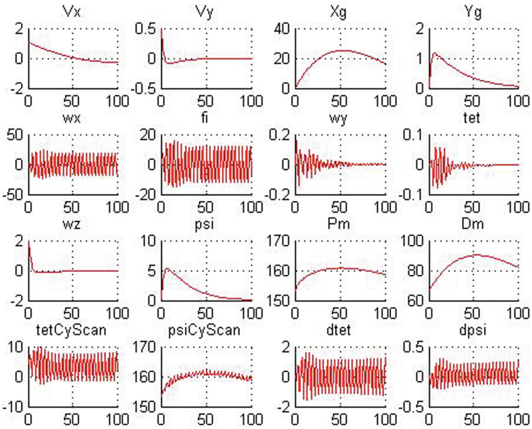


Fig. 3. Simulation results of the automatic beam aiming in conditions of strong pitching

Figure 4 present a simulation results of the automatic beam aiming at the center of the reflector under conditions of strong rolling. The results are given for the parameters of rolling (amplitude and frequency), which coincide with the corresponding parameters in a full-scale experiment. Furthermore, in order to create more severe conditions compared to the full-scale experiment, the initial values of the longitudinal (V_x), lateral (V_y) and angular (wz) ship speeds are set as well.

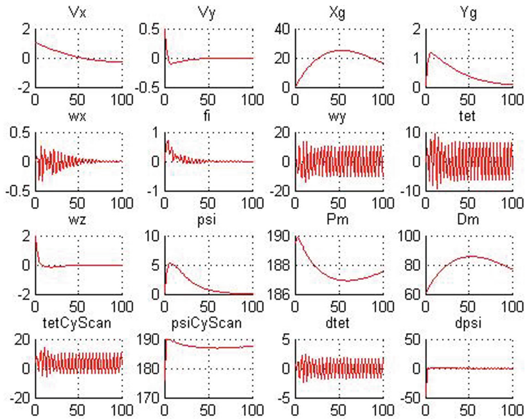


Fig. 4. Simulation results of the automatic beam aiming in conditions of strong rolling

The above results prove that the DP system ensures that the given initial speeds and the resulting displacements (X_g, Y_g, psi) are processed to zero in the presence of strong oscillations in the roll channel (ω_x(wx), φ(fi)) and trim (ω_y(wy), ϑ(tet)) from pitching or rolling.

The results of comparing the quality of the reflected signal Q for the known solution (CyScan) and the proposed (automatic beam aiming) are shown in Table 3.

Table 3. Results of comparing the quality of the reflected signal

Type of vessel motions	Vessel motions parameters		CyScan Q [%]	Automatic aiming	
	A [dgr]	T [sec.]		dtet, dpsi	Q [%]
Pitching	6–9	3–4	30	$\lvert dtet \rvert < 2°$, $\lvert dpsi \rvert < 0,25°$	100
Rolling	11–14	1,5–2	0	$\lvert dtet \rvert < 2°$, $\lvert dpsi \rvert < 0,25°$	100

The above results indicate that, for the amplitudes A and periods T of pitching and rolling indicated in the table, the quality of the reflected signal Q of the known solution (CyScan) is, respectively, 30% and 0% (signal loss) (see the data of the full-scale experiment in Fig. 2). For the same pitching and rolling parameters, the quality Q of the reflected signal with automatic beam aiming in both cases is 100%, since the deviation of the beam from the center of the reflector in the vertical plane $|dtet| < 2°$ is 6 times less than the beam width (12°) in the vertical plane, and the deviation of the beam in the horizontal plane $|dpsi| < 0,25°$ is commensurate with the width of the beam in the horizontal plane (0.13°). This means that the accuracy obtained by automatic beam aiming allows using not only Laser Rotation or Scan Mode, in which the beam position can be refined with a period of rotation or scanning of the laser unit, but even the Follow

Reflector Mode, in which the beam position can be refined on each clock cycle of the onboard controller.

5 Conclusion

The proposed method, algorithm and software for the system of automatic aiming of the LORS beam at the center of the reflector allow to significantly improve the accuracy and reliability of the dynamic positioning system as a whole in conditions of strong pitching and rolling. The known solutions implemented in the DP systems of Navis Engineering OY, Marine Technologies LL and Rolls Royce provide only the initial manual setting of the LORS optical axis elevation angle, which is not enough under conditions of strong pitching and rolling. As shown by the results of the full-scale experiment conducted on the vessel ESNAAD 225 with LORS CyScan, during strong pitching or rolling, the quality of the signal reflected from the reflector deteriorates significantly, and in some cases, it may even be lost. Such work of LORS is unacceptable when performing dynamic positioning or maneuvering operations near oil and gas platforms. Deterioration of the reflected signal quality or loss occur because of the excessive deviation of the signal from the center of the reflector in case of strong waves. The scientific novelty of obtained results lies in theoretical justification of design features of the original system of automatic aiming of the LORS beam at the center of the reflector, consisting in constant, on each clock cycle of the onboard controller measuring the angular displacements of the vessel from the basic position. Subsequent consideration of these deviations is used to calculate the direction of the optical axis to the center of the reflector. Bringing the current position of the optical axis to the calculated position is performed by automatically changing the elevation angle of the optical axis. The obtained results allow to significantly improve the quality of the reflected signal, to exclude signal loss under conditions of strong pitching and rolling. The practical value of the results obtained lies in the development and introduction into industrial production of the original system of automatic aiming of the LORS beam at the center of the reflector as well as the regulatory documentation for it being able to improve the quality of the reflected signal. Therefore, accuracy and reliability of the dynamic positioning system in general under conditions of strong pitching and rolling can be achieved. As a consequence, different kinds of risks can be reduced when performing operations near hazardous objects, including an oil and gas platform, which as a whole proves the practical value of the results obtained. Further research will be related to improving the quality of automatic aiming by taking into account the statistical characteristics of wave.

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