Human-machine system as a control shell in the implementation of mooring operations

S I Kondratyev¹, A L Boran-Keshishyan¹, A E Slitsan², V V Popov¹

¹ Admiral Ushakov Maritime State University, 93, Prospekt Lenina, Novorossiysk, 353924, Russian Federation
² Admiral Makarov State University of Maritime and Inland Shipping, 5/7, Dvinskaya st., Saint-Petersburg, 198035, Russian Federation

E-mail: 061202@rambler.ru

Abstract. Mooring is a complex and responsible process for a boat master, so modern trends determine the need to create automated and automatic systems for mooring vessels to minimize the human factor. The study researched the vessel ergatic control complex and the towing group with the use of mathematical apparatus in the implementation of mooring operations. The human-machine or “ergatic” system is the control shell under the active influences of the bridge complexes and is an auxiliary tool for the watchman on the navigation bridge. This is the essence – a human, as a controlling and observing link, is an integral part of the human-machine complex. Automation, even in systems with artificial intelligence, will not soon replace the flexibility of the human brain, despite possible and sometimes very serious human mistakes. Taking into account the fact that the automated mooring system applies all kinds of monitoring sensors to prevent docking impact, the control and responsibility for the mooring process still lie with the navigator operator.

1. Introduction
In the operational mode of the vessel, there is a need to moor to anchored vessels, set adrift, or mooring to the berth. Accident-free mooring operations depend on the knowledge and practical experience of the boat master, taking into account the maneuverability characteristics of the vessel, the reliable operation of the ship power plant, steering, rudder, and mooring device.

1.1. Determination of the required towing capacity
When preparing a vessel for a mooring operation, the maritime operating area, approach and mooring location, possible dangers and obstacles are studied in advance [1]. Depending on the prevailing forces and factors, the method of maneuvering the vessel when approaching the berth and at the berth is selected. The mooring scheme of the vessel is approved by the captain of the vessel, depending on the berthing vessel conditions. The mooring vessels process is mainly carried out with a towing group. In open sea conditions, the mooring is implemented without the tugs, taking into account the weather [2].

The number of tugs is ordered on the recommendation of the marine pilot in agreement with the captain of the ship and reasonable calculations of the towing support sufficiency [3].
The required number and power of tugs depend on the size of the vessel, its maneuverability, maneuvering area and mooring method. The main factor determining the required traction of the tug is the crosswind pressure, the value of which is determined by the formula:

\[ R_g = 0.65 \times 10^{-4} \times S_n \times w^2 \]  

(1)

where \( S_n \) — sail area of the vessel, m\(^2\); \( w \) — wind speed, m/s

Determination of the total required capacity of towing support for mooring operations:
- for oil tankers and large bulk carriers (in ton-force):

\[ T = ((60 \times DWT) + 100000) + 40 \]  

(2)

where: \( DWT \) - vessel displacement.

However, if the current displacement of the vessel is unknown, then for all vessels with a length between the perpendiculars of more than 140 meters, the total required power of towing support for vessels mooring operations can be determined by the formula:

\[ T = (0.7 \times LBP) - 35 \]  

(3)

where: \( LBP \) - the length between the perpendiculars.

Another method of approximate calculation is the use of the wind speed as an input argument; based on the course angle of the wind, the actual average pressure on 1 m\(^2\) of the surface normal to the wind is determined; the total value of the crosswind pressure is calculated using the formula (4).

\[ R_g = 0.001 \times S_n \times K_n \]  

(4)

where:
- \( S_n \) - sail area of the vessel, m\(^2\);
- \( K_n \) - means pressure per 1 square meter of surface, kg/m\(^2\).

Taking into account good maritime practice, we increase the obtained value of the total crosswind pressure by 15%, as a reserve of required power during mooring operations:

\[ R_g = 1.15 \times (0.001 \times S_n \times K_n) \]  

(5)

The optimal towing order is drawn up.

2. Problem statement

Automatic vessel mooring is understood as systems used for mooring a vessel without human assistance. Thus, changes in the approach speed of the vessel to the berth and the direction of the vessel will be the main parameters that need to be monitored during mooring.

Magnetic cushion system. It is not fully developed and has limitations: it is costly to operate (power consumption, maintenance, qualified personnel); it loads the hull (it can deform the side in the offshore wind conditions) – thus, the cushions must be placed in the area of the frames - that is, “adjust” to a specific hull; the reliability of the cushions - a broken tow can be quickly replaced, but a faulty cushion -not. The system works well, with fast work on receiving or mooring the ship-ferries; automatic tensioning systems are forbidden to use on tankers, as this can lead to deformation of the hull.

2.1. Automatic mooring system with vacuum gripper – "MoorMaster"

The "MoorMaster" automatic mooring system is the technology of the "Cavotec" automatic mooring system. This system uses large vacuum cushions with a gravity of 20 tons to create a fast and safe connection between the shore and the vessel. The vacuum cushions are controlled and positioned by a robotic mechanical coupling with a hydraulic drive [3,4]. One of the important elements of the system is the control module. It contains all the necessary information required for both the vessel and the shore. The data is transmitted via encrypted radio communication between the vessel, the shore and Internet-compatible software. If the vessel is equipped with a control module, the Captain can control mooring operations with just two buttons. MoorMaster controls the movements of the vessel at the
berth, ensuring efficient loading and unloading operations. The system is also able to keep vessels of all sizes in one place in ports where there are swells and in long rolling sea conditions [5].

2.2. The DOCKLOCK system.
Intelligent automatic magnetic mooring system from Mampaey Offshore Industries. The system consists of double dead anchors, fore and aft, equipped with magnetic cushions for secure and durable attachment to any hull, flat or curved, painted or corroded.

The cushions can move around the hull, taking into account changes in height. At the command of the operator, the DOCKLOCK system can moor the vessel fully autonomously. The operation principle of this system is based on electromagnetism. The gripping cushions contain magnets that can interact with each other when connected to a power supply.

When the vessel approaches, the cushions can change their position with the help of hydraulic cylinders, thus they can adapt. The presence of special sensors for monitoring the position of the hull of the vessel outputs information to the system, thus the skipper has the ability to control the distance to touch. The operator can intervene in the operation of the system at any time, and can independently choose which gripping devices will be attached first. In this regard, this mooring complex can be considered as a single human-machine system – or otherwise ergatic. Complexes of mooring operations form a single shell with work control tools, which also constitute an element of the ergatic system.

2.3. Docking mode system.
The mooring operation monitoring system integrated into the Electronic Chart Display Information System helps boat masters during the mooring process.

The control of mooring operations takes into account the maneuver situation of the vessel, the distance to the berth from the bow and from the stern, the centerline plane angle in relation to the berth, the course, the linear and angular speed of movement, as well as the speed of movement of stern and bow parts of the vessel. To obtain data, information from navigation sensors and the computing process of the navigation system are used. To predict the future positions of the hull, a simulation model of the vessel movement is used, which allows performing a calculation based on the current movement parameters. In many Electronic Chart Display Information Systems, the Kalman Filter or its elements are used for forecasting [6].

![Figure 1. Schematic display of the Electronic Chart Display Information System screen in the docking mode.](image-url)
3. Materials and methods

The accuracy of determining the position of the vessel from the two directions of the mooring navigation systems is adequate and comparable to the differential GNSS system. The maximum radial error of the vessel position in terms of bearing and distance to the berth is:

$$M = \frac{1}{\sin \theta} \left( \frac{m_p^2 D^2}{57.3^2} + m_D^2 \right)^{\frac{1}{2}}$$

(6)

where: $\theta$ - the angle between position lines, in degrees; $m_p$ - the bearing error, m; $D$ - the distance to the berth, according to the selected aids to navigation, in m.

From the motion equation of a large-tonnage vessel, in wind conditions with a constant speed:

$$\begin{align*}
Y_{\beta} - Y_A - Y_r &= 0 \\
M_{\beta} - M_A - Y_{r,m} &= 0
\end{align*}$$

(7)

where: $Y_{\beta}$ - the projection of the hydrodynamic force on the axis $Y$, corresponding to the movement of the vessel, $M_{\beta}, M_A$ - the projection of the moments of forces from external influences, kNm; $l_m$ - the distance of the steering gear baller from the gravity center of the vessel, m.

By modifying and calculating the equations included in the system, we find:

$$\begin{align*}
C_{Y_{\beta}} \frac{\rho V^2}{2} A_{As} - C_{Y_A} \frac{\rho V^2}{2} A_{vl} - C_{Y_r} (\delta - \eta \beta) \frac{\rho V^2}{2} A_r &= 0 \\
C_{M_{\beta}} \frac{2}{A_{As}} - C_{M_A} \frac{\rho V^2}{2} A_{vel} + C_{Y_{r,m}} (\delta - \eta \beta) \frac{\rho V^2}{2} A_{r,m} &= 0
\end{align*}$$

(8)

where: $C_{Y_{\beta}}$ - the coefficient of the positional force of the hull; $C_{M_{\beta}}$ - the coefficient of the positional moment of the hull; $C_{Y_A}, C_{MA}$ - the coefficients of normal line and wind moments of the hull; $A_{vl}, A_r$ - the area of projections on the surface of the parts of the vessel in the above-water and underwater state; $l_{r,m}$ - the length of the vessel along the current waterline; $V$ - the speed of the vessel.

We find dynamic expressions of the vessel characteristics:

$$\begin{align*}
C_{Y_A} &= \frac{C_{Y_{\beta}} \rho V^2}{2} A_{As} - C_{Y_r} (\delta - \eta \beta) \frac{\rho V^2}{2} A_r \\
C_{M_A} &= \frac{C_{M_{\beta}} \rho V^2}{2} A_{As} + C_{Y_{r,m}} (\delta - \eta \beta) \frac{\rho V^2}{2} A_{r,m}
\end{align*}$$

(9)

where: $\rho$ - the density of the medium; $\beta$ - the plane angles of the radii movement and control actions; $A$ - the rudder and hull parts area; $\eta$ - the coefficient of influence of the vessel hull; $\delta$ - the angle of the rudder shift.

A mathematical model of ship control during mooring operations using a towing group can apply a system of linear equations modified by technical coefficients:
\[
\begin{align*}
T_{e2} - T_{e1} &= X_A - X_\beta \\
F_y + T_\sigma &= Y_A - Y_\beta \\
T_\sigma x_\sigma &= F_y x_\sigma - M_A - M_\beta - M_{im}
\end{align*}
\]  
(10)

where: \(T_{e2}, T_{e1}\) - the propeller thrust of the vessel on the forward and reverse course; \(X_A, X_\beta\) - the projections of dynamic forces, kN; \(M_A, M_\beta, M_{im}\) - the dynamics moments of the impacting force impulses.

From the moderation of the equations, we find the necessary total force of the towing group power plant for the control actions on the processed vessel:

\[
\begin{align*}
T_\sigma &= Y_A + Y_\beta - F_y \\
x_\sigma &= \frac{F_y x_\sigma - M_A - M_\beta - M_{im}}{Y_A + Y_\beta - F_y}
\end{align*}
\]  
(11)

where: \(T_\sigma, x_\sigma\) - the traction of the towing group and the position of the tugs composition during evolutions in the water area.

For lateral displacement control, the bow thruster is used together with the main rudder blade. Unlike the axial rudder, the bow thruster operates on the principle of lateral displacement:

\[
\Delta Y = Y - Y_{adv}
\]  
(12)

In the case of lateral movement of the vessel during mooring, there is a limit on the value of the drift angle. Under such conditions, the law of the thruster control will be calculated as

\[
\frac{d\delta_{adv}}{dt} = K_1 \times D \times Y + K_2 (\beta - \beta_{adv}) - K_3 \times \delta_{adv}
\]  
(13)

where: \(\delta_{adv}\) - the angular velocity and the angle of the thruster shift; \(\beta\) - the drift angle; \(\beta_{adv}\) - the permissible value of the drift angle; \(Y\) - the current value of the lateral displacement of the vessel; \(K_1, K_2, K_3\) - the control coefficients.

4. Discussion of results

The mooring process begins from the moment when the vessel is in the operating water area – directly near the berth. In the ergatic system, the presence of a human is an important element, the skipper, sets the necessary control action, and the system generates signals to regulate certain values [6]. Using the signals from the positioning system (GNSS) corresponding to the current position of the vessel \((\varphi_{mex}, \lambda_{mex})\), a course to a given point is formed \((\varphi_{adv}, \lambda_{adv})\), corresponding to the endpoint near the berth:

\[
\tan^{-1} K_{adv} = \frac{\varphi_{mex} - \varphi_{adv}}{\lambda_{mex} - \lambda_{adv}}
\]  
(14)

\[
K_{adv} = \arctan^{-1} \left( \frac{\varphi_{mex} - \varphi_{adv}}{\lambda_{mex} - \lambda_{adv}} \right)
\]  
(15)

To maintain the set course, the necessary value is also set to the steering device:

\[
\delta_{adv} = k_1 (\varphi_{mex} - \varphi_{adv}) + k_2 \times \omega
\]  
(16)

\[
\frac{d\delta}{dt} = \delta_{mex} - \delta_{adv}
\]  
(17)
\[
\frac{d\delta}{dt} - \text{rudder shift speed signal; } \omega - \text{vessel angular velocity; } \delta_{\text{mec}} - \text{current shift value; } \\
\delta_{\text{зад}} - \text{set shift value; } k_1 \text{ and } k_2 - \text{control coefficients.}
\]

The required values for the bow thruster are also set:

\[
\frac{dT}{dt} = k_1(K_{\text{mec}} - K_{\text{зад}}) + k_2 \frac{dK_{\text{mec}}}{dt} + k_3 \int (K_{\text{mec}} - K_{\text{зад}}) \, dt - k_4 T
\]

(18)

To maintain the speed of the vessel, the skipper can change the speed stages, thereby accelerating or slowing down the speed of the main engine:

\[
\frac{dn}{dt} = k_1 (V_{\text{mec}} - V_{\text{зад}}) + k_2 \frac{dV}{dt}
\]

(19)

where: \( \frac{dn}{dt} \) and \( \frac{dV}{dt} \) - signals derived from the main propulsion engine and the speed of the vessel.

The system also takes into account the distances to the berth entered in the calculation block, and these values will be used to calculate the necessary control action for the thruster:

\[
\frac{dT}{dt} = k_3 \left( l_{\text{нос}} - l_{\text{корм}} \right) + k_4 \left( \frac{d}{dt} \left( l_{\text{нос}} - l_{\text{корм}} \right) \right) - V_{\text{неперп.}}
\]

(20)

where: \( l_{\text{нос}} \) and \( l_{\text{корм}} \) - signals of distances from the current location to the pier, respectively, from the bow and stern of the vessel; \( k_i \) - adjustment coefficients; \( V_{\text{неперп.}} \) - the specified transverse speed of the vessel.

Mathematically, the entire process of regulating and obtaining the specified values during mooring is performed automatically in the computing unit, and a person controls the process, up to the output values. To make changes, a human interferes with the system by increasing or decreasing the parameters, and the system automatically calculates the actual mooring conditions, such as the course, angular velocity, speed of movement of the bow and stern ends, and many other parametric data [7].

5. Conclusion

The study of the vessel mooring operations showed that the human-machine or "ergatic" system is the control shell under the active influences of the bridge complexes and is an auxiliary tool for the watchman on the navigation bridge. This is the essence – a human, as a controlling and observing link, is an integral part of the human-machine complex. Automation, even in systems with artificial intelligence, will not soon replace the flexibility of the human brain, despite possible and sometimes very serious human mistakes. Taking into account the fact that the automated mooring system applies all kinds of monitoring sensors to prevent docking impact, the control and responsibility for the mooring process still lie with the navigator operator.

References

[1] Dmitriev V I, Grigoryan V L, Kozik S V, Nikitin V A, Rassukovanny L S, Fadeev G G, Tsitrik Yu V 2009 Captain’s Handbook (St. Petersburg: Elmore)
[2] Subanov E E, Mironov A V, Chernoglavov D G 2014 Maneuvering and ship control (Novorossiysk: State Medical University named after F.F.Ushakov)
[3] Neustroev D I 2012 Calculation of towing support for mooring operations of large-tonnage vessels with limiting hydrometeorological factors (Novorossiysk: State Medical University named after F.F.Ushakov)
[4] Voronin V M 2017 Ergonomics of large systems (Yekaterinburg: URGUPS)
[5] Ostretsov G E, Klyachko L M 2009 *Methods of automation of ship motion control* (Moscow: FIZMALIT)

[6] Vagushchenko L L 2016 *Ship navigation and information systems* (Odessa: NU "OMA")

[7] Shikanov V V, Boran-Keshishyan A L, Popov V V 2019. *Model of an automatic control system for the transport process in the development of the concept of E-navigation, according to the network-centric configuration by the method of synthesis of control Petri nets* 234-239 (S-Pb.: Marine intelligent technologies)