About the geometrical form of the underwater robot platform with non-parallel system the anchor-rope propulsion

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Abstract. The underwater mobile transport robot, which is a platform assembled from the polygonal pontoon modules, is considered. The system are used anchor-rope movers, which ensures high stability and energy efficiency of the entire system due to interaction with the bottom surface. The aim of the study is to select the geometric shape of the module according to such criteria as specific heat losses in the movers, the length of the step and the tension of the ropes. The formulated criteria characterize the energy consumption and the level of dynamic loads in the considered dynamic system, and the achievement of their optimal values contributes to the increase of autonomy. It takes into account not only the exchange rate resistance to movement, but also the influence of the current, which, depending on the direction, can both promote the movement of the platform and counteract it.

1. Introduction
One of the types of underwater transport systems under development is a platform with positive buoyancy - pontoon, the principle of movement of which is based on the use of anchor-cable type engines. [1-3] the Principle of operation is shown in figure 1.

The propulsion unit is an anchor with two cables connected to the drums rotating according to certain laws. In beginning anchor, it occupies a position on one vertical with the drum. When the drum cable is strained and in the absence of slippage of the anchor on the bottom of the mobile robot moves. Then, the anchor moves to the new position by the joint coordinated control of the drums. Its lifting is promoted by the fact that one of the cables is close to the vertical position. Then the cycle repeats. The work of such an engine is similar to the work of a walking [4, 5, 6], and the difference is that the robot does not rely on it, but with its help clings to the support surface.

This type of engines is easy to operate, provides high profile permeability with different bottom topography and" stability" regardless of the distribution of the transported goods on the surface of the pontoon, as well as lower energy costs compared to other types of engines. Another advantage of such pontoon robots may be the ability to build a robot of any configuration using each of the pontoons as an elementary module.

Possible forms of such modules at the top view are shown in figure 2. To ensure the greatest "stability" anchor-cable movers are located on the edges of the modules. The limitation of module
shapes is explained by the requirement of tight packing of modules when assembling a robot pontoon of any configuration.

![Diagram](image-url)

**Figure 1.** The principle of operation of the anchor-cable motor of the mobile robot-pontoon. a-start position, b-end position (1-anchor, 2-cables, 3-controlled drums, 4-robot pontoon body, 5-bottom profile, AB- the trajectory of movement of the anchor, F-driving force, Q is the resistance of an environment).

Indeed, a robust dense packing is achieved if, in a proper convex polygon, the angle $\alpha$ between the sides satisfies the equation:

$$\alpha = \pi(1 - 2/n)$$

(1.1)

Where $n$ is the number of sides of the polygon.

In this case, $k$ is the maximum number of pontoon robots with a common point, determined by the equation:

$$k = 2n/(n - 2)$$

(1.2)

Therefore, the number of possible variants of geometric shapes of pontoon robots is limited to three cases: $n=3$-right triangle; $n=4$-square; $n=6$-hexagon.
Figure 2. Possible forms of a mobile robot pontoon. a-triangle, b-square, c-hexagon (1-initial position of the body, 2-final position of the body, 3-cable, 4-anchor, 5-controlled drum, F-control force, Q-resistance force of the medium).

Figure 3. Possible configurations of pontoon robots.

The disadvantages of such pontoon robots include the difficulty of controlling the exchange rate movement because the efforts developed in the anchor-cable movers in the direction, as a rule; do not coincide with the required direction of the robot-pontoon program movement.

Another drawback is that the movement of the robot pontoon in one step (one permutation of the anchors) is limited to the ability of the cables to work only in tension. With their help, you can only be attracted to the anchors, but not repelled. In mathematical calculations, this circumstance is a limitation on the amount of forces, the numerical values of which can only be positive.

2. Problem statement
We consider three forms of pontoon robot modules with the same area $S$, which at the same height of the platform $h$ corresponds to the same load capacity. Then the lengths of the sides $l$ for the modules of triangular, square and hexagonal shapes are respectively equal:

$$l_{tr} = (4S)^{0.5}/3^{0.25} \quad l_{sq} = S^{0.5} \quad l_{hex} = (4S)^{0.5}/108^{0.25}$$  \hspace{1cm} (2.1)
All robots make a translational motion with the same speed \( v \). The propellers are installed on all edges of the robot-pontoon. Then, at low speeds \( v \), the normal \( N \) and tangent \( T \) forces of resistance to motion acting on each face of the robot-pontoon, with a sufficient degree of accuracy are determined by expressions [2].

\[
N = \rho hl v^2 \sin \beta \quad T = hl \mu v \cos \beta \quad (2.2)
\]

Where \( \rho \) is the density of the liquid; \( \mu \) is the coefficient of viscous friction; \( \beta \) is the angle of attack, \( v \) is the velocity of the body.

The problem of determining the optimal shape of the robot pontoon by criterion I, consisting of additive indicators, including the maximum possible length of the \( L_{\text{max}} \) step and the level of heat loss \( W \), the condition of commensurability - the equality of the areas \( S \) of modules of all types is taken into account.

3. Method of solution
The solution is reduced to the geometric problem of establishing dependence for each type of robot-pontoon:

\[
\beta = \beta(L) \quad (3.1)
\]

And solutions of this equation for the determination of \( L_{\text{max}} \) at \( \beta = \pi / 2 \). Preparation of equations of translational uniform motion of pontoon robots. Based on nonlinear equations definition of laws of change of forces in anchor-cable movers depending on the passed way. Assessment of the level of heat loss per unit path based on the obtained laws of change of forces in the anchor-cable thrusters and characteristics of the driving engines. Obtaining dimensionless complex criterion I and determination of Pareto-optimal boundaries of the considered indicators.

\[
I = k_1 L_{\text{max}} + k_2 L_{\text{max}} \quad (3.2)
\]

3.1. The definition of the movement of the robot-pontoon in one step (one installation of anchors).
The maximum displacement of the pontoon corresponds to the angle \( \alpha \), determined from the equation:

\[
\alpha + \beta = \pi / 2
\]

Herewith:

\[
L_{\text{max}} = l \cos \beta \quad (3.3)
\]

3.2. The equations of the translational uniform motion and estimating the efforts of the ropes propulsion
The type of equations of motion depends on the number of engines performing work on the movement of the robot pontoon.

For a triangular robot, the required number of engines is two. Then the forces developed by the drive motors \( F_1, F_2 \) and resistance forces must be equal. The equation of motion is:

\[
0 = -2N \sin \beta - 2T \cos \beta + (F_1 + F_2) \cos (\alpha + \beta) \quad (3.4)
\]

Where:

\[
F_1 = F_2 = (\rho hl v^2 \sin^2 \beta + hl \mu v \cos^2 \beta) / \cos (\alpha + \beta) \quad (3.5)
\]

Where:

\[
\beta = \pi / 6; \alpha = \arctg (vt \sin \beta) / (l - vt \cos \beta) \quad (3.6)
\]
5

\( t \) - time of movement, changing in the interval:

\[ 0 < t < L \cos \beta / v \] (3.7)

For a square robot, the possible number of propellers is four. The flat movement of the robot pontoon is provided by four driving forces \( F_1, F_2, F_3, F_4 \) (figure 2) satisfying the system of equations:

\[
(F_1 + F_2 + F_3 + F_4) \cos(\alpha + \beta) - 2T \cos \beta - 2N \sin \beta = 0
\]

\[-(F_1 + F_3) \sin(\alpha + \beta) + (F_2 + F_4) \sin(\alpha + \beta) - (N_1 - N_2) \sin \beta + (T_1 - T_2) \cos \beta = 0\] (3.8)

\[\frac{l}{2}(F_2 - F_1) \cos \alpha + \frac{l}{2^{0.5}}(F_4 - F_3) \cos(\pi/4 - \alpha) = 0\]

Where \( \beta = \pi / 4; T_1, T_2, N_1, N_2 \) – are determined from the equations (2.2); \( \alpha \) is determined from the equation (3.6).

Execution of the last equation of the system (3.8) ensures the absence of rotational motion of the robot-pontoon relative to the center of mass. However, a feature of this system of equations is the presence of four control forces \( F_j \) in the three necessary conditions of the studied motion. Therefore, to uniquely determine the control forces it is necessary to involve an additional equation. It can be arbitrary, and its execution is provided by the control system [3]. It is most simple to provide a linear connection between \( F_j \) [7]

\[ \sum_{i=1}^{4} \gamma_i F_i = \sigma_i \] (3.9)

Where \( \gamma_i, \sigma_i \) is an arbitrary constant. It is also possible to solve the optimization problem, for example, to require a minimum of heat losses. If all drives are identical, this reduces to an additional equation [5, 8].

\[ \int_{0}^{T} \sum_{i=1}^{4} F_i^2 \, dt \Rightarrow \min \] (3.10)

Solved together with the equations of the system (3.8).

For a robot-pontoon in the form of a hexagon, the difference from the previous case will be that \( \beta = 60^\circ \), and the number of control forces is six.

3.3. An example of the numerical solution.

To solve the model problem, the control equations are of the following form: [9]

\[ \gamma_1 F_1 = F_2 \] (3.11)

square pontoon \( S=10; \) the height of the pontoon \( h=1; \) the density of the liquid \( \rho=1000; \) speed pontoon \( v=2; \) the coefficient of viscous friction \( \mu=0.0894; \) control coefficients: \( \gamma_1=1.7; \gamma_2=20; \gamma_3=4 \)
Figure 4. Dependence of the maximum cable tension force on the path.
I: $\gamma_1 = 1.7; \gamma_2 = 20; \gamma_3 = 4$
II: $\gamma_1 = 1.2; \gamma_2 = 25; \gamma_3 = 8$

Figure 5. Specific heat losses for all forms of modules, expressed in a logarithmic scale.

4. Result
Based on the results of the calculation, the triangular shape has a maximum step length and minimum heat losses in the engines, however, such a module has no parallel directional propellers and the tension forces are relatively high. The square module has average stride length, Maximum heat loss and maximum tensile forces. The hexagonal shape has a minimum tension force, average heat loss and a minimum step length; all the propellers are directed in parallel, which opens up the possibility of movement of tacks in case of need. At this stage of development, the hexagonal shape of the robot-pontoon is the most suitable.

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References
[1] Briskin E S, Kalinin Y V, Maloletov A V, Serov V A and Ustinov S A 2017 On controlling the adaptation of orthogonal walking movers to the supporting surface *J. of Comp. and Syst. Scien. Intl.* 3 T56
[2] Briskin E S and Leonard A V 2016 Energy profile and the open-loop control of the translational motion of the walking machine cyclone J. of Comp. and Syst. Scien. Intl. 6 T55
[3] Zhoga V V 1998 Computation of walking robots movement energy expenditure (Belgium, IEEE International Conference on Robotics and Automation) p 163-8
[4] Sychev V V and Bashkin V A 2003 Lectures on theoretical hydrodynamics studies. manual for University students in the direction of Butt. mathematics and physics vol 2 (Moscow: Phys.-tech. state University)
[5] Vasiliev A V 1989 Controllability of the ships (Leningrad: Shipbuilding) p 62
[6] Golubev Yu F and Pogorelov D Yu 1998 Computer simulation of walking robots vol 4 (Fundamental and applied mathematics) p 525-34
[7] Briskin E S, Sharonov N G, Efimov M I, Gulevsky V V and Penshin I S 2020 Some problems of controlling the cable propulsion devices of mobile robots 23rd Int. Conf. CLAWAR Robots in Human Life p 321-8
[8] Kalinin Y V and Miroshkina M V 2018 Dynamics walking robot with cyclic walking movers with minimum energy costs of moving 29-th Int. Conf. MICYSS p 283-5
[9] Chernyshev V V, Arykantsev V V, Kalinin Y V, Gavrilov A E and Sharonov N G 2015 Development of the walking mover for underwater walking vehicle (Vienna: Int. Conf. DAAAM) p 1143-8