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Original article

Thrust distribution of underwater salvage robot based on PSO optimization algorithm

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Abstract

In order to solve the problem of improper thrust distribution of each thruster of underwater vehicle, the PSO optimization algorithm is used to solve the problem of thrust distribution. According to the spatial layout of the thruster, the algorithm model of the underwater vehicle propulsion system is established. The thrust input is carried out under the broken line search trajectory, and the simulation verifies the thrust allocation results of the PSO algorithm and the traditional pseudo-inverse method. The simulation results show that compared with the traditional algorithm. First of all, the PSO algorithm can set the physical threshold for each thruster to prevent the thruster from having too much thrust. Secondly, it can ensure that the thruster can turn with a reasonable torque to prevent the robot from drifting due to the large thrust gap. This paper provides a theoretical reference for thrust distribution of underwater salvage robot, and has practical engineering significance.

Keywords: Underwater vehicle; thrust distribution; PSO algorithm; Pseudo-inverse method

https://doi.org/10.52820/j.enavi.2023.20.006

1. Introduction

With the development of science and technology and the development of marine resources, underwater vehicles are widely used in underwater exploration, operation and marine rescue. Some underwater vehicles are loaded with the number of thrusters exceeding their degrees of freedom to ensure their efficient movement and operation efficiency[1–3]. Because the number of thrusters exceeds the number of degrees of freedom, when the controller gives the target thrust and torque, the thrust distribution algorithm used needs to give the appropriate thrust size of each thruster, and the appropriate distribution algorithm can make the thrust distribution of each thruster more uniform.

The thrust distribution of the underwater vehicle distributes the target thrust and torque given by the controller to each thruster through the algorithm. The commonly used thrust distribution methods are direct method and pseudo-inverse method[4]. The direct method can realize the control in the horizontal plane and the vertical plane respectively[5]. According to the spatial structure, the thrust of the thruster is reversed from the target thrust and torque of the horizontal plane and vertical plane respectively, and the algorithm is simple and easy to use[6]. However, the spatial layout of the thruster needs to be considered in the design of the underwater vehicle, and the joint control is more complex and can not solve the problem of saturation. The pseudo-inverse method is used to calculate the pseudo-inverse of the thrust conversion matrix[7]. The thrust of each thruster is calculated by the pseudo-inverse matrix of thrust and moment controlled by the target, and the saturation problem needs to be solved by scaling or peak cutting. this will lead to a large gap between the actual thrust of each thruster and the torque and target value[8]. In recent years, scholars at home and abroad have some solutions to related problems. Wei Yanhui and others have proposed a thrust distribution strategy based on the least square method, which realizes the decoupling of each degree of freedom by establishing a thrust distribution model. and the least square method is used to solve the thrust of each thruster. Baldini et al. [9]proposed the fault-tolerant control strategy of underwater vehicle. On the basis of pseudo-inverse method, the influence of underwater thruster failure on robot motion control is taken into account. Shang Liubin[10], in view of the fact that the swarm intelligence algorithm is easy to encounter bottlenecks such as local optimization and long computing time in solving the dynamic positioning thrust distribution problem, based on the particle swarm optimization algorithm, they explore the influence of different particle decision variables on the result of thrust allocation. Particle swarm optimization algorithm is used to solve the problem of dynamic positioning thrust allocation. In recent years, with the progress of control algorithms and computer technology, adaptive control algorithms based on particle swarm optimization have been gradually developed. Particle swarm optimization algorithm is a random search algorithm developed by simulating the foraging behavior of birds[11].

The motion of the underwater salvage robot is inseparable from the power output of the thruster at each degree of freedom. The underwater salvage robot designed in this paper has eight underwater thrusters, and the thrust distribution of the underwater salvage robot is to be studied. In this paper, firstly, the thrust distribution problem of underwater salvage robot is changed into the optimization problem of mathematical model, which will be solved by traditional pseudo-inverse method and PSO algorithm respectively. Finally, the thrust of each thruster output by pseudo-inverse method and PSO algorithm is compared by simulation experiment. The results show that the physical threshold of each thruster can be set by using PSO algorithm to prevent the thruster from having too much thrust. Secondly, it can ensure that the thruster can turn with a reasonable torque to prevent drift due to the large thrust gap.

2. Mathematical modeling of propulsion system of underwater salvage robot

The arrangement of the thruster of the underwater salvage robot is first given before the thrust distribution of the underwater salvage robot. In figure 1, a 、b represents the transverse distance and the longitudinal distance between the center point of the thruster axis, and c represents the angle between the thruster and the forward direction. The angle is designed to be 45 °. The underwater plane motion of the robot is accomplished by the cooperation of the four vector arrangement thrusters.

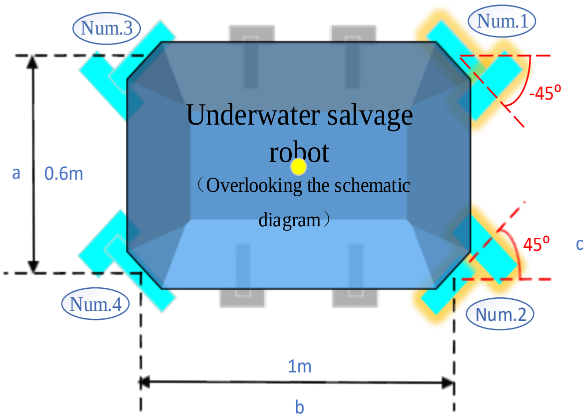

Figure 1: schematic diagram of overlooking structure of salvage robot

According to the arrangement characteristics of the thruster of the underwater salvage robot, the force and torque of each thruster in each direction during the horizontal three-degree-of-freedom motion are calculated. so that $U=[u_1,u_2,u_3,u_4]^T$ represents the output matrix of the four vector arrangement thrusters in the horizontal motion. where u_1,u_2,u_3,u_4 represents the thrust output of the four thrusters respectively. $\tau=[\tau_u,\tau_v,\tau_r]^T$ represents the control input of the control system respectively, where τ_u,τ_v,τ_r is the longitudinal force, transverse force and steering torque calculated by the control system during the motion of the robot. The longitudinal force, transverse force and steering torque required by the four thrusters to achieve plane motion require the following thrust distribution expressions:

$$\begin{aligned}\tau_u &= u_1\cos a + u_2\cos a - u_3\cos a - u_4\cos a\\ \tau_v &= u_1\sin a - u_2\sin a + u_3\sin a - u_4\sin a\\ \tau_r &= (u_1 - u_2 - u_3 + u_4)\left(\frac{a}{2}\cos a + \frac{b}{2}\sin a\right)\end{aligned} \quad (1)$$

Organize the formula (1) into matrix form:

$$\begin{bmatrix}\tau_u\\ \tau_v\\ \tau_r\end{bmatrix} = G\begin{bmatrix}u_1\\ u_2\\ u_3\\ u_4\end{bmatrix} \quad (2)$$

In the formula, the expression of G matrix is:

$$G=\begin{bmatrix}\cos a & \cos a & -\cos a & -\cos a\\ \sin a & -\sin a & \sin a & -\sin a\\ B & -B & -B & B\end{bmatrix} \quad (3)$$

In the equation $B=\frac{a}{2}\cos a+\frac{b}{2}\sin a$, so the relationship between the thruster thrust and the control system input is established:

$$\tau = GU \quad (4)$$

3. Research on propulsion system of underwater salvage robot

The core idea of thrust distribution is to use the optimal distribution of four thrusters on the horizontal plane of the robot to complete the control objectives of three virtual inputs of the control system, of which three virtual inputs are the control forces and moments of model heave, yaw and yaw. There is a threshold for practical engineering application in the output of the thruster, so optimization constraints need to be considered to effectively complete the thrust distribution, so there are two key indicators for the optimal allocation, one is to meet the actual thrust output threshold of the system engineering after thrust distribution. The second is to optimize the control torque after settlement to ensure that the optimal result of thrust distribution can be obtained.

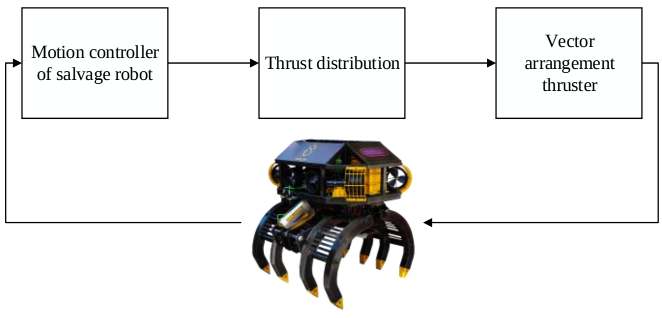

Figure 2:flow chart of thrust distribution of underwater salvage robot

4. Research on pseudo-inverse thrust distribution method.

As a classical thrust distribution method, pseudo-inverse thrust distribution is widely used in engineering practice. it has the characteristics of strong solving ability and less operation data, which is of great practical significance for the thrust distribution of multi-thruster ship robot in engineering applications. to prepare for the real-time thrust distribution in the case of follow-up complex faults. In this paper, the pseudo-inverse matrix is explained. First of all, the basic principle of the pseudo-inverse method is: suppose there is a nonsingular matrix A, and according to the relevant theoretical knowledge in linear algebra, then there must be an inverse matrix X corresponding to the A matrix, then the following formula holds:

$$AB = BA = E_n \tag{5}$$

In the formula E_n is the unit matrix of order n. When the A matrix is determined, there is and only one inverse matrix B corresponds to it.

At this time $B = A^{-1}$, when solving the system of equations $Ax = b$, when it is determined that A in the equation is an invertible matrix, then the equation has and only one solution $x = A^{-1}b$. However, when the matrix A is not a reversible matrix, the solution of the equation can not be solved by the above method, but needs to be solved by pseudo-inverse.

Because the installation angle of the horizontal thruster of the underwater salvage robot is fixed, the layout matrix of the thruster is a known matrix, and the quadratic optimization objective function is defined:

$$\begin{cases} min \quad f = U^T WU \\ \text{s.t.} \quad \tau - GU = 0 \end{cases} \tag{6}$$

In the formula, W is a fourth-order positive definite diagonal matrix, f is the energy consumption of the thruster, u is the output value of the four thrusters allocated by the pseudo-inverse method, G is the thruster layout matrix, and τ is the control input of the control system. According to the above objective function, the constraint lagrange function is established as shown in the following formula:

$$L(U, \lambda) = U^T WU + \lambda^T (\tau - GU) \tag{7}$$

Where λ is the lagreange operator.

U to solve partial differential in equation (7)

$$\begin{aligned} &\frac{\partial L}{\partial U} = 2WU - G^T \lambda = 0 \\ &U = \frac{1}{2} W^{-1} G^T \lambda \end{aligned} \tag{8}$$

Replace the formula into the objective function (8)

$$\begin{aligned} &\tau = GU = \frac{1}{2} GW^{-1} G^T \lambda \\ &\lambda = 2\left(GW^{-1}G^T\right)^{-1} \tau \end{aligned} \tag{9}$$

Type (9) instead of (8)

$$U = W^{-1}G^T \left(GW^{-1}G^T\right)^{-1} \tau = G^+ \tau$$

(10)

Simplified by formula (10)

$$G^+ = W^{-1}G^T \left(GW^{-1}G^T\right)^{-1}$$

(11)

When W is a unit matrix, the solution formula of pseudo inverse matrix can be obtained

$$G^+ = G^T \left(GG^T\right)^{-1}$$

(12)

5. Research on thrust Distribution method based on PSO Optimization algorithm

First of all, it is necessary to summarize the mathematical problems of thrust distribution of underwater salvage robot and refine the mathematical model. The essential problem of thrust distribution is to input the three system controllers on the left side of the formula and calculate the most suitable thrust values of the four thrusters on the right by exhaustive method. It is explained mathematically that the values of each of the four independent variables are given the values of three dependent variables. Therefore, there are numerous groups of independent variables, but the value of independent variables is not arbitrary, there is a range of independent variables, and there are engineering constraints for equipment to save energy and reduce wear and tear among independent variables. even if there are multiple constraint independent variables, there are still infinitely many cases, for countless kinds of power output cases, it is necessary to choose the best case. Through the transformation of mathematical analysis, the thrust distribution problem of underwater salvage robot is transformed into the optimal solution problem under constraints. The mathematical model is:

$$\left\{\tau = GU \mid U_{\min} \le U \le U_{\max}\right\}$$

(13)

Where $U_{\min}, U_{\max}$ is the minimum and maximum value of the thruster output, respectively.

Determine the evaluation index: 1. Calculate the error index. The error between the optimized output solution of the algorithm and the actual thruster output is minimized. two. Thrusters contribution indicators. By measuring the contribution index of each thruster, the output value of the four thrusters will not be overworked to use a thruster within a reasonable range, thus aggravating the wear and tear of the thrusters.

According to the above evaluation index, the mathematical model and constraint function of thrust distribution of underwater salvage robot are established.

$$\min J = \| GU - \tau \|_2^2 + h \| \tau - \tau_0 \|_2^2$$
$$\text{s.t.} U_{\min} \le U \le U_{\max}$$
(14)

In the formula, $h \ge 0$, as a weighting coefficient, adjusts the proportion of $\| \tau - \tau_0 \|$ in the model.

On this basis, the robot is designed to operate with appropriate force to prevent drift due to the large thrust gap. The mathematical model obtained is:

$$\min J = \| GU - \tau \|_2^2 + h \| \tau - \tau_0 \|_2^2 + v \left| u_1 \cos a - u_2 \cos a - u_3 \cos a + u_4 \cos a \right|$$
$$\text{s.t.} U_{\min} \le U \le U_{\max}$$
(15)

In the formula, $v \ge 0$, as a weighting coefficient, adjusts the proportion of $\left| u_1 \cos a - u_2 \cos a - u_3 \cos a + u_4 \cos a \right|$ in the model.

Therefore, through the above mathematical analysis, the thrust distribution problem of the underwater salvage robot becomes the optimization problem of the mathematical model. This section will use the particle swarm optimization algorithm (PSO) to solve.

Principle of particle swarm optimization algorithm.

Particle swarm optimization (PSO) was proposed by Kennedy and Eberhart in 1995. It is to find the optimal solution of the optimization problem through the iterative cycle of particles and the iterative cycle of particle swarm. The representation of the algorithm is the search process in which the algorithm particles follow the optimal particles to the better solution. This method has the advantages of simple operation, small operation load and few parameters, so it is a hot method in the field of modern optimization research.

6. Optimal Design and Simulation experiment of PSO thrust Distribution

Carry on the simulation design on the basis of broken line:

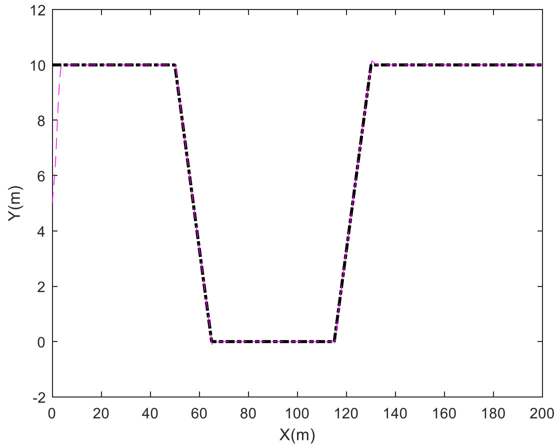

Figure 3: Broken line trajectory diagram

The desired torque diagram of the longitudinal, horizontal and steering control system is as follows:

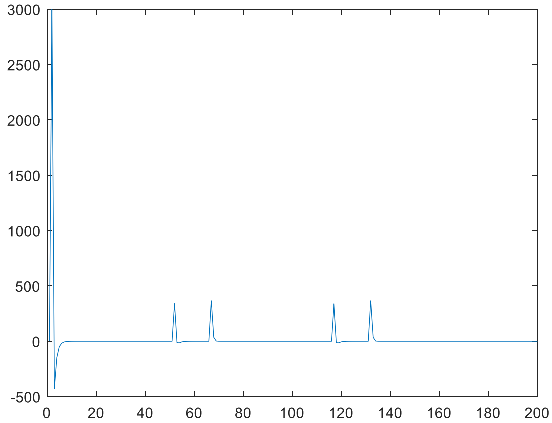

Figure 4: Desired torque of longitudinal control system

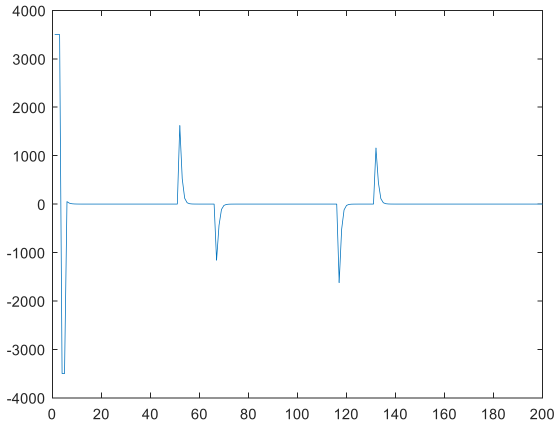

Figure 5: Desired torque of lateral control system

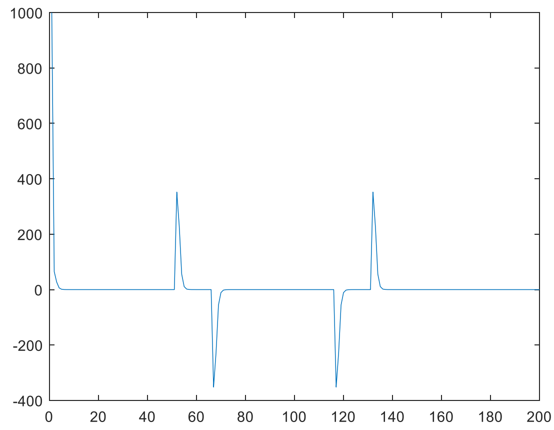

Figure 6: Desired torque of steering control system

The mathematical model of thrust distribution of underwater salvage robot is

$$\min J = \|GU-\tau\|_2^2 + h\|\tau-\tau_0\|_2^2 + \text{v}\left|u_1\cos a - u_2\cos a - u_3\cos a + u_4\cos a\right|$$
$$\text{s.t.}U_{\min} \le U \le U_{\max}$$
(16)

According to the actual working knowledge of the underwater salvage robot, $h=0.8, \tau_0=\begin{bmatrix}0 & 0 & 0\end{bmatrix}^T$, $\text{v}=1.0$ is designed, and the ultimate thrust threshold of the thruster is $+130\text{kgf} \sim -110\text{kgf}$. in order to reduce the full load operation of the thruster, the optimized thrust threshold is designed at $+100kgf \sim -100kgf$. The design parameters of PSO algorithm are as follows: particle swarm size $N=20000$, number of iterations $K=20000$, inertia factor $w=0.5$, weight parameter $c_{ij}, i:1-4$ is thruster number, $j:1,2$ is self-cognitive learning factor and group cognitive learning factor. Where $c_{11}=0.6, c_{12}=0.9, c_{21}=1.2, c_{22}=1.3, c_{31}=1.3$ $c_{32}=1.4, c_{41}=1.2, c_{42}=1.5$ and particle velocity constraint $v:[-75,75]$. The pseudo-inverse method and PSO method are used to calculate the thrust of each thruster, and then the thrust and torque can be calculated according to Line chart. In order to verify the thrust distribution effect of underwater salvage robot based on PSO algorithm, the real-time thrust distribution of thruster is optimized and compared with pseudo-inverse algorithm.

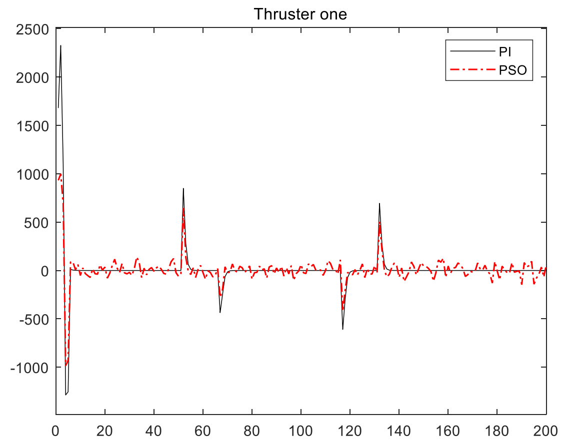

Figure 7: thruster-thrust output

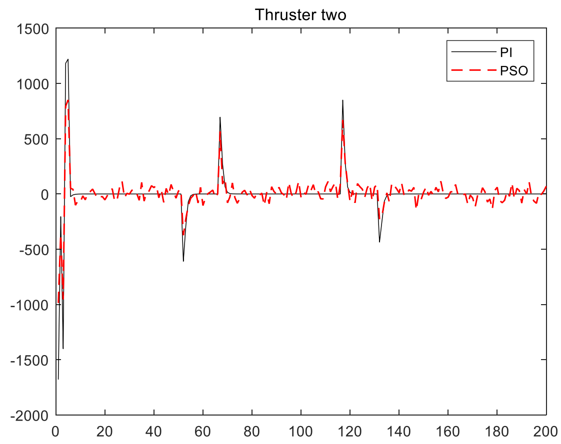

Figure 8: two-thrust output of thruster

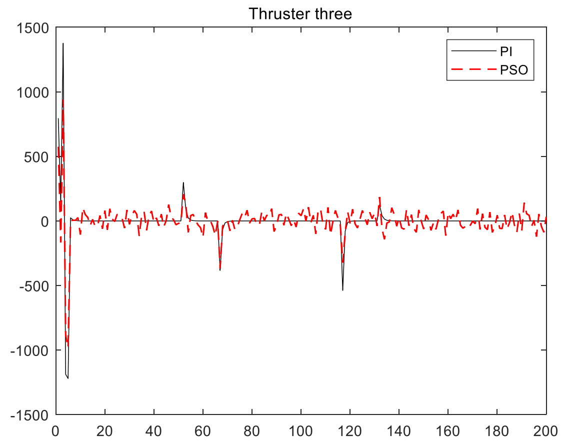

Figure 9: three-thrust output of thruster

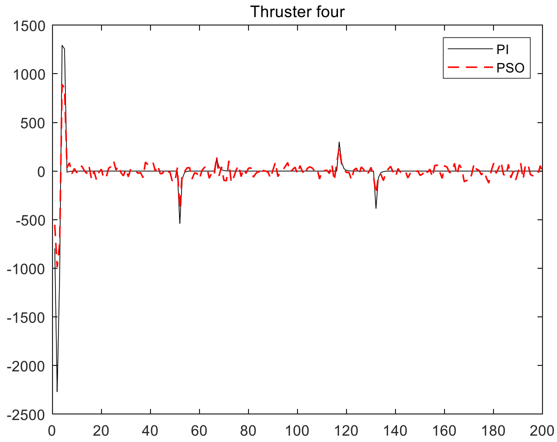

Figure 10: four-thrust output of thruster

The thruster thrust calculated by the original pseudo-inverse method will exceed the upper and lower limit of the thruster thrust. Here, the PSO method is used to deal with the saturation problem of the pseudo-inverse method. It can be seen that the thrust of all thrusters calculated by PSO method does not exceed its upper and lower limits. It can be seen from the figure that there is a large gap between the thrust and torque of the thruster obtained by the pseudo-inverse method and that of the target, while the gap between the thrust and torque of the thruster obtained by the PSO algorithm and the target thrust and torque is small. At this time, the thrust and torque of the thrust combination obtained by the PSO method of the thruster can be nearly equal to that of the target.

7. Conclusions

The mathematical model of propulsion system is established by matrix operation, and the simulation results are obtained by comparing PSO algorithm with traditional pseudo inverse method in the process of thrust distribution. The results show that PSO algorithm can constrain the thrust of underwater salvage robot, overcome the problem of thrust saturation, and distribute thrust to each thruster reasonably. It can ensure that the thruster can carry out predetermined steering and other operations to prevent drift.

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Received 28 May 2023
Revised 26 June 2023
Accepted 29 June 2023