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Quadratic Programming Thrust Allocation and Management for Dynamic Positioning Ships

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Abstract

To solve the complex thrust allocation problems of dynamic positioning ship with azimuth thrusters, the quadratic programming thrust allocation and management system was built. The power optimal thrust allocation was formulated as a quadratic programming problem by the linear treatments of inequality constraints and the optimal solution could be found in a finite amount of time. And some influence factors of thruster allocation were separated from algorithms and treated as a superstratum management module. In this system, online adjustment of input constraints and singularity avoidance could be realized, and the reliability and adaptability of thrust allocation were improved consequently. Finally, the validity and excellent performance of this method was proved by the simulation.

Keywords*: dynamic positioning system, azimuth thruster, thrust allocation management, thrust allocation, quadratic programming.*

1. Introduction

Dynamic Positioning System (DPS) is the primacy support equipment for a marine vessel used in deep-sea working, especially for engineering ships which engaged in deepwater oil and gas exploitation for long term such as drilling vessel, survey ship, floating crane, pipelaying vessel and cable layer etc. New Dynamic Positioning (DP) ships have gradually abandoned the conventional concept that assembling a ship with main propeller, lateral thruster and rudder, and began to use steerable or azimuthing thrusters as main propulsion units [1]. Compared with conventional propulsion, azimuth thruster can produce thrust force of the horizontal plane in any direction, arrange more freely, and very suitable for the work characteristics of DP ships.

Thrust allocation in DPS offers the advantage of a modular design where the high-level motion control algorithm can be designed without detailed knowledge about the effectors and actuators. The thrust allocation problems task is to distribute the commanded generalized force which computed by the motion controller to thrust devices, and compute the desired thrust force and direction of each thruster and rudder onboard the vessel. Good maritime application overviews of thrust allocation can be found in [2-4].They are naturally formulated as a constrained optimization problems and solved on-line to find the actuator commands that implement the desired generalized forces while satisfying power, magnitude, rate, and other constraints. In this paper, the thrust allocation problem is treated as a convex quadratic optimization problem with linear constraints and solved by Quadratic Programming (QP) algorithm. The benefits of using QP algorithms are that it is guaranteed that the existence of only one minimum or an infeasibility solution will be found in a finite amount of time, whereas with non-linear optimizations techniques these guarantees cannot be given.

When designing a thrust allocation scheme some choices must be made towards robustness and performance. It is difficult to find a method adapt to all types of thrust allocation problems, especially when changing of operating conditions, thruster faults, or changing of actuator configurations are occurred. Moreover optimization of the power consumption in thrust allocation tends to rotate the thrusters into near singular configurations. These might make the thrusters toward the mean environmental forces, and sudden forces acting perpendicular to the direction of the thrusters might get the ship out of its position. In these cases there are a trade-off between having the best maneuverability and the best power-efficient solution. Singularity

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avoidance is useful to avoid temporarily loss of controllability and stream interactions between thrusters, however it represents a challenging problem for ships with azimuth thrusters since a non-convex nonlinear program must be solved. To solve the above problems, the concept of thrust allocation management was introduced and the influence factors of thruster allocation were treated as a superstratum management module and separated from algorithms. Applying the scheme, the thrust allocation procedures were simplified effectively, and the optimization calculation time and singular configurations were improved significantly.

2. Architecture of Thrust Allocation and Management System

The thrust allocation and management system is composed of two parts: thrust allocation algorithm and thrust allocation management [5]. The DP control loops with the thrust allocation and management system are defined as Figure 1.

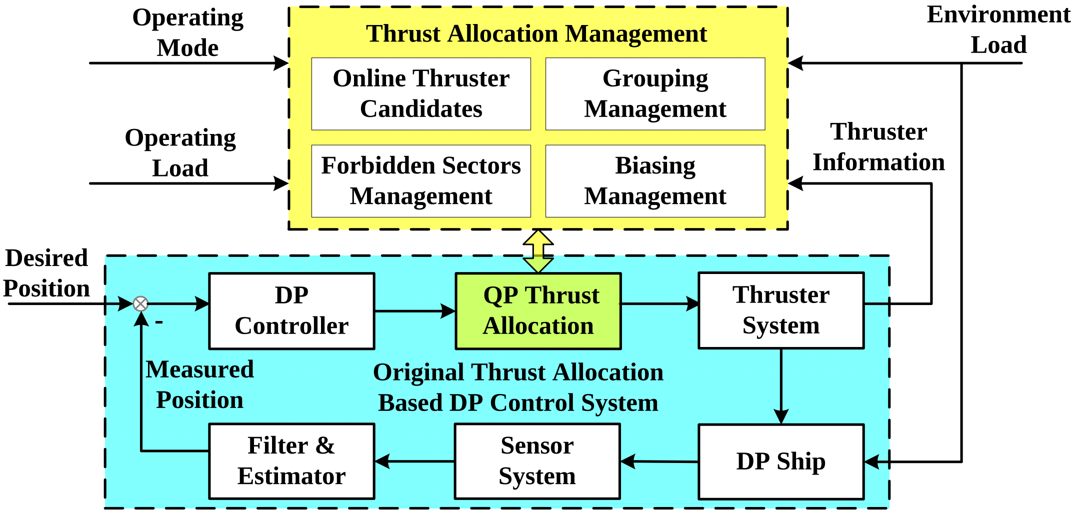

Figure 1. The DP control loops with the thrust allocation and management system

The thrust allocation algorithm is the foundation of the system. It calculates a set of feasible effectors and actuators deflections that will generate the required control commands. Optimization methods can commonly be used, in order to seek the energy optimal solution that implement the desired generalized forces in surge, sway, and yaw. The object function of power optimization algorithm is total power consumptions, and power limits and actuator constraints (e.g. forbidden sectors and thruster faults) are taken into account simultaneously. In addition, thruster efficiency and wear/tear of motor should be concerned.

The thrust allocation management is the upper level system based on the algorithm. It helps to improve the flexibility and adaptability of the thrust allocation algorithm. Actuators candidates and forbidden sectors should be determined and implemented in this module according to the status information of DP ship such as operating mode, thruster faults, actuator configurations, operating load and environmental load etc. Grouping and biasing are also utilized on the basis of the thruster configuration in order to solve the singularity problems and avoid stream interactions between thrusters.

3. Quadratic Programming Thrust Allocation

3.1. Power Optimal Thrust Allocation

The power optimal thrust allocation is a complex mapping from a demanded force and turning moment to a set of thrust and azimuth setpoints. In order to avoid the complicated relationship of nonlinear, we follow the procedure in [6] where the concept of extended thrust force is introduced. Defined the thrust and azimuth of actuator by $\mathrm{f}, \alpha \in \mathbb{R}^{n\times 1}$, the power optimal thrust allocation can be generally stated as follows:

$$\begin{aligned} & \mathrm{J} = \min\left\{\mathrm{u}^{\mathrm{T}}\mathrm{W}\mathrm{u}\right\} \\ & \text{s.t.} \quad \mathrm{Bu} = \tau, \quad \sqrt{\mathrm{u}_{\mathrm{i,x}}^2 + \mathrm{u}_{\mathrm{i,y}}^2} \le \mathrm{f}_{\mathrm{i,max}} \end{aligned} \tag{1}$$

where $u^T W u$ denotes energy consumptions, the cost/weight matrix W is a diagonal matrix with the positive cost factors on the diagonal, $\tau = [\tau_x \ \tau_y \ \tau_m]^T \in \mathbb{R}^{3\times 1}$ represent the commanded generalized force computed by the motion controller, $f_{\max}$ is the maximum force of thruster , B and u are the extended configuration matrix and thrust force vector respectively, the extended thrust force is given as follow:

$$\begin{cases} u_i = [u_{i,x}, \ u_{i,y}]^T \\ u_{i,x} = f_i \cos\alpha_i, \quad u_{i,y} = f_i \sin\alpha_i \end{cases} \tag{2}$$

But the inequality constraints in equation (1) cannot meet the requirements of QP algorithm. They are nonlinear constraints and cannot be solved by QP method, therefore need to be linearized.

3.2. Inequality Constraints Linearization

The thrust region for an azimuth thruster without any forbidden zones has a circular shape with radius $R = f_{\max}$. As shown in Figure 2, it can be approximated by a inscribed N-sided regular polygon ($N \ge 3$) with a approximation error [7]. The regular polygon divides the circular region into N circular sectors, each having a central angle of $\theta = 2\pi/N$.

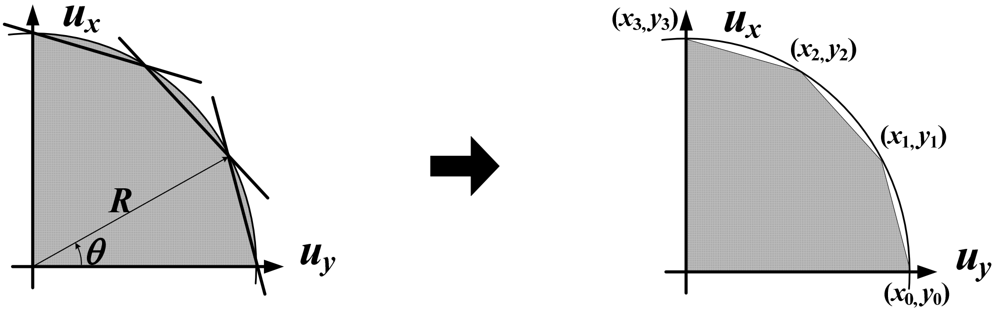

Figure 2. The thrust region approximated by a regular polygon

Forbidden zones of azimuth thrusters can be defined by taking out some portion of the thrust region. As a result, some circle sector/pie shaped regions are left over. This way the solver is prevented from allocating thrust in the defined forbidden zone, because it will no longer be part of the feasible set in which the solver searches for its solution. To create pie shaped thrust regions, the similar approximation method can be used again.

To obtain the inequality constraint for every pie shaped region, we define (x_k, y_k) as the approximation polygon vertices, $k = 0,1,\cdots,N$. Assuming that the polygon vertices are ordered counterclockwise the thrust region is defined by:

$$\begin{bmatrix} a_{i,11} & a_{i,12} \\ a_{i,21} & a_{i,22} \\ \vdots & \vdots \\ a_{i,N1} & a_{i,N2} \end{bmatrix} \begin{pmatrix} u_{i,x} \\ u_{i,y} \end{pmatrix} \le \begin{bmatrix} b_{i,1} \\ b_{i,2} \\ \vdots \\ b_{i,N} \end{bmatrix} \Leftrightarrow A_i u_i \le b_i, \quad \begin{aligned} a_{k1} &= y_k - y_{k-1} \\ a_{k2} &= x_{k-1} - x_k \\ b_k &= x_{k-1} y_k - x_k y_{k-1} \\ (x_N, y_N) &= (x_0, y_0) \end{aligned} \tag{3}$$

3.3. QP Thrust Allocation Models

In order to generate a solution always and avoid solutions with large differences in the amount of thrust, the slack variable and penalty to the maximum thrust force are introduced [7]. The thrust allocation models are defined by:

$$\begin{aligned} & J = \min_{u,s,\bar{u}} \left\{ u^T W u + s^T Q s + \beta \bar{u} \right\} \\ & s.t. \qquad Bu - s = \tau \\ & \qquad Au \le b, \quad -\bar{u} \le u \le \bar{u} \end{aligned} \tag{4}$$

Therefore the QP models of thrust allocation are given as follow:

$$\begin{aligned} & J = \min_{u,s,\bar{u}} \begin{bmatrix} u \\ s \\ \bar{u} \end{bmatrix}^T \begin{bmatrix} W & 0 & 0 \\ 0 & Q & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ s \\ \bar{u} \end{bmatrix} + \begin{bmatrix} 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} u \\ s \\ \bar{u} \end{bmatrix} \\ & s.t. \quad \begin{bmatrix} B & -I & 0 \end{bmatrix} \begin{bmatrix} u \\ s \\ \bar{u} \end{bmatrix} = \tau \quad , \quad \begin{bmatrix} A & 0 & 0 \\ -I & 0 & -1 \\ I & 0 & -1 \end{bmatrix} \begin{bmatrix} u \\ s \\ \bar{u} \end{bmatrix} \le \begin{bmatrix} b \\ 0 \\ 0 \end{bmatrix} \end{aligned} \tag{5}$$

where s is the slack variable, $\bar{u} = \max_i |u_i|$ is the largest force among extended thrusts, and $\gamma \ge 0$, $Q \gg W > 0$. It can be solved by mathematical optimization software easily.

4. Thrust Allocation Management

4.1. Online Actuators Management

Because of the high actuator redundancy, it is unnecessary that all the thrusters bring into operation simultaneously. Thus, online thrusters candidates need be implemented and corresponding forbidden sectors should be determined. The function of online actuators management is to list the candidate thrusters for thrust allocation according to the operating mode, thruster faults, actuator configurations, operating load and environmental load etc.

To avoid numerical problems, the QP problem can be scaled before it goes to the QP solver. After the scaled QP problem is solved, the solution is scaled back again. Especially when the quadratic weight/cost coefficients (in the matrices W and Q) are large, numerical problems can arise, therefore the scaling factor c_{scale} is chosen such that：

$$c_{scale} \left| f_{\max} \right|^2 \approx 1 \tag{6}$$

Forbidden sectors can be also defined for an azimuth thruster because the exhaust flows of azimuth thruster might impact other adjacent thrusters or underwater equipments. Forbidden sectors are illustrated by the angle between the axis of the two propellers and relate to the distance between the two thrusters and the thruster diameter. The estimations of the thrust losses for the downstream thruster to the practical engineer accuracy which proposed by Dang etc. are used in the calculation of forbidden sectors by the most dynamic positioning equipment suppliers including KONGSBERG. When the angle between the axis of the two propellers is ϕ, the thrust losses t_ϕ is defined by [8]:

$$t_\phi = t + (1-t)\frac{\phi^3}{130/t^3 + \phi^3} \qquad (7)$$
$$t = 1 - 0.75^{(x/D)^{\frac{2}{3}}}$$

where, x is the distance between the two thrusters, D is the thruster diameter, and t is the thrust losses while $\phi = 0$.

4.2. Grouping and Biasing

Thruster biasing allows azimuth thrusters to counteract each other among a group so that the effect of the biasing is zero. In many cases, it is utilized such as an azimuth thruster cannot give zero thrust, a higher power consumption is required or the weather is calm. The rotation of azimuth thrusters can be reduced significantly while commands changing. Thruster biasing does not limit the capacity of the thrusters because the counteraction will be reduced along with the increase of total demand. Benefit from the characteristics of grouping and biasing, singularity problems and stream interactions between thrusters can be improved effectively without solving a non-convex nonlinear program. The details of grouping and biasing are illustrated in [9].

5. Simulation Results

According to [5], the same ship models and controllers are adopted. The configuration and grouping of the thruster system is shown in Figure 3. The forbidden sectors of thrusters are illustrated by Table 1.

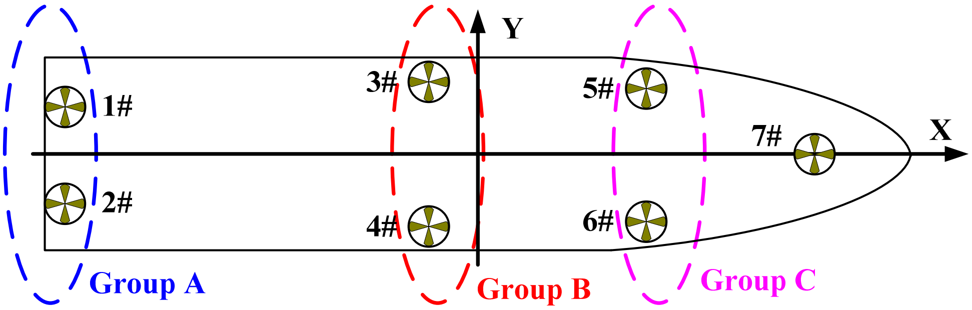

Figure 3. The configuration and grouping of the thruster system.

Table 1. The forbidden sectors of azimuth thrusters.

Number	Interaction centre	forbidden sectors
1#	-90°	16°
2#	90°	16°
3#	-90°	12°
4#	90°	12°
5#	-90°	13°
6#	90°	13°
7#	-	-

Position control is implemented from its initial position (0m, 0m, 0°) to object position (5m, 5m, 10°). In simulation, all the thrusters are working from 0s to 50s, and 3#, 4# and 7# are shut down after 50s. Biasing factor of every group is defined as 30%. Weight coefficients are as follow: $W = I^{14\times14}$, $Q = diag\{100,\ \ 100,\ \ 200000\}$, $\gamma = 1$.

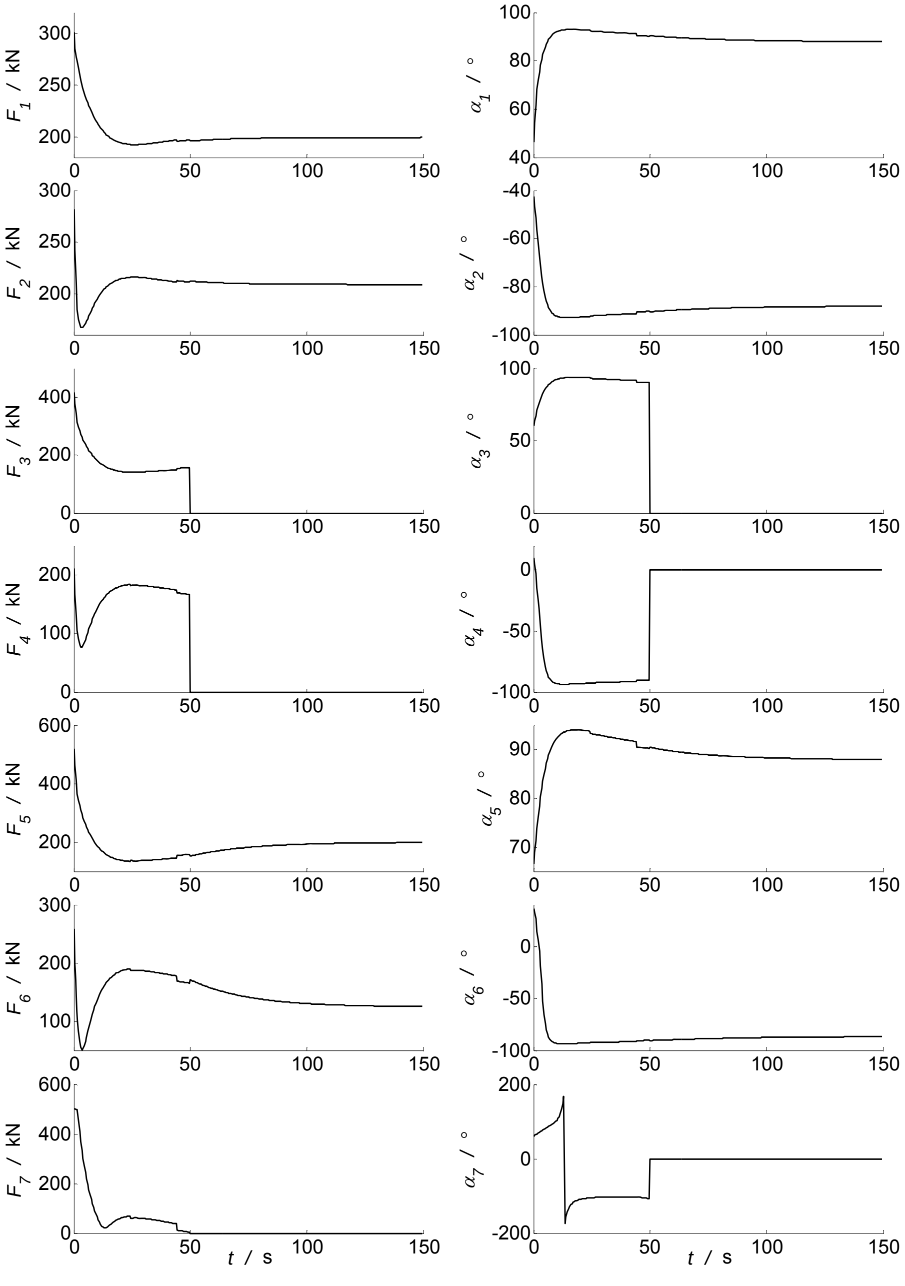

Figure 4. The Thrust forces and azimuths of thrusters.

In the simulation, the DP ship moves to object position slowly and remains stable with tolerated error after about 100s. Figure 4 shows the simulation outputs of azimuth thrusters. It is seen that the thrust forces and azimuth angles keep rapid changes since the simulation beginning and become slow at about 20s. After 3#, 4# and 7# shutting down, their outputs return to zero and the others tend to stability after about 100s. During simulation, the azimuths of online thrusters are distributed in four quadrants and thus singular configurations are avoided.

6. Conclusion

Thrust allocation and management system is presented based on quadratic programming algorithm in this paper. The power optimal thrust allocation is formulated as a quadratic programming problem by the linear treatment of inequality constraints. Online actuator candidates, forbidden sectors, grouping and biasing of thrusters are treated in the management module. It is helpful to improve the flexibility and adaptability of QP thrust allocation algorithm. Simulation results are satisfying and solidity. Applying the method, online adjustment of input constraints and singularity avoidance can be realized, and the reliability and adaptability of thrust allocation were improved consequently.

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