P-8

Ship Berthing Assistant System Design with Tugboats

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Introduction

In marine literature review, ship berthing maneuvering is considered as the most complex mission, with high pressure to ensure safe operation. The motion of ship in this stage is usually required as pure sway motion without tuning and rotating around a position. In order to realize these missions, the ship master has to detect exactly ship position as well as accurately predict her motion to prevent collision. These tasks often exceed the limit information processing ability of human.

For above reason, automatic berthing approaches have been concerned from early 1990's. It is noticed that recent researches concentrate to develop intelligent control strategies without knowledge of model such as fuzzy control methods and neural network techniques with advantages of embed human experiences and knowledge about ship behavior into control strategies. However, in these approaches, the limits of actuator controllability in dead slow velocity condition have not been solved yet.

To overcome these drawbacks and reach to a fully automation solution, in this paper, we propose the new approach for ship berthing by using autonomous tugboats. The modeling of system is presented and discussed. Also, the control allocation problem for this over-actuated system is formulated as optimization problem and solved by using redistributed pseudo inverse matrix approach.

System Model

With considering of low speed maneuvering, the motion of ship can be linearized and vectorized by following form [1]

$$M\dot{v} + Dv = \tau, \qquad (1)$$
$$\dot{\eta} = R(\varphi)v$$

where $M \in R^{3\times3}$ and $D \in R^{3\times3}$ are the inertia and damping matrix. $\eta = [x, y, \varphi]^T \in R^3$

represents the inertial position (x, y) and the heading angle φ in the earth fixed coordinate frame, $v=[u, v, r]^T \in R^3$ describes the surge, sway and yaw rate of ship motion in body fixed coordinate frame, and $R(\varphi)$ denotes the rotation matrix which translates ship coordinate into inertial coordinate frame.

By using assistance of tugboats, the vector of total forces and moment in surge, sway and yaw, $\tau=[X, Y, N] \in R^3$ is the result of combined efforts of four tugboats and are related by following combination

$$\tau = Bf \tag{2}$$

where $f=[f_1\, f_2\, f_3\, f_4]^T \in F$ is the vector unidirectional control force of tugboats. The set of F is described as $0 < f_i < f_{\max}, \forall i \in (1, ..., 4)$. Geometric configuration matrix $B \in R^{3\times 4}$ captures relationship between tugboats and ship.

Assume that we can parameterize the i^{th} contact point by using the angle θ_i measured clockwise, relative to X axis of the body fixed coordinate frame as $\{x(\theta_i)\vec{i}+y(\theta_i)\vec{j} \in \partial C\}$ where ∂C is the boundary of ship. In addition, we define a parameter α_i which indicates the direction of tugboat, measured clockwise and relative to X axis of the body fixed coordinate frame. So, the vector forces and moment τ can be expressed in form of matrix B and vector control force f as

$$\tau = \begin{bmatrix} c\alpha_1 \; s\alpha_1 - y(\theta_1)c\alpha_1 + x(\theta_1)s\alpha_1 \\ c\alpha_2 \; s\alpha_2 - y(\theta_2)c\alpha_2 + x(\theta_2)s\alpha_2 \\ c\alpha_3 \; s\alpha_3 - y(\theta_3)c\alpha_3 + x(\theta_3)s\alpha_3 \\ c\alpha_4 \; s\alpha_4 - y(\theta_4)c\alpha_4 + x(\theta_4)s\alpha_4 \end{bmatrix}^T \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{3}$$

where $s\alpha_i = \sin(\alpha_i)$ and $c\alpha_i = \cos(\alpha_i)$

Formulation of Control Allocation

Control Allocation Problem

Control allocation determines the direction α_i and the required force f_i for each tugboat to give the desired forces in surge and sway motion as well as moment in yaw motion from controller signal τ_c. It is formulated as optimization [2] so that

1. $\| \tau(\alpha_i, f_i) - \tau_c \|$ is small to minimize the error between actual thrusts and desired signals from controller
2. $\| \tau(\alpha_i, f_i) \|$ is small to minimize the power consumption
3. $\alpha_i(t)$ is slow varying to suit with the dynamic response of tugboats and minimize

Solution for Varying Direction

Suitable direction for tugboat can be handled by using extended control force representation. The thrust supplied from each tugboat is separated into two elements, relative to x and y direction of body fixed coordinate frame, and the direction of tugboat can be found as follows

$$\alpha_i = \begin{bmatrix} \tan^{-1}\left(\frac{F_{iy}}{F_{ix}}\right) \text{ if } \underline{x} \leq \alpha_i \leq \overline{\alpha} \\ \underline{\alpha} \text{ if } \alpha_i < \max(\alpha_{\min}, \alpha_{i-1} - \Delta t.\dot{\alpha}) \\ \overline{\alpha} \text{ if } \alpha_i < \min(\alpha_{\max}, \alpha_{i-1} + \Delta t.\dot{\alpha}) \end{bmatrix} \quad (5)$$

Solution for Magnitude Force

In this paper, control force optimization is solved by using the redistributed pseudo inverse method. This approach is the constrained optimization technique. After solving force distribution. If no control f_i exceeds their minimum or maximum values, the process stop and this solution is used. However, if one of them exceeds limits, the problem is solved again.

Simulation Results

To demonstrate this study, a model ship, Cybership I with have following particulars, is simulated through the Matlab environment. Ship is maneuvered from the starting point (0, 0) with 45 degree in the orientation to end point (5, 5) with the 0 degree in yaw angle. Fig.4 shows good performance of ship motion without oscillation, overshoot and steady state error. The direction and control force of tugboats is shown in Figs. 5~6. It satisfies to minimize power consumption supplied from tugboats in constraints about slow change direction and power saturation.

Conclusion

In this paper, we proposed the new approach for ship berthing with assistance of autonomous tugboats. The modeling of system is figured out as well as control allocation optimization is presented. Efficiency of proposed approach is also evaluated through simulation of model ship in Matlab environment. It showed good performance and possible to extend this study in future by testing the model in real condition.

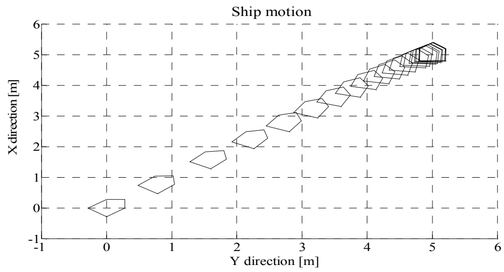

Fig.4 Ship motion in horizontal plan

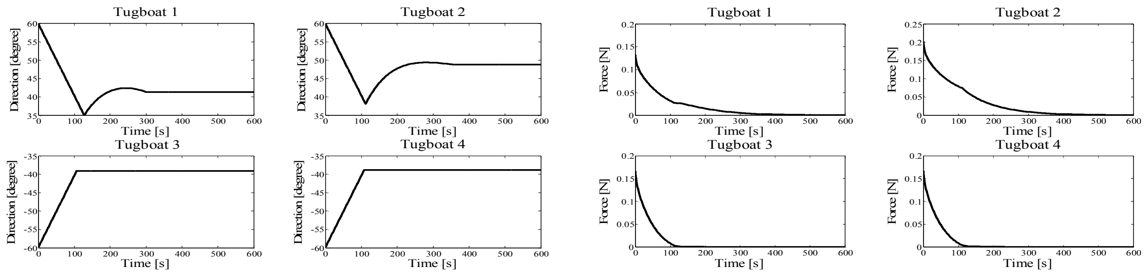

Fig.5 Direction and distribute force of tugboats

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