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A Development of Constrained Control Allocation for Ship Berthing by Using Autonomous Tugboats
터그보트를 이용한 선박접안제어기술 개발에 관한 연구

H. M. Bae, V. P. Bui, S. S. Lee and Y. B. Kim
배헌민 · 부이반퍽 · 이동석 · 김영복

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주요용어 : 선박모델(Ship model), 선박접안(Ship Berthing), 제어력분배(Control allocation), 터그보트(Tugboat), 접안지원시스템(Berthing Assistant System)

요약 : 접안을 위해 선박이 안벽으로 접근할 때나, 좁은 항내에서 선박을 조종할 때는 항해 중에서보다 많은 제약이 따른다. 그것은 대형 선박일수도 큰 관성력으로 인해 효과적인 제어가 어렵기 때문이다. 그래서 터그보트를 수동적으로 제어하여 선박을 접안시키는 것이 현재로선 가장 일반적이 접안기술이라 할 수 있다. 지능적인 제어기술을 적용하여 자동접안을 시도하려는 연구결과가 보고되고 있으나, 대부분이 auto-pilot 기술에 지나지 않으며 어느 것 하나 안정적인 접안을 위한 접안기술로 볼 수 없다. 이와 같이 터그보트를 이용할 수밖에 없는 현실이라면, 보다 효과적인 터그보트 제어기술을 기반으로 한 접안지원시스템을 개발하는 것이 우선일 것이다. 그래서 본 논문에서는 터그보트의 원격제어를 통해 모선을 효과적이고 안정적으로 접안하는 문제에 대해 고찰하였다. 즉, 터그보트로 조종되는 선박조종시스템에 대한 모델링을 수행하고, 터그보트로부터 발생되는 제어력을 적절히 분배하여 모선을 제어하는 새로운 접안지원시스템을 개발하였다. 시뮬레이션을 통해 제안된 시스템의 유효성을 검증하였다.

Ⅰ. Introduction

In marine literature review, ship berthing maneuvering is considered as the most complex mission, with high pressure to ensure safe operation. Compared with the other missions as autopilot for steering, position tracking (that includes the trajectory tracking and path following), dynamic positioning or station keeping, it requires many process from helmsman. At the stage, where the vessel moves from the open sea to confined water, the ship velocity has to be kept in dead slow, so the controllability of actuators (main propeller, rudder and so on) is significantly reduced. Especially, when the ship commences to a jetty, it is a stressful and hard work for maneuvering. 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. He has to consider a lot of information, for examples condition of maneuvering, characteristic of actuators, effect of wind, wave and current disturbances as well as condition of tugboats. These tasks often exceed the limit information processing ability of human.

For above reason, automatic berthing approaches have been concerned from early 1990's. With difficulties to capture the change of hydrodynamic coefficients, it is not surprising to notice that recent researches concentrate on developing intelligent control strategies without knowledge of model such as fuzzy control methods[1,2] and neural network techniques[3-5] with

배헌민(교신저자) : 국립수산과학원
E-mail : hmb0202@nfrdi.go.kr, Tel : 051-720-2220
Van Phuoc Bui, 이동석 : 부경대학교 대학원
김영복 : 부경대학교 기계시스템공학과

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. So it is too risk for applying these methods into the real situation. Although the advent of new propulsion technologies such as tunnel thruster, accurate differential global positioning system (DGPS) and camera sensing system, it still has not a complete automation solution for ship berthing. Until now, large ship maneuvering in the harbor area is still done by assistance of tugboat manually.

To overcome these drawbacks and reach to a fully automation solution, in this paper, we propose a 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. One of objectives of this approach is to minimize the control power produced from each tugboat subject to slow varying direction, unidirectional thrust(pushing), contact angle between ship and tugboat as well as power saturation.

The remainder of this paper is structured as follows. In Section II, we provide the second order dynamic system of ship considered in horizontal plane. The thrust configuration matrix is studied through force decomposition analysis. Control allocation problem based on redistributed pseudo inverse matrix is built. Optimal solution for power consumption subject to constraints of tugboat dynamic is presented in section III. Section IV estimates the efficiency of proposed approach by model ship control simulation. Conclusion and future research are summarized and discussed in the Section V.

II. System Model

With considering of low speed maneuvering and under hypothesis that the ship is symmetry through XZ plane as well as the center of gravity coincides with center of geometry, the motion of ship can be linearized and vectorized by following form[6)]

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

where $M\in R^{3\times3}$and $D\in R^{3\times3}$ are the inertia and damping matrix. These can be determined respectively as follows

$$M=\begin{bmatrix} m-X_{\dot{u}} & 0 & 0 \\ 0 & m-Y_{\dot{v}} & -Y_{\dot{r}} \\ 0 & -N_{\dot{v}} & I_z-N_{\dot{r}} \end{bmatrix},\qquad D=\begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix} \tag{2}$$

$\eta=[x,y,\varphi]^T\in R^3$ 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 and given by

$$R(\varphi)=\begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

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 as shown in Fig. 1 and are related by following combination

$$\tau=Bf \tag{4}$$

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 $0<f_i<f_{\max},\ \forall i\in(1,\ldots,4)$.

Geometric configuration matrix $B\in R^{3\times4}$ captures relationship between tugboats and ship.

Assume that we can parameterize the i^{th} contact point $\{x_i,y_i\}$ by using the angle θ_i measured clockwise, relative to X axis of the body fixed coordinate frame as $\{x(\theta_i)\vec{i}+y(\theta_i)\vec{j}\in\partial C\}$

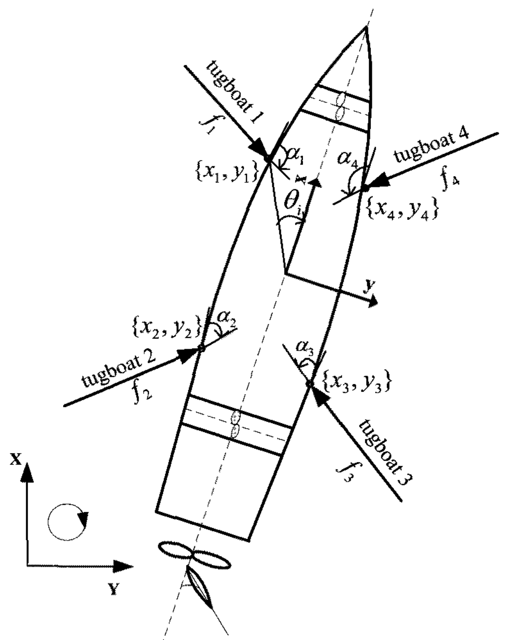

Fig. 1 System description

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 contact configuration of the tugboat i^{th} can be presented by a vector $[\theta_i, \alpha_i]$ as follows

$$B_i = \begin{bmatrix} \cos(\alpha_i) \\ \sin(\alpha_i) \\ -y(\theta_i)\cos(\alpha_i) + x(\theta_i)\sin(\alpha_i) \end{bmatrix} \tag{5}$$

So, the vector forces and moment τ can be expressed in form of matrix B and vector control force f as

$$\tau = \begin{bmatrix} c\alpha_1 & s\alpha_1 & -y(\theta_1)c\alpha_1 + x(\theta_1)s\alpha_1 \\ c\alpha_2 & s\alpha_2 & -y(\theta_2)c\alpha_2 + x(\theta_2)s\alpha_2 \\ c\alpha_3 & s\alpha_3 & -y(\theta_3)c\alpha_3 + x(\theta_3)s\alpha_3 \\ c\alpha_4 & s\alpha_4 & -y(\theta_4)c\alpha_4 + x(\theta_4)s\alpha_4 \end{bmatrix}^T \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{6}$$

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

In this paper, we assume that the contact positions between ship and tugboats are fixed. The set adequate (α_i, f_i) which are produced from forces and moment of controller signals will be solved by control allocation approach.

III. Formulation of Control Allocation

3.1 Control Allocation Problem

Control allocation is the problem of distribution from the small signal vector into the bigger ones. It is emphasized to place on over-actuated system where the number of actuators is greater than the degree of freedom of vehicle. In this paper, control allocation can be formulated as shown in Fig. 2. It 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.

In this case, control allocation is formulated as optimization[7] with subject to limitations of contact angle, slow varying direction, unidirectional thrust and power saturation 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 which is supplied from tugboats
3. $\alpha_i(t)$ is slow varying to suit with the dynamic response of tugboats and minimize the wear and tear on the thrust devices.

The approach presented in this paper can be outlined as follows and more detail in flow chart diagram(Fig. 3).

Calculate the angles α_i to minimize the control errors. Generated angles have to satisfy angle limitation $\alpha_{\min} \le \alpha \le \alpha_{\max}$. They should be chosen to avoid the slipping phenomenon. Furthermore, these are suitable for slow varying constraint $\dot{\alpha}_i < \dot{\alpha}$. In digital computer implement, we can combine these constraints as $\underline{\alpha} \le \alpha_i \le \overline{\alpha}$ where:

$$\begin{cases} \underline{\alpha} = \max(\alpha_{\min},\ \alpha_{i-1} - \Delta t \cdot \dot{\alpha}) \\ \overline{\alpha} = \min(\alpha_{\max},\ \alpha_{i-1} + \Delta t \cdot \dot{\alpha}) \end{cases} \tag{7}$$

The geometric configuration matrix based on the given α_i is calculated. After that, we choose the vector control forces f in the situation of minimized power consumption.

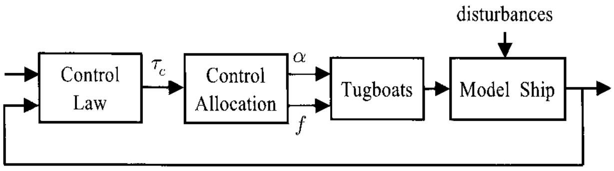

Fig. 2 Control allocation for system by using thrust of tugboats

3.2 Solution for Varying Direction

The 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, then the vector control force f is represented by vector f' as follows

$$f' = [f_{1x}, f_{1y}, f_{2x}, f_{2y}, f_{3x}, f_{3y}, f_{4x}, f_{4y}]^T \quad (8)$$

where $f_{ix} = f_i \cos\alpha_i$ and $f_{iy} = f_i \sin\alpha_i$ and geometry configuration matrix B is extended in form B' as:

$$B' = \begin{bmatrix} 1 & 0 & \cdots & 1 & 0 \\ 0 & 1 & \cdots & 0 & 1 \\ -y(\theta_1) & x(\theta_1) & \cdots & -y(\theta_4) & x(\theta_4) \end{bmatrix} \quad (9)$$

The vector f' is computed by using the Moore Penrose pseudo inverse matrix, which is a special case of pseudo inverse approach (presented later for more detail).

$$\tau_c = B' f' \Rightarrow f' = B'^{*} \tau_c \quad (10)$$

where $B'^{*} = B'^{T}(B' B'^{T})^{-1}$. The direction of tugboat can be found as follows.

$$\alpha_i = \begin{cases} \tan^{-1}\left(\dfrac{F_{iy}}{F_{ix}}\right), \text{ if } \underline{x} \le \alpha_i \le \overline{\alpha} \\ \underline{\alpha}, \text{ if } \alpha_i < \max(\alpha_{\min}, \alpha_{i-1} - \Delta t \cdot \dot{\alpha}) \\ \overline{\alpha}, \text{ if } \alpha_i < \min(\alpha_{\max}, \alpha_{i-1} + \Delta t \cdot \dot{\alpha}) \end{cases} \quad (11)$$

Notice that, with the constraint in rate change, we can decrease jump of tugboat direction at each sample.

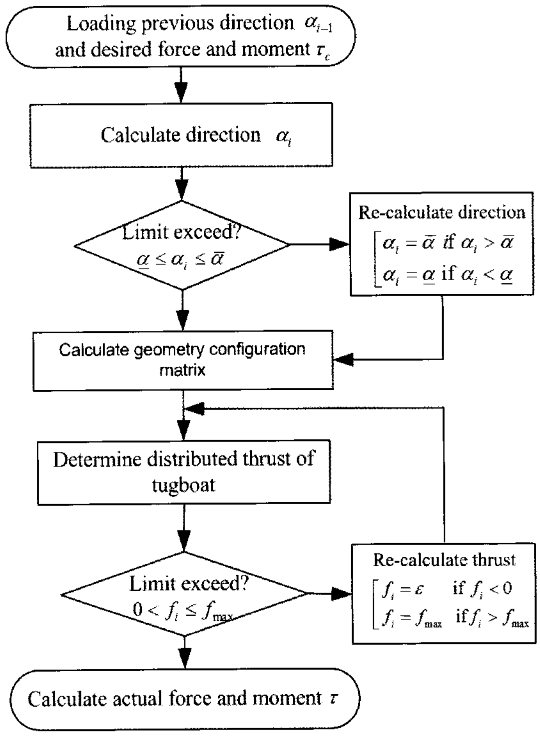

Fig. 3 Flow chart diagram of directions and forces calculation

3.3 Solution for Force Magnitude

In this paper, control force optimization is solved by using the redistributed pseudo inverse method. This approach is the constrained optimization technique. It requires a pseudo inversion of a matrix B which is generally non square and it can be stated as follows

$$\min_f J = \min_f \frac{1}{2}(f + c)^T W (f + c) \quad (12)$$

subject to

$$\begin{aligned} &\tau - Bf = 0 \\ &f_{\min} \le f_i \le f_{\max} \end{aligned} \quad (13)$$

where $W \in R^{n \times n}$ is the weighting matrix and $c \in R^n$ is the offset vector. To solve this problem, we find the Hamiltonian(H) as

$$H = \frac{1}{2}(f^T W f + c^T W f + f^T W c + c^T W c) + \xi(Bf - \tau) \quad (14)$$

where $\xi \in R^n$ is a undetermined Lagrange multiplier. Taking the partial derivative of H and setting these results to zeros, we have

$$\frac{\partial H}{\partial f} = Wf + \frac{1}{2}(c^T W)^T + \frac{1}{2} Wc + (\xi B)^T = 0 \quad (15)$$
$$\Rightarrow Wf = - Wc - B^T \xi^T$$

$$\frac{\partial H}{\partial \xi} = Bf - \tau = 0 \Rightarrow BW^{-1} Wf = \tau \quad (16)$$
$$\Rightarrow BW^{-1}[- Wc - B^T \xi^T] = \tau$$

Solving Eq. (16), we find down ξ^T

$$\xi^T = - (BW^{-1}B^T)^{-1}(\tau + Bc) \quad (17)$$

Substituting Eq. (17) in to Eq. (15) produces

$$Wf = - Wc + B^T(BW^{-1}B^T)^{-1}(\tau + Bc) \quad (18)$$
$$\Rightarrow f = - c + W^{-1}B^T(BW^{-1}B^T)^{-1}(\tau + Bc)$$

If we set $B^* = W^{-1}B^T(BW^{-1})^{-1}$, Eq. (18) is simplified in form

$$f = - c + B^*(\tau + Bc) \quad (19)$$

Notice that, if W is identity matrix, B^* will be called Moore Penrose pseudo inverse matrix.

After solving force distribution by using Eq. (19) with c which is initially a vector zero, if no control f_i exceeds their minimum or maximum values, the process stops. However, if one of them exceeds limits, the problem is solved again. In the next step, the zero value is set to all element of column i^{th} of matrix B which corresponds to the position of the saturated f_i. And the i^{th} element of vector c is set as the negative saturated value.

IV. Simulation Result

The primary focus of the simulation studies is to investigate the performance of the ship motion as well as tugboats dynamic with the mathematical system and the optimal control allocation algorithm described above. This study is demonstrated using the model ship, Cybership I[8] with following particulars, through the Matlab environment.

$$M = \begin{bmatrix} 19(\mathrm{kg}) & 0 & 0 \\ 0 & 35.2(\mathrm{kg}) & -70.7(\mathrm{kg \cdot m^2}) \\ 0 & -0.7(\mathrm{kg}) & 1.98(\mathrm{kg \cdot m^2}) \end{bmatrix} \quad (20)$$

$$D = \mathrm{diag}\{4(\mathrm{kg/s}),\ 6(\mathrm{kg/s}),\ 1(\mathrm{kg \cdot m^2/s})\}$$

The tugboats configuration around the ship and their constraints are described in Eq. (21). In the constraint of slow varying direction, it is emphasized that the adequate set of the initial direction α_{10}, α_{20}, α_{30}, α_{40} considerably affect the direction and control force of tugboats during simulation.

$$\dot{\alpha} = \frac{\pi}{90}(\mathrm{rad/s}) \quad (21)$$
$$f_{\max} = 0.5(\mathrm{N}),\ f_{\min} = 0$$
$$\alpha_{10} = \alpha_{20} = \frac{\pi}{3},\ \alpha_{30} = \alpha_{40} = -\frac{\pi}{3},$$
$$\theta_1 = -\frac{1}{9}\pi,\ \theta_2 = -\frac{8}{9}\pi,\ \theta_3 = \frac{8}{9}\pi,\ \theta_1 = \frac{8}{9}\pi,$$
$$\alpha_{12\max} = \frac{2\pi}{3},\ \alpha_{12\min} = \frac{\pi}{6},\ \alpha_{34\max} = -\frac{\pi}{6},\ \alpha_{34\min} = -\frac{2\pi}{3}$$

The model 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 Fig. 5 and Fig. 6. It satisfies to minimize power consumption supplied from tugboats in the constraints about slow direction change and power saturation.

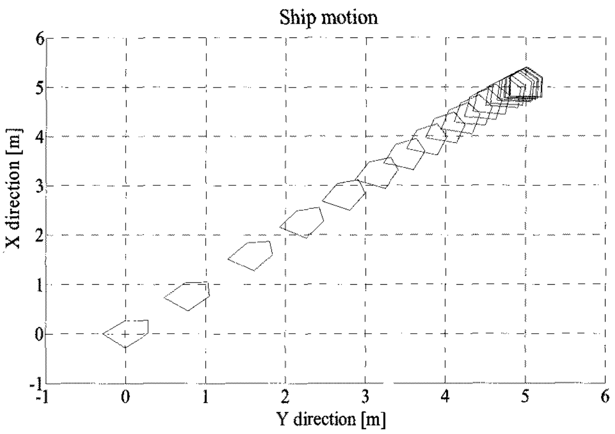

Fig. 4 Ship motion in horizontal plan

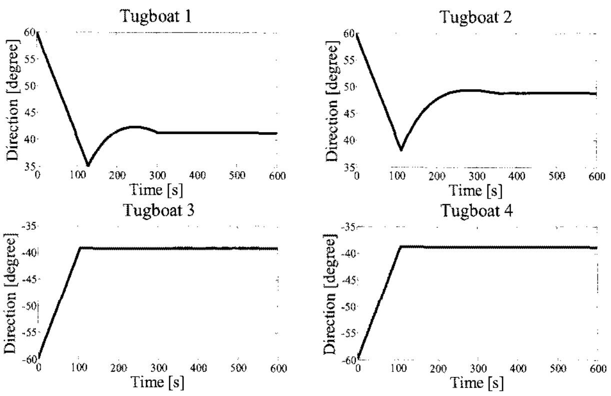

Fig. 5 Directions of tugboats

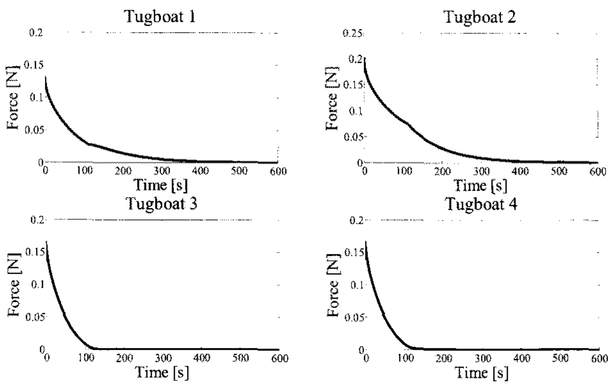

Fig. 6 Distributed forces from tugboats

V. Conclusions

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 to the real world by testing the model in real condition.

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