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# Design of an adaptive backstepping controller for auto-berthing a cruise ship under wind loads

Jong-Yong Park[1] and Nakwan Kim[2]

[1]*Department of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, Korea*
[2]*Department of Naval Architecture and Ocean Engineering and Research Institute of Marine Systems Engineering, Seoul National University, Seoul, Republic of Korea*

**ABSTRACT:** *The auto-berthing of a ship requires excellent control for safe accomplishment. Crabbing, which is the pure sway motion of a ship without surge velocity, can be used for this purpose. Crabbing is induced by a peculiar operation procedure known as the push-pull mode. When a ship is in the push-pull mode, an interacting force is induced by complex turbulent flow around the ship generated by the propellers and side thrusters. In this paper, three degrees of freedom equations of the motions of crabbing are derived. The equations are used to apply the adaptive backstepping control method to the auto-berthing controller of a cruise ship. The controller is capable of handling the system non-linearity and uncertainty of the berthing process. A control allocation algorithm for a ship equipped with two propellers and two side thrusters is also developed, the performance of which is validated by simulation of auto-berthing.*

***KEY WORDS:*** Auto-berthing; Crabbing; Adaptive backstepping control; Control allocation.

## INTRODUCTION

Berthing is the process of positioning and mooring a ship beside a quay, jetty, or floating dock, usually for the purpose of loading or unloading. For large ships such as a container or a cruise ship, berthing is done with the aid of tug boats. When the ship approaches the berthing position, forward tug boats are used to hold the bow to prevent the ship from contacting the quay. Aft tug boats are then used to push the ship towards the quay. If the lateral speed of the ship is higher than the desired speed, the tug boats would be used to retard it. By careful operation of the propellers and rudder, the ship is positioned a few meters away from the quay, and thereafter brought nearer by means of tug boats and mooring ropes. The entire operation is actually very complex and time consuming.

Crabbing is the pure sway motion of a ship without surge velocity, and is induced by a peculiar operation method known as the push-pull mode. The push-pull mode is induced by the combined manipulation of the main propeller and side thrusters. The two propellers are made to generate the same amount of thrust while rotating in opposite directions, thereby exerting a yawing moment on the vessel without inducing longitudinal motion. By the simultaneous operation of the side thrusters, the push-pull mode is implemented, resulting in the generation a large lateral force. When a ship is in the push-pull mode, an interaction force is induced by complex turbulent flow around the ship generated by the propellers and side thrusters. Crabbing is a slow sway motion and can thus be applied to berthing if the ship is equipped with propellers and the thrusters are close to the berthing

Corresponding author: *Nakwan Kim*, e-mail: *nwkim@snu.ac.kr*

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position. Some requirements for effective crabbing and berthing were presented by Quadvlieg (1998), namely the maintenance of a lateral speed of 0.25(*m/s*) against a Beaufort 6 wind. For cruise ships, the requirement for effective berthing is often the ability to berth and unberth in a wind speed corresponding to Beaufort 7 without the aid of tug boats. Without the use of tug boats, it is difficult to manually manipulate the propellers and side thrusters during the berthing operation, which has given rise to the need to apply a controller.

There have been some recent studies on crabbing. Lee et al. (2000) simulated crabbing of a ship with twin rudders and twin skegs. However, whereas crabbing involves low-speed maneuvering and pure lateral motion, their mathematical model was a conventional model used for simulating longitudinal maneuvers. According to Yoshimura (1988), the forces acting on a ship are generated by the cross flow drag-which is proportional to the square of the lateral speed-and not by the lift in low speed manoeuver. Experiments on the hydrodynamic forces of a ferry in crabbing motion involving pure sway and pure yaw without longitudinal velocity were conducted by Yoo et al. (2006). Based on experimental investigation, Quadvlieg and Toxopeus (1998) proposed simple techniques for calculating the interaction force, but the techniques were shown to be inadequate for estimating crabbing capability. Studies of auto-berthing are mainly based on the optimal control theory, the neural network theory, or an expert system (Yamato et al., 1990; Yamato et al., 1992; Hasegawa and Kitera, 1993; Im and Hasegawa, 2001). A system for planning the optimal berthing path of a ship was developed by Djouani and Hamam (1995). Yamato and Koyama (1992) and Hasegawa (1994) proposed auto-berthing controllers based on the neural network theory for considering the nonlinear characteristic of low-speed ship maneuvering. Im and Hasegawa (2001) proposed a parallel hidden layer neural network controller for improving auto-berthing performance beyond that achieved by a conventional neural controller. They, however, focused on berthing with the aid of a rudder, which is not realistic for extremely low-speed maneuvering, wherein the rudder is incapable of generating sufficient lateral force and yaw moment. There has hardly been any study that took into consideration the interaction force and severe environmental disturbances such as strong winds. Moreover, there have been few studies on auto-berthing by crabbing.

An auto-berthing controller should be able to handle the uncertainty in modeling the interaction force, as well as the nonlinearity of the force acting on the hull during crabbing. Adaptive control is a control method that adapts to a system with uncertainty, whereas backstepping control was developed by Kokotovic (1992) for designing the controller of nonlinear dynamic systems. Adaptive backstepping control is a combination of the two methods and is used for systems characterized by nonlinearity and uncertainty, such as those used for crabbing.

In this paper, we develop a mathematical model of crabbing for enhanced berthing simulation. The interaction force and wind force are incorporated in the model, and are assumed to be unknown disturbances during the design of an adaptive backstepping controller that can adapt to unknown disturbances. The Lyapunov stability theory is employed in the design of the controller, which is verified by simulations of crabbing, berthing, and unberthing under wind conditions. The paper is finally concluded by drawing some conclusions.

## MATHEMATICAL MODEL

### Overview

The coordinate system used in this study is shown in Fig. 1. It consists of the body-fixed coordinate $O_b - x_b y_b z_b$ and space-fixed coordinate $O_s - x_s y_s z_s$. The origin of the body-fixed coordinate is located at the middle of the ship, on the centerline. The z-axis is positive downward and all angles are positive in the clockwise direction. The kinematic equations of the motion on the horizontal plane can be expressed as

$$\begin{bmatrix} \dot{x}_s \\ \dot{y}_s \\ \dot{\psi} \end{bmatrix} = J(\psi) \begin{bmatrix} u \\ v \\ r \end{bmatrix}, \quad where\ J(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where $u$ and $v$ are respectively the linear surge and sway velocities defined in the body-fixed coordinate, $r$ is the yaw rate, and $\beta$ is the drift angle. The orientation of the body-fixed coordinate relative to the inertia coordinate is described by the Euler angles rotated by the yaw angle $\psi$.

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