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# Fuzzy sliding mode control of an offshore container crane

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ABSTRACT

A fuzzy sliding mode control strategy for offshore container cranes is investigated in this study. The offshore operations of loading and unloading containers are performed between a mega container ship, called the mother ship, and a smaller ship, called the mobile harbor (MH), which is equipped with a container crane. The MH is used to transfer the containers, in the open sea, and deliver them to a conventional stevedoring port, thereby minimizing the port congestion and also eliminating the need of expanding outwards. The control objective during the loading and unloading process is to keep the payload in a desired tolerance in harsh conditions of the MH motion. The proposed control strategy combines a fuzzy sliding mode control law and a prediction algorithm based on Kalman filtering for the MH roll angle. Here, the sliding surface is designed to incorporate the desired trolley trajectory while suppressing the sway motion of the payload. To improve the control performance, the discontinuous gain of the sliding control is adjusted with fuzzy logic tuning schemes with respect to the sliding function and its rate of change. Chattering is further reduced by a saturation function. Simulation and experimental results are provided to verify the effectiveness of the proposed control system for offshore container cranes.

## 1. Introduction

Cranes are widely used for loading and unloading containers from and to container ships in quay terminals. In recent years, with the rapid increase of world trade as well as the need for larger container ships, shipping companies have resorted to an increase of the vessel size (Pang and Liu, 2014; Steenken et al., 2004). In December 2014, the biggest container ship, the MSC Oscar, with the capacity of 19,224 TEU (twenty-foot equivalent unit) began to operate. Several mega ships over 18,000 TEU are in order and they are expected to be the main operators in various shipping companies. So as to keep up the ever-increasing ship sizes, the stevedoring industry has applied several ways to deal with the new trend. One possible option is to improve the efficiency and productivity in cargo handling demands (García-Morales et al., 2015; Ranga Rao and Sundaravadivelu, 1999; Yin et al., 2011). In addition, the container cranes have to become bigger and faster thanks to suitable controllers that can improve the transfer time as well as ensure the safety requirements (Hong and Ngo, 2012). Despite these improvements, many terminals are still faced with two problems: (i) the difficulty in accommodating the mega container ships due to the shallow water depth, and (ii) the port congestion due to the increase of cargo ships. Fortunately though, a special crane-equipped ship, or mobile harbor, capable of open-sea loading and unloading of containers from a large anchored container ship, or mother ship, is a potential solution (Ngo and Hong, 2012b).

During the process of loading and unloading containers, the payload oscillations and the method to suppress them to avoid any damage or accidents caused by these oscillations is always the main concern in a container terminal. From the crane control aspect, various control algorithms have been proposed to deal with sway suppression. These methods include open-loop control, such as input shaping control for gantry cranes, bridges (Ngo et al., 2012; Hong et al., 2003; Huey et al., 2008; Robertson and Singhose, 2009; Singhose et al., 2000; Sorensen et al., 2007; Sorensen and Singhose, 2008; Sung and Singhose, 2009a, 2009b), and flexible systems in general (Hong et al., 2003; Huey et al., 2008; Robertson and Singhose, 2009; Singhose et al., 2000; Sorensen et al., 2007; Sorensen and Singhose, 2008; Sung and Singhose, 2009a, 2009b) as well as closed-loop control, such as optimal control (Al-Garni

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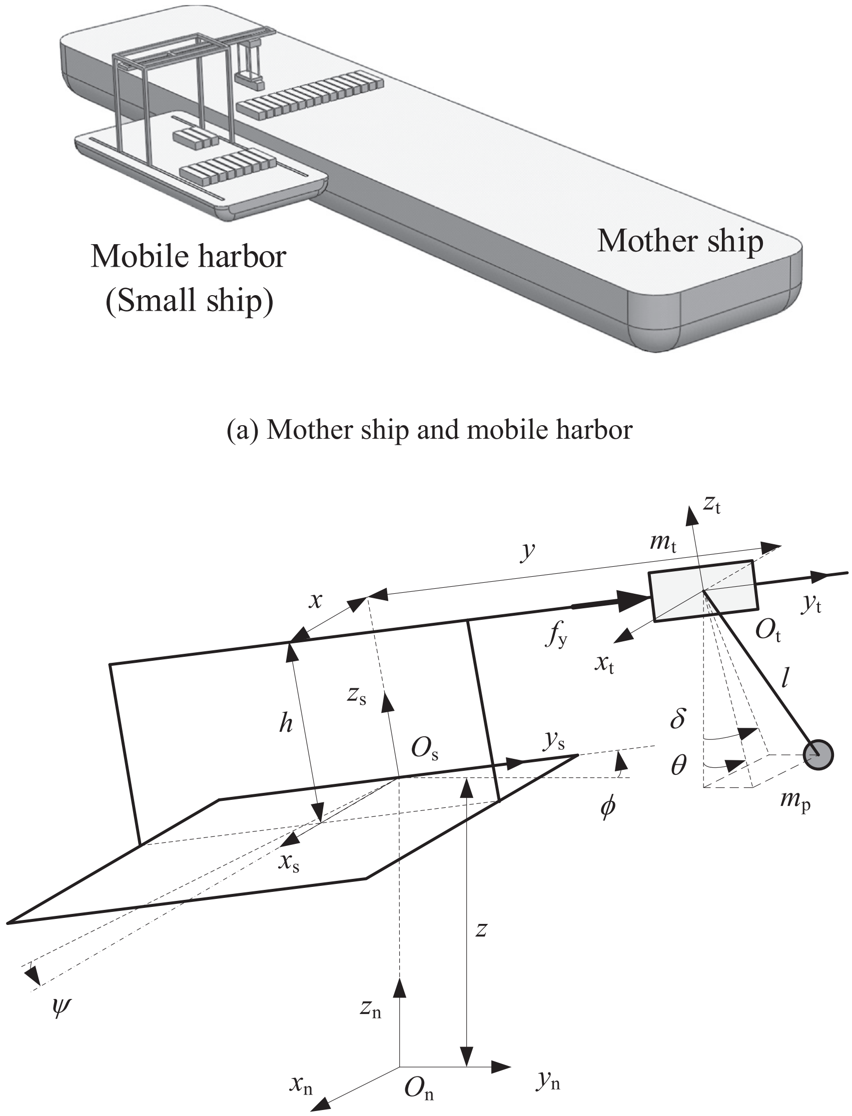


(b) Coordinate frames: reference (mother ship), mobile harbor and trolley

**Fig. 1.** Offshore crane arrangement and coordinate systems (Hong and Ngo, 2012). (a) Mother ship and mobile harbor (b) Coordinate frames: reference (mother ship), mobile harbor and trolley.

et al., 1995; Hong et al., 2000), state feedback control (Kim et al., 2004; Kłosiński, 2005; Messineo et al., 2008; Park et al., 2007; Sawodny et al., 2002), fuzzy control (Ahmad, 2009; Benhidjeb and Gissinger, 1995; Chang and Chiang, 2008; Chen et al., 2009; Cho and Lee, 2002; Omar et al., 2004), adaptive control (Cheng-Yuan, 2007; Liu et al., 2005; Messineo and Serrani, 2009; Mizumoto et al., 2007; Ngo and Hong, 2012a; Tuan et al., 2013; Yang and Yang, 2007), and robust control (Almutairi and Zribi, 2009; Bartolini et al., 2002a, 2002b; Lee, 2004a, 2004b, 2005; Lee et al., 2006; Ngo and Hong, 2012b; Orbisaglia et al., 2008; Xi and Hesketh, 2010).

The conventional control methods developed for offshore container cranes may be unsuitable to mobile harbor cranes due to the effect of sea-excited motions (Ngo and Hong, 2012b). Disturbances such as strong sea waves and gusty winds tend to exacerbate the pendulum oscillations of the crane's hanging load. Therefore, its trolley has to move along a suitable trajectory to compensate for the MH motion so that the container will be kept in a desired region to guarantee the normal operations of open-sea loading and unloading.

For offshore crane control, many researchers have focused on addressing challenges in offshore installations, such as underwater conveying systems for oil and gas field, see e.g., Skaare and Egeland (2006); Messineo and Serrani (2009); and Kuchler et al. (2011). In this context, Hong and Ngo (2012) developed the first mathematical model of the container crane equipped/mounted on a ship with sea-excited motion, whereby a sliding mode control (SMC) strategy was introduced for mobile harbor cranes (Ngo and Hong, 2012b). Robustness of the control system is emphasized by using for offshore boom cranes a second-order sliding mode controller (Raja Ismail and Ha, 2012), and an optimal sliding mode controller (Raja Ismail et al., 2015). In these papers, the system responses were verified through simulations while the trolley trajectory did not take into account compensation for the MH motion in the control strategy. The relationships between waves and ocean structures were also the topics of intense research for other researcher (Cha et al., 2010; Clauss et al., 2009; Do and Pan, 2008; Kyoung et al., 2005; Zhu et al., 2001). In this context, Ngo et al. (2011) first proposed the idea of utilizing the trolley displacement for MH motion compensation, based on a geometric analysis, to not only suppress payload oscillations but also keep the container position in a desired region.

In this paper, by taking advantage of MH motion compensation while enhancing system robustness and control performance, we propose a new control strategy containing these features: (i) path