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Unscented Kalman Filter trained neural networks based rudder roll stabilization system for ship in waves

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ABSTRACT

The large roll motion of ships sailing in the seaway is undesirable because it may lead to the seasickness of crew and unsafety of vessels and cargoes, thus it needs to be reduced. The aim of this study is to design a rudder roll stabilization system based on Radial Basis Function Neural Network (RBFNN) control algorithm for ship advancing in the seaway only through rudder actions. In the proposed stabilization system, the course keeping controller and the roll damping controller were accomplished by utilizing modified Unscented Kalman Filter (UKF) training algorithm, and implemented in parallel to maintain the orientation and reduce roll motion simultaneously. The nonlinear mathematical model, which includes manoeuvring characteristics and wave disturbances, was adopted to analyse ship's responses. Various sailing states and the external wave disturbances were considered to validate the performance and robustness of the proposed roll stabilizer. The results indicate that the designed control system performs better than the Back Propagation (BP) neural networks based control system and conventional Proportional-Derivative (PD) based control system in terms of reducing roll motion for ship in waves.

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1. Introduction

For most ships, it is unavoidable to encounter severe sea conditions when they carry cargoes from and to the port of destination. When these ships are advancing in rough seas under severe weather conditions, the large roll motion would be occurred due to the external environmental disturbances, such as strong winds, waves and currents. As one of the most undesired phenomena, the severe roll motion will enormously affect the safety of crew, cargoes and ships. Generally, it may lead to the working inefficiency of seafarers and results in discomfort of the passengers because of the seasickness. In addition, the huge roll movement may cause stability loss and cargos damage for ships. Even worse, the vessel might be in danger of capsizing because of the severe roll motion. Therefore, reducing roll motion is very important for the ship advancing in the seaway from the prospective of safety.

Conventionally, course altering or heaving to is a good choice for the deck officers to reduce the large roll motions. However, for the ship which is in special conditions, such as executing maritime search and rescue mission, sailing in the area of traffic separation scheme, or having strict liner shipping schedule, it is necessary to maintain course and advancing while reducing roll motion. Thus, apart from the seamanship, roll damping facilities are needed in some cases. Many attempts have been previously carried out to reduce the roll motion, such as the application of moving weights, bilge keels, anti-roll tanks, gyroscopic stabilizers, and stabilizing fins. Although the above-mentioned method and facilities have been validated to be efficient, the ship's carrying capacity would be affected by the weight increase and space decrease. The installations of additional devices and appendages also impact on the hydrodynamic performance, seaworthiness and structure strength of the ship. Besides, the costs of ship building and maintenance will be raised. Thus, other rational and feasible methods are demanded for ships to maintain orientation and stability.

As the rudder is usually located after and under the ship's centre of gravity, apart from yaw movement, altering rudder angle will generate additional roll force and moment to the hull. Thus, besides being used as the yaw control facility, the rudder could be employed to reduce the roll motion for the ship whose rudder is capable to generate enough roll moments. Especially, when the range of rudder area is larger than 3% of $L \times T$ (i.e. Ship's Length $\times$ Draught), it would be more efficient to supply moment and force to reduce roll motion in use of rudder. But the challenge is how to select the effective control method for the ship to maintain the tracking and reduce roll motion synchronously only through altering the deflections of rudder. The background of the

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rudder roll stabilization design was reviewed by Lloyd [1]. Although the conventional Proportional-Integrative-Derivative (PID) based rudder roll stabilizer was effective and reliable in some cases, it could not work well in heavy seas because its fixed parameters were optimized corresponding to specific operating conditions [2]. In order to improve the performance of the control systems, various adaptive control methods had been adopted to stabilise the roll motion of ships [3,4,5,6]. At present, with the development of modern control theory, rudder roll stabilization systems accomplished with batch-adaptive control [7], fuzzy logic control [8], receding horizon control [9], H_∞ robust control [10], and sliding mode control [11] have been developed. Considering the excellent capability in approximating, neural network control algorithms have been widely utilized by Alarcin and Gulez [12], Fang et al. [13], Li et al. [14] and Fang et al. [15] to design the rudder roll stabilizer. In comparison with some multilayer feed forward neural network controller, it is indicated that the RBFNN controller has the advantages of good generalization capability and simple architecture, which are beneficial to avoid unnecessary and lengthy calculations [16], therefore it is applied to design the rudder roll stabilization system in this study.

The training algorithm plays an important role in designing the neural network based control system. Some commonly employed training algorithms, e.g. BP [17], gradient descent [18] and backstepping [19] have been validated to be effective to optimize the artificial neural network controller, but the performance of the proposed controller might be plagued by converging to poor local optimal and low learning velocity [20]). In order to overcome the above-mentioned flaws, the Kalman Filter variants could be the alternatives to train the neural networks based controllers [21]. In comparison with the Extended Kalman Filter (EKF), which has the potential to propagate errors through its linearization, the UKF used deterministic sampling method and achieved a better level of estimation accuracy [22].

The main objectives of this study are

- to formulate the desired feedback RBFNN based control algorithm whose weights are updated by a modified UKF method;
- to propose the rudder roll stabilization system utilizing UKF RBFNN for ship advancing in waves;
- to achieve roll damping and trajectory tracking simultaneously only through rudder actions; and
- to validate the superiority of the designed roll stabilization system in comparison with the BP RBFNN and PD based control system.

This paper is organized as follows: the 2nd section briefly presents the mathematical model including manoeuvring characteristics for ships sailing in waves. The following sections focus on the design of rudder roll stabilization system. In the 3rd section, the principle of feedback RBFNN control method and UKF training algorithm are addressed. The UKF RBFNN based controller is applied to develop the rudder roll stabilization system for roll damping and track keeping. After that, different sailing conditions are adopted to investigate the yaw control ability and roll reduction performance. Finally, the conclusions are presented in the last section.

2. Mathematical model of ship motions in waves

In this section, the nonlinear model containing steering and sea-keeping characteristics for the ship with external wave disturbances is introduced. The motion equations, which can be utilized to describe the responses of the ship under rudder actions, are given in the Earth-fixed and Body-fixed coordinate systems as shown in Fig. 1.

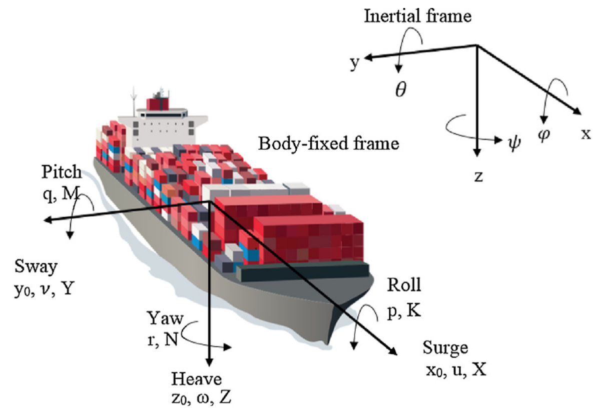

Fig. 1. Earth-fixed and Body-fixed frames for a surface vessel.

Deduced from Newton's second law, the six degrees of freedom (DOF) dynamic equations of ship represented by Fossen [23] can be expressed as:

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau + \tau_E \quad (1)$$

where $\nu = (u, v, w, p, q, r)^T$ is the velocities of the vessel's translated motion and rotation motion; M is the inertia matrix; τ is the vector of control inputs; τ_E is the vector of environment forces and moments; $C(\nu)$ is the matrix of Coriolis and centripetal terms containing the added mass; D is the matrix of damping terms; $g(\eta)$ is the vector of restoring forces and moments arisen from gravity and buoyancy; η represents ship's position and orientation.

Considering the aims of roll damping and trajectory tracking, the motions of pitch and heave can be overlooked in comparison with the motions of surge, sway, yaw and roll. Thus the nonlinear four DOF non-dimensional model can be employed to describe the dynamic motions of the proposed vessel, see in Son and Nomoto [24].

In this study, the modified Pierson-Moskowitz (PM) wave spectrum model recommended by ITTC and outlined in Perez [25] is utilized to simulate ship's response in random waves. According to the research of Sgobbo and Parsons [6], the forces and moments generated by waves can be added to the right hands of the motion equations to represent the environmental forces and moments.

3. UKF trained RBFNN control algorithm

In this section, the feedback control method based on the RBFNN is presented. In order to get higher training velocity and mapping accuracy, the modified UKF is employed as the training algorithm for the neural network controller.

3.1. RBFNN based feedback control scheme

The main motivation of utilizing neural networks is to remove the necessity of the plant's numerical model when designing the controller. The proposed control scheme in this study is demanded to address the nonlinear dynamics of the vessel and the uncertainties of wave disturbances.

After firstly performed by Broomhead and Lowe [26], the capability of RBFNN in approximating unknown functions was demonstrated by Park and Sandberg [27]. It is a kind of artificial neural networks with three layers (i.e. input layer, hidden layer, and output layer) and its main feature is that the radial basis function is adopted in the hidden layer as the activation function, shown in Fig. 2.

Based on the investigation of Ge et al. [28], for the nonlinear system with unknown parameters and coefficients, the RBFNN can

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