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Adaptive motion/force control strategy for non-holonomic mobile manipulator robot using recurrent fuzzy wavelet neural networks

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ABSTRACT

In our study, we develop an adaptive position tracking system and a force control strategy for non-holonomic mobile manipulator robot, which combine the merits of Recurrent Fuzzy Wavelet Neural Networks (RFWNNs). In order to deal with the unknown knowledge problems of the robotic system, an adaptive RFWNNs control scheme with the dynamic structure and online learning ability is utilized to approximate unknown dynamics without the requirement of prior controlled system information. In addition, an adaptive robust compensator is proposed to eliminate uncertainties that consist of approximation errors, disturbances. According to the adaptive position tracking control design, an adaptive robust controller is also considered for the non-holonomic constraint force. The design of the adaptive online learning algorithms is derived by using the Lyapunov stability theorem. Therefore, the proposed controllers prove that they not only can guarantee the stability but also the tracking performance of the mobile manipulator robot control system. The effectiveness and robustness of the proposed method are demonstrated by comparative simulation and experimental results that are implemented in an indoor cleaning crawler-type mobile manipulator robot system.

1. Introduction

In recent decades, mobile manipulator robot control is always an interesting topic, which has attracted a lot of attention from a lot of researchers. With including robotic arms and mobile platform, the structure of the mobile manipulator robot is subject to kinematic and dynamic constraints, which make it a highly coupled dynamic nonlinear system. Many control strategies for the mobile robot manipulator system have been successfully developed in various literatures and applied in practical applications. Based on the assumption of known dynamics, some researchers have constructed controllers by applying the feedback techniques (Yamamoto and Yun, 1996; Khatib, 1999; Watanabe et al., 2000; Tan et al., 2003). Inoue et al. (2001) proposed a disturbance observer to estimate the external forces that had adverse impacts on the mobile manipulator robot system. Tsai et al. (2006) have applied the backstepping technique and the filtered-error method in the nonlinear control laws for the mobile manipulator robot control system to compensate the dynamic interactions (non-holonomic constrain) and guarantee the path tracking. The knowledge of the mobile manipulator robot system is difficult to construct exactly, so the control methods with the requirement of the known dynamics are not easy to apply in real control applications. This problem can be solved with the adaptive control techniques (Dong, 2002; Li et al., 2007a, 2008, 2010b, 2010c; Li and Chen, 2008; Li and Kang, 2010a; Andaluz et al., 2012; Boukattaya et al., 2012; Cheng et al., 2013). Dong (2002) proposed an adaptive control scheme based on a suitable reduced dynamic model for the mobile manipulator robot to guarantee performance of the tracking position and the non-holonomic constraint force. However, the disturbances and friction problems were not considered specifically. Li et al. (2007a, 2008, 2010b, 2010c), and Li and Kang (2010a) have proposed and developed several adaptive robust control strategies for the mobile manipulator robot system that guaranteed not only the performance of the tracking errors and holonomic/non-holonomic constraint force but also the uncertain parameters and disturbances elimination.

The methods using adaptive control techniques based on neural networks (NNs) are also the useful methods to deal with the unknown/uncertain dynamics problem of the mobile manipulator robot system. The NNs have self-learning characteristics and good approximation capabilities (Omidvar and Elliott, 1997; Jang et al., 1997; Lewis et al., 1999; Haykin, 1999), and they have been applied successfully in the robotic control systems (Lewis et al., 1996a, 1996b; Kim and Lewis, 1999; Lin and Goldenberg, 2001; Lee et al., 2002; Li et al., 2007b; Wang et al., 2009; Xu et al., 2009). Lin and Goldenberg (2001) proposed an adaptive NNs controller to

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identify online the dynamics of the mobile manipulator robot and eliminate disturbances. But the parameters of the Gaussian functions were all chosen *a priori* and kept fixed (Lin and Goldenberg, 2001; Lee et al., 2002). Li et al. (2007b) presented a neuro-adaptive force/motion controller for the mobile manipulator robot in the presence of an unknown dynamic model and an uncertain constraint. In (Xu et al., 2009), a robust neural network based on sliding mode controller, which has used the NNs to identify the unstructured system dynamics directly, is proposed. This controller is capable of disturbance rejection in the presence of unknown disturbances bound, but the assumption of the bounded parameters, the fixed parameter and approximation errors of the NNs still need to be improved.

Fuzzy NNs (FNNs) are the combination of the NNs and fuzzy that contains both the interpretability of the fuzzy logics and learning ability of the NNs (Casillas et al., 2003; Lughofer, 2013). Therefore, the NNs have a good support for the fuzzy system in tuning the fuzzy rules and membership functions (Jang, 1993; Topalov et al., 1998; Kasabov, 2001; Leng et al., 2005; Mbede et al., 2005; Wai and Chen, 2006; Chen, 2008; Li and Chen, 2008;). For the mobile robot manipulator control, Mbede et al. (2005) developed a modular fuzzy navigation method in changing dynamic unstructured environments. In this method, the integration of a robust controller and a modified Elman NNs is to deal with uncertainties. However, the bounded-parameters (disturbances, Taylor parameters) are assumed to be known. The aforementioned applications presented the FNNs-structures that were only capable of the static mapping of input–output training data due to theirs feed-forward network structure. The disadvantage of the feed-forward network structure is presented in the requiring of a large number of neurons to capture dynamical responses in the time-domain, and its approximating-ability is sensitive to the training data. To overcome this drawback, the recurrent FNNs (RFNNs) (Lin and Wai, 2003; Hsu and Cheng, 2008; Wai and Liu, 2009; Chen, 2010; Park and Han, 2011) have been proposed to associate the dynamic structures in the form of the feedback links employed as internal memories. Therefore, the RFNNs have a dynamic mapping and they present a good control performance under uncertainties variation. In (Lin and Wai, 2003), the authors proposed a robust RFNNs control system to improve the tracking position performance and the RFNNs-controller was used to mimic an ideal feedback linearization control law. This proposed scheme relaxed the requirement for the bound of the lumped uncertainty by a robust controller but the fixed parameters of the RBF function should be more considered. Hsu and Cheng (2008) presented a dynamic RFNNs scheme with a structure-learning strategy that enabled to determine the nodes dynamically and achieve the optimal network structure. In (Hsu and Cheng, 2008), the RFNNs also mimicked an ideal controller and a compensation-controller was designed to compensate the difference between the NNs controller and the ideal controller. The learning algorithms of this scheme were derived by the Lyapunov theorem, so the stability was guaranteed but the constraint bound of some parameters in the controller required to be known. Park and Han (2011) developed a model-free RFNNs control system to approximate the ideal backstepping control law. In addition, in this method, a simple dead-zone estimator and a friction compensator were applied to estimate the unknown dead-zone width and friction-parameters. Although the algorithms of the estimator and the compensator were derived by using the Lyapunov theorem but the online-learning algorithm of the RFNNs-parameters was determined by Gradient descent method, so the learning rate-factors were not easy to obtain. In general, the controllers-based NNs have the advantages in the control applications but they still contain some obstacles need to be improved, such as the learning speed, the approximation errors and poor convergence problems.

Recently, wavelets NNs (WNNs) have also attracted a lot of attention from researchers. The WNNs combine the learning capability of NNs and the decomposition capability of the wavelet function (Zhang and Benveniste, 1992; Delyon et al., 1995; Zhang et al., 1995; Zhang, 1997; Jin and Liu, 2008). Therefore, they are able to overcome drawbacks of the FNNs/NNs, especially in the highly nonlinear dynamic systems. The WNNs can converge faster; achieve smaller approximation errors and size of networks than the NNs (Zhang and Benveniste, 1992; Zhang, 1997). Several controllers-based WNNs have been proposed in literatures (Wai and Chang, 2003; Yoo et al., 2006a, 2006b; Lin et al., 2006; Hu, 2009). In these control applications, the WNNs have been applied to approximate the unknown dynamics of the controlled systems. The adaptive robust techniques were often combined with the WNNs to improve learning laws of WNNs parameters that were determined by the Lyapunov stability theorem (Wai and Chang, 2003; Yoo et al., 2006a; Lin et al., 2006). The main advantage of these adaptive learning laws is that the stability of the control systems is guaranteed. Some researchers presented the learning laws of the WNNs with the gradient descent algorithm, but we should pay attention to the adaptive learning rate and momentum parameters to ensure the stability of control systems, especially in practical control applications (Yoo et al., 2006b; Hu, 2009).

In accordance with the advantages in many previous control applications, the WNNs and the RFNNs shall be considered in our work. In recent years, Fuzzy WNNs (FWNNs) have been presented in some application areas (Ho et al., 2001; Abiyev and Kaynak, 2008; Yilmaz and Oysal, 2010; Lu, 2011; Hsu, 2011; Davanipoor et al., 2012; Bodyanskiy and Vynokurova, 2013). The FWNNs, the combination of fuzzy concept and the WNNs, can bring the low level learning and good computational capability of the WNNs into fuzzy system and also high humanlike IF-THEN rule thinking and reasoning of fuzzy system into the WNNs. Based on the theory of multiresolution of wavelet transforms and the fuzzy concept, Ho et al. (2001) proposed a FWNNs structure for approximating arbitrary nonlinear functions. By tuning the shape of the membership functions, the approximating process of the FWNNs could be improved without increasing the number of wavelet bases. Some researchers (Abiyev and Kaynak, 2008; Yilmaz and Oysal, 2010; Lu, 2011; Davanipoor et al., 2012; Bodyanskiy and Vynokurova, 2013) proposed the FWNNs for identification-control, and used the gradient method to update/adjust the parameters of the networks (translations, dilations of fuzzy wavelet functions and weights of networks). The results of these methods have good performance and achieve higher precision than FNNs or WNNs methods. Hsu (2011) proposed an adaptive FWNNs controller with the adaptive update laws based on Lyapunov theory. In this method, the training of the FWNNs converged in a smaller number of iterations and the performance of FWNNs achieved better approximation-accuracy in comparison with the NNs. Therefore, in our proposed method, we decide to apply the adaptive FWNNs to deal with the high dynamics and constraints of the mobile manipulator robot system.

In this study, an adaptive position/force tracking control scheme for the mobile manipulator robot using the RFWNNs is proposed. In the RFWNNs structure, a recurrent unit is added into the FWNNs to guarantee the RFWNNs can overcome the static problem of the FWNNs. Our proposed controllers are designed without requiring the knowledge of the robotic control system. The approximation capability of the RFWNNs is applied in the main controller to deal with the unknown highly coupled dynamics of the robot controlled system. The purpose of this approach is to improve the adaptive ability and the tracking performance of the mobile manipulator robot control system under the time-varying uncertainty conditions. An adaptive robust compensator (RC) is also proposed to compensate uncertainties