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# Neural network-based bounded control of robotic exoskeletons without velocity measurements

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## ABSTRACT

This paper proposes a novel neural output feedback trajectory tracking controller for robotic exoskeletons. The controller is developed by defining auxiliary dynamics, and utilizing an adaptive feedforward neural network (NN) term to compensate for unknown nonlinear dynamics of the system. The proposed approach only needs position information in both the controller and adaptation rule of the NN weight matrix. In addition, the controller provides an *a priori* bounded control command. The performance of the controller is validated through simulations and experiments conducted on a lower-limb robotic exoskeleton. It is shown through experiments that the NN term of the controller has assist-as-needed property, such that its contribution in the controller output decreases when the user can follow the desired trajectory in a rehabilitation task.

## 1. Introduction

Powered robotic exoskeletons have recently received an increased interest in several applications including rehabilitation and carrying heavy loads. These systems are equipped with actuators to deliver a desired power augmentation to the human wearer. This power can be easily adapted to the application of interest through the programmable actuators, which make the robots multipurpose exoskeletons and give a versatile functionality for these systems. Using these mechanical systems in rehabilitation has shown significant advantages over the traditional rehabilitation methods, performed by physiotherapists (Ayas & Altas, 2017). This is due to the fact that the robotic systems can provide repetitive training for a longer duration, which plays an important role in the efficiency of a rehabilitation process. Examples of rehabilitation exoskeletons are Colombo, Joerg, Schreier, and Dietz (2000), Nef, Guidali, and Riener (2009) and Perry, Rosen, and Burns (2007).

The motion control of exoskeletons has always been a challenging problem. The control problem is generally defined based on the application of interest. In some applications, the precise trajectory tracking problem is considered in either joint space or Cartesian space of the robot (Ayas, Altas, & Sahin, 2018). In rehabilitation, this performance is of interest in the early stages of treatment for patients with a high level of injury (He, Ge, Li, Chew, & Ng, 2015). Path following and velocity field tracking problems are studied in the cases that timing freedom is required in the desired task (Asl, Narikiyo, & Kawanishi, 2017; Duschau-Wicke, von Zitzewitz, Caprez, Lunenburger, & Riener, 2010). Assist-as-needed (AAN) control problem is investigated by researches to facilitate active participation of patients during the rehabilitation process (Wolbrecht, Chan, Reinkensmeyer, & Bobrow, 2008). Control schemes based on electromyography signals are also studied (Li, Kang, Xiao, & Song, 2017).

Ensuring the stability of the system in the above-mentioned control problems is an important issue and needs to be taken into account. Its importance comes from the fact that apart from the uncertainties of the robot dynamics, there are also unknown external inputs to the system exerted by the human subject, which affect the performance and stability of the system. Besides these, one should also consider the hardware constraints of the system. In many practical systems, the velocity information is not available with high accuracy for a reliable control process. Limited actuation amplitude is another hardware constraint that should be considered in the controller design in order to guarantee the stability.

Several control techniques have been developed in the literature for the robotic exoskeletons. Proportional–integral–derivative (PID) controllers are well studied in Kong, Moon, Hwang, Jeon, and Tomizuka (2009) and Suzuki, Mito, Kawamoto, Hasegawa, and Sankai (2007). A nonlinear computed torque controller is studied in Rahman, K-Ouimet, Saad, Kenn, and Archambault (2011). The authors in Lee et al. (2012) have proposed a model-based force controller for an upper-limb exoskeleton robot. A switching control scheme is given in Oh et al. (2015) for lower-limb exoskeletons, in which pressure sensors detect the motion phases of the human subject gait and activate a specific controller

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for each phase. In order to deal with the uncertainties of the robot–human model, different robust and adaptive controllers are proposed by researchers. A learning adaptive scheme is proposed by the authors in Lu, Li, Su, and Xue (2014), and experimentally tested on a lower-limb rehabilitation exoskeleton. A sliding mode robust controller is given in Madani, Daachi, and Djouani (2016) for a lower-limb exoskeleton, which guarantees the finite-time convergence of the tracking error. In this regard, an adaptive impedance controller is designed in Hussain, Xie, and Jamwal (2013), and a Fuzzy-based controller is proposed in Li, Su, Li, and Su (2015a).

Adaptive artificial neural networks (NNs) are also implemented to deal with the modeling uncertainties of the robotic systems. The NNs have an advantage over the model-based adaptive controllers mainly in the point that no specific regression matrix is required to be determined. A radial basis function (RBF) neural network is applied in Daachi, Madani, Daachi, and Djouani (2015) to design an adaptive controller for one-degree-of-freedom (DoF) lower-limb exoskeleton. In Panwar, Kumar, Sukavanam, and Borm (2012), a feedforward adaptive NN is designed for robotic manipulators for cooperative object grasping. Researchers in Patre, MacKunis, Kaiser, and Dixon (2008) combines the RISE controller with a multi-layer feedforward NN to gain asymptotic performance. The universal approximation property of NNs holds over a compact set depending on the arguments of the function under approximation. This set can be easily determined in feedforward NN compensators due to the known and bounded arguments of the function. Another advantage of the feedforward NNs over the feedback ones is that the input of the network depends on the desired values, where these values, in many control systems, are defined without using sensor measurements, which are prone to be augmented with noise. Considering these advantages, this paper will utilize a feedforward NN to compensate for uncertainties in the dynamic model of the system.

Researchers have studied the output feedback NN control of robotic systems when the velocity information is not available with high accuracy. Kim and Lewis (1999) have presented an NN-based observer and an NN controller for trajectory tracking of robotic manipulators. A backstepping output feedback NN controller is designed for formation control of wheeled robots in Dierks and Jagannathan (2010). The authors in Yu and Rosen (2013) have studied neural PID controllers for upper-limb exoskeletons, where a local stability is guaranteed for their output feedback controller. Assuming an *a priori* bounded estimation error for the velocity observer, the authors in He et al. (2015) have developed an output feedback NN controller for rehabilitation robots. Unfortunately, the adaptive NN output feedback controllers utilize the estimates of the velocity in the adaptation law of the NN weight matrix, while the estimation error cannot be evaluated in the stability analysis. The adaptation law developed in this paper only depends on the position information.

In practice, the actuators of robot have an amplitude saturation limit. Showing the stability of the system by taking this constraint into account introduces new challenges. A series of bounded-input controllers for nonlinear systems have been developed in the literature; examples include Gao and Selmic (2004), Jin, He, and He (2016), Li, Li, and Li (2011) and Wen, Zhou, Liu, and Su (2011). This type of controllers has also been specifically developed for robotic systems. A saturated robust tracking controller is developed for underwater robots in Chen, Jiang, Zou, and Feng (2010). A bounded-input controller is developed for robotic manipulators in Su, Muller, and Zheng (2010), where the global stability result is achieved under the assumption that no external disturbances exist in the system. Using a barrier Lyapunov function, the authors in He, Chen, and Yin (2016a) present an NN saturated controller for robotic systems. Rifai, Mohammed, Hassani, and Amirat (2013) proposes an adaptive saturated controller for an actuated knee joint orthosis. In the mentioned works, velocity information is required in the controller. A bounded output feedback NN controller is given in He, Dong, and Sun (2016b), where the adaptation law for the NN weight matrix has the above-mentioned analysis problem. Similar to this work, Li, Su, Wang, Chen, and Chai (2015b) utilizes a high-gain observer to design a velocity-free bounded NN controller for robotic exoskeletons.

This paper proposes a novel neural output feedback controller for robotic exoskeletons. By defining new auxiliary dynamics, the controller only needs position information of the joint variables. These dynamics also facilitate to guarantee an *a priori* bounded control command. A feedforward RBF NN is utilized to compensate for the uncertainties in the dynamic model of the system, while the adaptation law of the NN weight matrix only needs the position information. The stability analysis shows that the closed-loop system is semi-globally uniformly ultimately bounded (UUB). The performance of the controller is evaluated both by simulations and experiments conducted on a lower-limb exoskeleton. The experiments are carried out on TTI-Knuckle1 exoskeleton for the knee joint rehabilitation and the walking task. It is also shown in the experimental results that the NN term of the controller has a forgetting factor to adjust the support provided by this control term, which means that the proposed method achieves both the precise tracking control and the AAN performance. In comparison to the existing works, the contributions of this paper can be summarized as follows: (i) in contrast to the model-based controllers, e.g. Lee et al. (2012) and Rahman et al. (2011), the proposed method does not need to know about the dynamics of the system and learns about them through the NN term; (ii) in the proposed scheme, a well-designed adaptive NN could be applied for a large range of exoskeleton, while the classic adaptive techniques, e.g. Dixon (2007), need to determine the regression matrix for each robot; (iii) different from Daachi et al. (2015), Dierks and Jagannathan (2010), Kim and Lewis (1999), Panwar et al. (2012), Patre et al. (2008) and Yu and Rosen (2013), the given control command is saturated; (iv) more importantly, the controller only needs position information of joints, while the bounded NN controllers in Gao and Selmic (2004), He et al. (2016a) and Rifai et al. (2013) require velocity information, the given output feedback NN controllers in He et al. (2015) and He et al. (2016b) utilize estimates of velocity in the adaptation law of NNs without taking into account the estimation error in the stability analysis, and the proposed approach in Zou and Kumar (2012) exploits a sliding mode-based observer, which suffers from the chattering phenomenon. Among these, the main design challenge was to simultaneously satisfy the items (iii) and (iv).

This work is an extension to the previous work (Asl, Narikiyo, & Kawanishi, 2018), in which the saturated state feedback NN control of robotic exoskeletons has been addressed and also an output feedback controller is developed. The designed output feedback controller in Asl et al. (2018), apart from utilizing auxiliary dynamics, requires an explicit NN-based observer for velocity estimation and, similar to Sun, Sun, and Woo (2001), approximated adaptation laws for the NN terms are utilized. Therefore, the presented method in this paper is computationally lighter and provides a more rigorous stability result.

The rest of the paper is organized as follows. Section 2 gives some useful preliminaries. The dynamic model of the system is provided in Section 3. The proposed neural output feedback controller is given in Section 4. Simulation and experimental results are presented in Section 5, and finally, conclusions are given in Section 6.

## 2. Preliminaries

### 2.1. Notations

In this paper, the Euclidean norm of a vector $\mathbf{x} \in \Re^n$ is denoted by $\|\mathbf{x}\|$. $\Re^+$ denotes the positive real values. For a matrix $\mathbf{A} \in \Re^{n\times n}$, $\lambda_{\min}(\mathbf{A})$ and $\lambda_{\max}(\mathbf{A})$, respectively, denote the minimum and maximum eigenvalues of $\mathbf{A}$. Also, $\|\mathbf{A}\| \triangleq \sqrt{\lambda_{\max}(\mathbf{A}^\top\mathbf{A})}$ is the induced norm, $\|\mathbf{A}\|_F$ is the Frobenius norm, and $\mathrm{tr}(\mathbf{A})$ denotes the trace of $\mathbf{A}$.