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Adaptive force–environment estimator for manipulators based on adaptive wavelet neural network

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ABSTRACT

This study focuses on the accurate tracking control and sensorless estimation of external force disturbances on robot manipulators. The proposed approach is based on an adaptive Wavelet Neural Network (WNN), named Adaptive Force-Environment Estimator (WNN-AFEE). Unlike disturbance observers, WNN_AFEE does not require the inverse of the Jacobian transpose for computing the force, thus, it has no computational problem near singular points. In this scheme, WNN estimates the external force disturbance to attenuate its effects on the control system performance by estimating the environment model. A Lyapunov based design is presented to determine adaptive laws for tuning WNN parameters. Another advantage of the proposed approach is that it can estimate the force even when there are some parametric uncertainties in the robot model, because an additional adaptive law is designed to estimate the robot parameters. In a theorem, the stability of the closed loop system is proved and a general condition is presented for identifying the force and robot parameters. Some suggestions are provided for improving the estimation and control performance. Then, a WNN-AFEE is designed for a planar manipulator as an example, and some simulations are performed for different conditions. WNN_AFEE results are compared attentively with the results of an adaptive force estimator and a disturbance estimator. These comparisons show the efficiency of the proposed controller in dealing with different conditions.

1. Introduction

Regarding to developments in robot applications and their participating in human society, position control considering interactions with environment is more desirable. In many tasks, robot is in touch with different surfaces and moves on them. It produces an unknown variable force interacting with the end-effector. Furthermore, some position-controlled robots may damage themselves, environments or humans that are collided to reach their desired positions. Therefore, measuring this interactive force is necessary for control, analysis, or decision purposes. Mounting sensors on the end-effector for measuring this force was the only way for years, which led to high cost of repairs and maintenance. High noise, soft structure, limited dimensions of sensing and increasing complexity, are the other drawbacks of force sensors [1,2]. Recent advances in processors let the control algorithms to eliminate some instruments and consequently simplify the complexity of the system and reduce the cost.

A common method to eliminate force sensors is employing disturbance observers (DO). In last two decades, many researches focused on DOs and developed them in many applications. The main application of DO is compensating disturbances in precision positioning. Some researchers used these observers for torque or force sensing and control [1–3]. In [2], authors studied the validation of Disturbance Observer (DO) for force control and compared its results with those of using force sensors. In [4], the authors analyzed the stability of a DO with limited variations of inertia. There are many interests in expanding DO for bilateral force control and haptic applications too [5,6]. The majority of these observers are based on linear systems, therefore compensating all nonlinearities before using them are required [7]. Consequently, some researchers present nonlinear-based designs of DOs [8–10]. However, they usually need accurate model of the friction and robot dynamics in order to be used instead of a force sensor. In [1,6,11], the authors estimated the robot dynamics in different phases where no force is exerted on the robot and finally they used the disturbance observer with the identified accurate model

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to control the force. Although disturbance observers are commonly used in estimating external forces, they have weaknesses in dealing with uncertainties. Another method that is presented for the force estimation in tracking control is the adaptive disturbance estimator [12], where an extended Kalman filter and an adaptive law are used to estimate the states and update the estimated disturbance, respectively. However, all disturbance observers or estimators detect the effects of forces on joints. Therefore, an important limitation for such schemes is the necessity of calculating the inverse of Jacobian transpose to compute the force, which causes some problems for the system in the vicinity of the robot singular points.

Another approach is estimating the external force using an adaptive force estimator [13]. This approach compensates disturbing force using an adaptive law that updates the estimated force in the control law. There is no need to compute the inverse of Jacobian transpose, hence, controller works efficiently around singular points. The other advantage of that scheme is that no acceleration measurement is required for force estimation. The method was developed to estimates both force and robot parameters simultaneously in [14]. Although the estimator performs desirable, it shows some weaknesses in dealing with fast fluctuating forces, since it is designed based on the assumption of constant or low variant forces and has a limited estimation bandwidth. Some researches show that force sensing bandwidth limitation may cause instability in force control, thus, they try to widen it using different approaches [3,15].

This limitation in estimating the variable forces motivated this research to develop the adaptive force estimator to a wider bandwidth estimator. Assume that an assembler robot stretches a spring to fix its end on a device. The exerted force is a function of end-effector position and the spring stiffness. If the environment model is identified, then estimating the force will be enough fast using the end-effector position and velocity. Thus, the model of environment should be identified to attain quick force estimating. Adaptive networks such as fuzzy and Neural Networks (NN) are widely used in control applications to identify nonlinear systems [16–23]. Although, these networks are powerful in approximating nonlinear functions, they have limited capabilities in characterizing the local time-frequency features such as discontinuities or sudden jumps. Regarding to this drawback, wavelet neural networks (WNN) has been developed which had significant improvements in estimating accuracy and convergence speed [24–27]. Unlike the spatially expanded sigmoid functions, wavelet functions are localized in both time and frequency domain [34]. This makes WNN desirable for characterizing the local time-frequency features. They combine the learning ability of Neural Networks and the decomposition capability of Wavelet [30]. These advantages focused many researchers attention on WNN in control systems (e.g. [29–33]). In many applications, WNN plays the role of adaptive network that uses adaptive laws for online tuning of its parameters [28–30]. Discontinuity and nonlinearity are commonly happening in environments that interact with robots. Moreover, force is computed based on this estimated environment model and consequently the speed of environment estimation is so important. Therefore, WNN is chosen for environment modeling in this study.

This paper uses a WNN as an adaptive force-environment estimator (WNN-AFEE) that compensates disturbing forces in position tracking control by modeling the environment. Adaptation laws make WNN suitable to estimate the force directly and guarantee the stability of the system in the sense of Lyapunov. In this approach, the robot Jacobian matrix appears in online learning laws. Therefore, system works desirable in singular points since computing the inverse of Jacobian transpose is not necessary any more. An additional condition specifies the accuracy of WNN-AFEE in estimating the external forces. The overall advantages of the proposed schemes can be briefly expressed as follows:

1. WNN_AFEE can estimate external forces in the presence of parametric uncertainties. As it was mentioned before, other force estimating schemes such as DOs [1,2,4] suffer from the uncertainties in the robot model.
2. WNN_AFEE can estimate variable forces, thus, the limitation of estimating constant or slowly varying forces are removed from the adaptive force estimator [13,14].
3. WNN_AFEE can work efficiently in the vicinity of singular points, while some of the other proposed schemes suffer from computing the inverse of Jacobian transpose in singular points [1,2,7,11,12].
4. The environment may change in some robot tasks repeatedly. Therefore, WNN_AFEE is desirable for estimating the environment model since it has the advantages of the WNN discussed before.

To verify the above claims and support each of the proposed WNN_AFE advantages, several numerical simulation results are provided in simulation section that are compared with both the other schemes, disturbance observer (here is estimator) and adaptive force estimator, in different conditions.

The remainder of this paper is organized as follows. The Section 2 consists of preliminaries and has two parts. The first part explains the robot dynamics, and the second part presents concepts of WNNs. The Section 3 explains the proposed controller design and presents some suggestions for improving control performance. As a case study, a WNN-AFEE is designed for a 2-DOF revolute planar manipulator in Section 4. Results of the simulations are presented in Section 5. Finally, Section 6 contains the conclusions of the paper.

2. Preliminaries

2.1. Robot dynamic

Consider dynamic equations of an n-joint rigid robot manipulator described by

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{V}_m(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{J}(\boldsymbol{q})^T\boldsymbol{f}_{ext} + \boldsymbol{C}(\dot{\boldsymbol{q}}) = \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{q}$ is the vector of joints positions. $\boldsymbol{M}(\boldsymbol{q})$ is the symmetric positive definite inertia matrix, $\boldsymbol{V}_m(\boldsymbol{q},\dot{\boldsymbol{q}})$ denotes Coriolis and centripetal matrix and $\boldsymbol{G}(\boldsymbol{q})$ is the gravity vector, $\boldsymbol{\tau}$ is the vector of input joint torques. $\boldsymbol{f}_{ext}$ is the external force vector exerted on the environment, and $\boldsymbol{J}(\boldsymbol{q})$ is the Jacobian matrix, and $\boldsymbol{C}(\dot{\boldsymbol{q}})$ denotes joints frictions. Based on the linear parameterization property of robots, dynamic motion equations can be expressed by

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{V}_m(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{C}(\dot{\boldsymbol{q}}) = \boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\boldsymbol{\phi} \tag{2}$$

where $\boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})$ is the regression matrix, and $\boldsymbol{\varphi}$ is the parameters vector.

2.2. Wavelet neural network

A wavelet family is represented as

$$\Psi_{a,b}(x) = |a|^{-1/2}\psi\left(\frac{x-b}{a}\right) \tag{3}$$

where $\psi(x)$ denotes a mother wavelet and $\Psi_{a,b}(x)$ is the dilated and translated version of this mother wavelet by a and b. Note that for the q-dimensional input space, the multivariate wavelet can be