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Adaptive chaotification of robot manipulators via neural networks with experimental evaluations ☆

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ABSTRACT

Chaotification is a problem that has been studied in recent years. It consists in injecting a chaotic behavior by means of a control scheme to a system, which in natural form does not present it. This paper explores the chaotification (also denoted anticontrol of chaos) of robot manipulators. Adaptive neural networks have the advantage of compensating the dynamics of a system with practically null information about this. By using a Lyapunov-like framework, chaotification of robot manipulators is assured with an adaptive neural network control law. A two layer neural network is used. Adaptation of the output weights are designed. Real-time experiments in a two degrees-of-freedom robot are presented. The new neural network-based controller is compared theoretically and experimentally with respect to a regressor-based controller.

1. Introduction

A deterministic system is said to be chaotic whenever its evolution sensitively depends on the initial conditions. This property implies that two trajectories emerging from two different close initial conditions separate exponentially in the course of time. The necessary requirements for a deterministic system to be chaotic are that the system must be nonlinear, and be at least three dimensional [8].

For many years, the unusual behavior of nonlinear dynamics and chaos has prompted the attention of many researchers and engineers from different areas. Chaotic phenomena and chaotic behavior have been observed in natural and model systems on physics, chemistry, and biology. Sophisticated engineering applications have been developed in telecommunications and mechanics, for example [12].

Anticontrol of chaos refers to the problem of generating chaos from an originally non-chaotic system by using a control law. In the next, a literature review on anti control of chaos of mechanical systems is given.

One of the first results reported on anti control of chaos of manipulators was introduced in [22], where the simple PD-type controller was proved to introduce chaos in planar two degree-of-freedom robot. In [23], a mechanical oscillator with a dry friction nonlinearity and feedback control was studied, showing to exhibit anti-control of chaos. The work in [4] proved the existence of chaos in mechanical system fed back with a simple proportional controller and affected by saturation. An application for industrial mixing was developed in [45] by using an electrical chaotization technique based on time-delay feedback control. More recently, the paper in [35], presented a general methodology, which includes adaptive controllers for the anti control of chaos of linear and non linear systems. The method relies in finding a diffeomorphism and transforming the original system into a special normal form where the controller is designed. The work in [46] proposed a chaotification method for a rigid body by using a variable speed control moment gyroscope as an internal torque generator. By using a procedure similar to [35], adaptive anti control of chaos of a direct current motor was proposed in [2]. There, numerical results were used to support the main result. In [14], a new identification method was proposed by using a chaotic system together with a tracking controller. In [44], anti control of chaos for nonholonomic mobile robot system was proposed by using the feedback linearization technique and the dynamics of a chaotic gyroscope. The work in [31] proposed the chaotification of a permanent magnet DC motor by a dynamical state feedback as matching the closed loop dynamics to the well-known Chua's chaotic circuit. In our previous work [24], the anti control of chaos of manipulators was addressed and experimentally tested in a planar two degrees-of-freedom manipulator. In [43], a control law to ensure a chaotic motion to an autonomous mobile robot was experimentally

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investigated. The PID control to produce chaos in nonlinear system, where mechanical systems and included, was explored in [5].

Important research advances have been carried out on neural network control. The advantage of neural networks is its ability of estimating nonlinear functions without any special requirement on structure of the function to be compensated. Specifically, neural networks exhibit the universal approximation property which has been useful in the development of compensators. See for example [34,40,39,27], where the neural networks have been used to compensate nonlinear dynamics in motion controllers.

Neural networks have been used in many classes of problems in complex systems and chaos. For example, in [19] a fractional-order four-cell cellular neural network was used to generate chaos. By using mean-field analysis, in [29] a study was conducted on how a neural network that intrinsically generates chaotic patterns of activity can remain sensitive to extrinsic input. More recently, in the work introduced in [28], a neuronal model of epileptiform activity which is driving to periodicity, simulating seizures, is chaotified via two chaos anticontrol algorithms. The appearance of cyclic and toroidal chaos in Hopfield neural networks was discussed in [3].

To the best of our knowledge, the idea of using adaptive neural network compensation to achieve the chaotification of robot manipulators is new.

The main aim of this paper is to introduce a new adaptive neural network chaos anti-controller for robot manipulators. Thanks to the universal approximation property of the neural networks, the new controller has the advantage that the knowledge of the robot model is completely omitted, including the robot regressor matrix. The problem formulation departs from the specification of a *chaotic reference field*, which in this paper is defined as the vector field that defines a chaotic system. Thus, anti control of chaos is assured if the robot joint velocity matches asymptotically the *chaotic reference field*, while the output weights of the neural network are estimated on-line.

For experimental comparison purposes only, inspired from the results reported in [24], an adaptive regressor-based controller is briefly discussed.

The new neural network controller is experimentally compared with respect to the regressor-based controller. The real-time experiments are carried out in a two degrees-of-freedom robot with gravitational term. It is worthwhile to notice that robots with gravitational term have a more complex dynamics and have more dynamic parameters [9,20].

A jerk-type system reported in [37] has been used to generate the *chaotic reference field*. The experimental tests for both neural network-based controller and regressor-based algorithm show the chaotic behavior of the robot. However, the former has the advantage that no information on the robot model is required.

This paper is organized as follows. Section 2 is devoted to the robot model, chaotic systems, control goal and the concept of Poincaré map. The proposed adaptive controller is introduced in Section 3. A regressor-based version of the controller is discussed in Section 4. Section 5 addresses some discussions on the attenuation of the chattering phenomenon and the connection between the asymptotic convergence of the chaotification error and Poincaré map. The experimental tests are addressed in Section 6 Finally, some conclusions are provided in Section 7.

2. Robot model, chaotic systems, control goal and Poincaré map

2.1. Model and properties

The dynamics in joint space of a serial-chain n-link robot manipulator considering the presence of friction at the robot joints can be written as [20,33,9],

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}}+C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})+F_v\dot{\boldsymbol{q}}=\boldsymbol{\tau}, \tag{1}$$

where $\boldsymbol{q}$ is the $n\times 1$ vector of joint displacements, $\dot{\boldsymbol{q}}$ is the $n\times 1$ vector of joint velocities, τ is the $n\times 1$ vector of applied torque inputs, $M(\boldsymbol{q})$ is the $n\times n$ symmetric positive definite manipulator inertia matrix, $C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ is the $n\times 1$ vector of centripetal and Coriolis torques, $\boldsymbol{g}(\boldsymbol{q})$ is the $n\times 1$ vector of gravitational torques, and F_v is a $n\times n$ diagonal positive definite matrix which contains the viscous friction coefficients of each joint.

In reference to the manipulator model (1), notice that a more complex friction model could have been considered, for example, a dynamic friction model [32]. Usually, other types of effects, such as static friction, are considered as disturbances.

A property that is convenient to remark is that the inertia matrix $M(\boldsymbol{q})$ is a positive definite matrix, that is,

$$\boldsymbol{x}^T M(\boldsymbol{q})\boldsymbol{x}>0, \quad \forall \boldsymbol{x}\neq 0. \tag{2}$$

Besides, by assuming that the matrix $C(\boldsymbol{q},\dot{\boldsymbol{q}})$ is obtained by using Christoffel symbols, the property [20]

$$\boldsymbol{x}^T\left[\frac{1}{2}\dot{M}(\boldsymbol{q})-C(\boldsymbol{q},\dot{\boldsymbol{q}})\right]\boldsymbol{x}=0, \quad \forall\ \boldsymbol{x},\boldsymbol{q},\dot{\boldsymbol{q}}\in\mathbb{R}^n, \tag{3}$$

is satisfied.

2.2. Chaotic systems

Roughly speaking, a chaotic system can be defined as the one that is locally unstable but with solutions globally bounded. Consider the system given by

$$\dot{\boldsymbol{x}}=\boldsymbol{f}(\boldsymbol{x}), \tag{4}$$

with $\boldsymbol{x}\in\mathbb{R}^l$, $\boldsymbol{f}:\mathbb{R}^l\to\mathbb{R}^l$, and $l>n$. The system (4) is chaotic if [17]:

- it is sensitive to initial conditions;
- it is topologically mixing; and
- its periodic orbits are dense.

In this paper, the function $\boldsymbol{f}(\boldsymbol{x})$ related to the system (4) will be called *chaotic reference field*, and will be used in the chaos anti-control schemes to be discussed.

2.3. Control goal

Assume that the robot joint displacement $\boldsymbol{q}(t)$ and joint velocity $\dot{\boldsymbol{q}}(t)$ are available for measurement.

Now, let us define the *extended coordinate* in terms of generic variables

$$\overline{\boldsymbol{q}}=\begin{bmatrix}\overline{q}_1\\ \overline{q}_2\\ \vdots\\ \overline{q}_l\end{bmatrix}$$

Being defined $\boldsymbol{p}=[p_1\ \cdots\ p_{n-l}]^T\in\mathbb{R}^{n-l}$, the definition (5) can be written as

$$\overline{\boldsymbol{q}}=\begin{bmatrix}\boldsymbol{q}\\ \boldsymbol{p}\end{bmatrix}\in\mathbb{R}^l. \tag{5}$$

The formulation of the control goal is based in the specification of a reference chaotic field, corresponding to the chaotic system (4), which written in terms of the extended coordinate $\overline{\boldsymbol{q}}$ is given by the general structure

$$\dot{\overline{\boldsymbol{q}}}=\boldsymbol{f}(\overline{\boldsymbol{q}}).$$

As previously pointed out, the *chaotic reference field* is given by vectorial function $\boldsymbol{f}(\overline{\boldsymbol{q}})$.