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Preventing bursting in adaptive control using an introspective neural network algorithm

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ABSTRACT

This paper presents a solution to the problem of weight drift, and associated bursting phenomenon, found in direct adaptive control. Bursting is especially likely to occur when systems are nonminimum phase or open-loop unstable. Standard methods in the literature, including leakage, e-modification, dead-zone, and weight projection, all trade off performance to prevent bursting. The solution presented here uses a novel introspective algorithm operating within a Cerebellar Model Arithmetic Computer (CMAC) neural network framework. The introspective algorithm determines an estimate of the derivative of error with respect to each weight in the CMAC. The local nature of the CMAC cell domains enables this technique, since this derivative can be calculated at the moment a cell is deactivated – based on the error within the cell's domain. If the derivative looks significant, the resulting weight change (due to a Lyapunov-stable adaptive update law) remains in the cell's memory. An insignificant derivative results in the weight change being discarded before the cell's next activation. The algorithm can prevent bursting without sacrificing performance, verified through an experiment with a (nonminimum phase) flexible-joint robot and a simulation of an (open-loop unstable) quadrotor helicopter.

1. Introduction

Approximate adaptive control designs, where direct-adaptive control methods update neural network nonlinear approximators in an on-line manner, have shown great potential for controlling nonlinear systems. They have proved especially useful in robotics for trajectory-tracking problems, where traditional linear or nonlinear methods would require very accurate models of the system and/or excessive control signals to achieve high performance. The direct adaptive approach, however, naturally mitigates control signals by increasing control effort only enough to achieve the desired performance. Applications have remained limited in practice due to the difficulty in applying the methods to open-loop unstable and nonminimum phase systems; stability issues arise when there are persistent oscillations due to sinusoidal trajectories, underdamped dynamics, disturbances, or indeed any combination of these. Oscillations can cause adaptive parameters, like neural network weights, to drift to large magnitudes – eventually leading to a chattering control signal and sudden increases in state error, referred to as *bursting*. When chatter excites unmodeled dynamics in additional degrees of freedom, bursting may be unstable. Even without unmodeled dynamics, guaranteed bounds may be so large that if the trajectory approaches those bounds it would be unstable for any practical purpose. Previously proposed methods for preventing bursting often sacrifice too much performance to be useful, especially when nonlinearities are large along the desired trajectory. For a contemporary review of proposed methods to prevent bursting see [1], which for the most part concentrate on simple mathematical modifications to the adaptive update laws. In this work we propose a different approach, a neural-network based scheme that is *introspective* and utilizes the CMAC – Cerebellar Model Arithmetic Computer [2] (or Articulation Controller in [3]). Specifically, the decision on whether to update a weight is based on the CMAC's own perception of how the weight affects the error over its local domain. To summarize, the available literature does not offer an approach for direct adaptive control that avoids bursting when the system has all the following properties:

- contains non-zero nonlinearities at the origin,
- is nonminimum phase or open-loop unstable,
- is subject to persistent vibrations,
- requires high-performance trajectory tracking.

The proposed method addresses control of systems with these properties.

Developing novel techniques that allow a neural network to supervise its own training, in *reinforcement learning*, remains a popular area of research and recent results can guarantee

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control-system closed-loop stability [4]. However, reinforcement algorithms typically assume little knowledge of the system and take a proactive approach for exploring the weight space, slowing training/adaptation. In contrast, in our proposed method the adaptation takes place quickly with any direct-adaptive control, as the sign (direction) of weight change is not in question. Deciding when to stop the update, in order to achieve the best performance without risk of bursting, becomes the important consideration. Thus, the term *introspective* neural network algorithm offers a suitable nomenclature, which was a phrase coined for techniques used in case-based reasoning [5]. “Introspective learning has a process to detect deviations that show when the learning is needed as well as what the learning needs… it acquires problem-solving knowledge by monitoring its run-time performance, seeking chances in this process to learn by itself” [6] and more specifically “monitoring the results of problem solving in relation to an objective function and adjusting memory indices as a function of the comparison.” [7]. This describes our approach nicely from a high-level perspective, yet our particular algorithm and application are unique to the best of our knowledge.

Associative memories, where a weighted sum of basis functions provides the output, serve as better nonlinear approximators than multilayer perceptron backpropagation networks in robotics applications, due to faster speed of adaptation and convergence. Proposed basis functions for associative memories include spline polynomials [8,9], Gaussian Radial Basis Functions (RBFs) [10,11], original binary CMAC [12], modified non-binary CMAC [13], and fuzzy membership functions [14]. In this work we choose CMAC, in order to take advantage of the unique properties of local-domain memory. Specifically, the proposed algorithm keeps track of the average error inside the local domain of each local basis function. This enables introspective decision-making about the effect of weight updates on the change in local error.

In order to halt weight drift and subsequent bursting, researchers typically modify training rules – creating robust weight updates. Those applied to neural-adaptive control include adaptive-parameter projection [15], dead-zone [11,16], leakage (also called σ-modification) [17] and e-modification (or simply e-mod) [18–20]. In order to achieve both acceptable performance and avoid bursting, each method relies on robust mathematical modifications that critically rely on a choice of parameters in those modifications. Parameter projection requires fairly accurate knowledge on the maximum magnitude of ideal weights. Dead-zone requires fairly accurate knowledge of the maximum disturbance bound. Both leakage and e-mod use parameters which do not require system knowledge, but in practice must be found through some testing under maximum disturbance conditions. In general, a larger-than-expected disturbance can lead to bursting with any of these methods. A weight-smoothing technique may be able to fix the problem [21]. More recently, many have started using leakage that utilizes *a priori* knowledge of nonlinearities and corresponding reasonable weight estimates (for example [22,23]) to good effect. Avoiding *a priori* knowledge of the nonlinearities and/or disturbances, an adaptive dead-zone that changes size in response to disturbances has been proposed [24] but the dead-zone size remains rather conservative. The current work may be considered within an *adaptive dead-zone* category, with the introspective reasoning determining when weight updates should halt and thus indirectly deciding a nonconservative dead-zone size.

Performance and stability in the proposed method do not depend critically on a choice of any particular parameter. Rather, the method takes advantage of the unique local domains in the CMAC algorithm, and keeps track of the average error over each domain. The introspective component evaluates, within a local domain, the ratio of the change in average error to the previous Lyapunov-stable weight update. The evaluation occurs after the state input has moved out of the domain, at which point the algorithm makes a decision on a discrete off-line update to be added to permanent memory. In fact the algorithm looks at the effect of the weights on error in all currently activated basis functions, getting a better sense of behavior in the local area, in order to decide whether to keep the weight in question in permanent memory. If the weight update is not deemed helpful, it is discarded and, in addition, the permanent weight is moved back toward the weight associated with the lowest error found so far in that domain.

The advantage of our method over previous methods, like dead-zone, is that it examines the rate of change of error instead of just the error itself. The introspective method halts weight updates when it perceives they are not reducing the error, which can happen when the system has converged or when a disturbance causes errors to increase. An important advantage is that rather than producing excessive weight drift and bursting if disturbances turn out to be larger than expected, our introspective method will simply recognize that the weights should no longer be updated. We note that weight drift and bursting are not normally problems (for e-modification or deadzone) when the system being controlled is minimum phase and open-loop stable. Under these conditions internal unwanted persistent vibrations are not normally seen, and external vibrations usually pose no threat to stability. With nonminimum phase or open-loop unstable systems these types of unwanted vibrations become a threat to stability, even when small in magnitude. Thus, in this work the proposed method is tested on an open-loop unstable quadrotor helicopter simulation affected by sinusoidal disturbance, and an experimental nonminimum phase flexible-joint robot tracking a difficult trajectory.

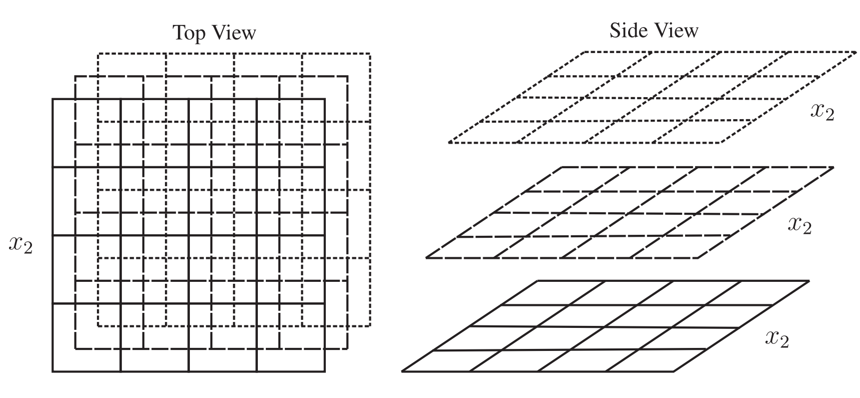

Fig. 1. Binary CMAC with 4 quantizations, 2 inputs x_1 and x_2, and 3 layers.