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A Review of Adaptive Control of Delayed Nonlinear Systems Subjected to Hysteresis

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ABSTRACT: This document presents a review of developments reported in the field of adaptive controller designed for a class of uncertain nonlinear systems subjected to hysteresis like actuator nonlinearities. Controller design for a class of nonlinear delayed system subjected to hysteresis has attracted many researchers due to challenges posed in defining a well defined control scheme for this class of system. This work investigates the development and points out the research gap in this field.

KEYWORDS: Non-linear delayed system, Adaptive Control, Hysteresis, Neural Network.

I. INTRODUCTION

Controller design for nonlinear systems is an active area of research since last few decades. Several methodologies based on Jacobean linearization or feedback linearization are reported in the literature. Feedback linearization techniques offer more promising results as compared to Jacobean linearization techniques as it enhances the region of stability. Among the various feedback linearization techniques SLIDING mode control, input state linearization and output linearization are considerable.

A nonlinear system with delayed states is a particular case of nonlinear systems, which due to its inherent complexities poses challenges for controller design. Presence of delay deteriorates the system performance and sometimes even leads to instability. For this class of systems, controllers can be categorized as delay dependent and delay independent controller design. Former assures the stability of system for a particular range of delay with a memory less controller whereas later guarantees system stability independent of delay range. Stability issues of this class can be analyzed by using Lyapunov-Krascvcki functional or control Razumikhin function.

Controller design proposed for nonlinear systems satisfies control objective with prescribed accuracy only if the control dynamics is exactly known. However, in this quite difficult to obtain accurate mathematical model for most of the nonlinear systems due to their inherent complexities or external disturbances, which are difficult to model, these uncertainties often degrades the performance. To cater these nonlinearities adaptive controller designs to proposed by the researchers, these schemes augment the baseline controller with some adaptive tool like neural network or fuzzy network. These tools act like an adaptive approximator and mimic the uncertainties of the system. These tools due to their universal approximation property approximate system uncertainties accurately and assure semi global boundedness of closed loop signals.

In real time control system, actuator nonlinearities considerably affect the system performance, phenomenon like saturation, dead zone, hysteresis are considerable actuator nonlinearities. Presence of these nonlinearities detunes the system states as well as controller and even lead to instability. Controller design for such systems so as to achieve desired performance in presence of these nonlinearities is an active area of research. Controller strategies cited in literature mainly deals with augmentation of base line controller with an inverse operator for actuator nonlinearity. Recently researchers are inclined towards designing of neural network or fuzzy logic inverse operators for actuator nonlinearities. These adaptive tools are designed to compensate the nonlinearities introduced by actuator and even relax the constraint of accurate model of nonlinearity.

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This paper is organized as follows. Section II describes and reviews the developments cited in the literature and identify the need for further development in practical applications, and to conduct further research in directions that are identified, this issue is highlighted in section III.

II. REVIEW OF LITERATURE

This section focuses on the research findings in the field of adaptive controller design for nonlinear systems. Objective of this section is to describe the research findings and analyze them for need of further research.

Automatic control plays a vital role in modern life from space-vehicle systems to industrial processes. Starting from James Watt's centrifugal governor for the speed control of a steam engine in the eighteenth century, automatic control has evolved a long way to today's adaptive controllers that can perform sufficiently well in vastly diverse operating conditions with little information about the system.

Advances in control theory have been motivated by the requirements imposed by real world applications. Until the late 1950s, the frequency response and root locus methods, the core tools of the classical control theory, have been mainly used to design control systems that satisfy performance and robustness requirements [1], [2]. Emerging complex systems with many inputs and outputs led researchers to focus on alternative approaches to deal with such systems. Development of digital computers made time-domain analysis of complex systems possible and led to development of modern control theory, emphasizing time-domain analysis and synthesis methods in the state space [3], [4]. Optimal and robust control of linear deterministic and stochastic systems were fully investigated from 1960s to 1980s [5], [6].

Development of advanced nonlinear systems, such as those in aerospace applications, forced researchers to investigate nonlinear control, as the assumption of linearity no longer held. Research in nonlinear control theory yielded several analysis and synthesis tools including feedback linearization and recursive backstepping methods [7], [8].

Systems for which no reasonably accurate low order models exist, such as flow and combustion processes, as well as systems where dynamic characteristics change rapidly in time (perhaps due to failures or environmental changes), have motivated research in adaptive control. In the early 1980s, significant advances in adaptive control started to appear, albeit under restrictive assumptions such as known system structure, affinity in the control and/or unknown parameters [9], [10]. More recently, research has focused on relaxing these assumptions by incorporating neural networks (NNs) to model complex nonlinear physical phenomena. A detailed survey of NNs and fuzzy logic systems in feedback control can be found in [11].

One major limitation that prevents direct use of a majority of control methods on real systems stems from the fact that for many systems it is not possible, or practical to measure all the state variables. This motivated researchers to develop output feedback control methods that utilize available measurements only. The traditional approach to output feedback has been to make use of state estimation, which implies that the dimension of the plant is known. Recently, an inverting adaptive direct output feedback controller has been developed that is applicable to non-affine in control systems having unknown dimension with the assumption that the relative degree of the regulated output is known [12]. The linear-in-parameters NN used in this approach to approximate the modeling error has been replaced with a single hidden layer (SHL) NN to accommodate a larger class of nonlinearities by introducing a linear observer for the tracking error dynamics [13]. This formulation has been extended to multi-input multi-output (MIMO) systems in [14]

Although novel adaptive control methods have shown excellent performance on several challenging numerical and experimental problems, it appears that for such controllers to be broadly used in military and commercial applications, a higher level of maturity has to be reached in the theory. Boundedness of error signals can be guaranteed for a wide class of problems, however, direct control of the error bounds and transient performance remain open issues. Under these circumstances, it is hard to expect industry to be willing to abandon well established approaches to control design. Inspired by this perception, an adaptive augmenting controller was developed in [15] in full state feedback setting. Adaptive output feedback controllers that augment general linear controllers following the ideas of [12] and [13] have followed in [16] − [23]. These approaches keep all the benefits of the years of experience gained on designing the existing controllers, and add the advantages of adaptive control.

Physical limitations of actuation devices, such as position and rate limits, or other nonlinearities introduced at the input level such as quantized [24] or discrete actuation [25] that adaptive controllers cannot adapt to, has stimulated research in this area. A novel approach called pseudo-control hedging (PCH) for treating nonlinearities at the input level in a dynamic inversion based controller has been proposed in [26] − [28]. Later it has been integrated in an output feedback setting [23] and in an augmenting approach [17] − [18].

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NN based adaptive controllers have attracted great attention in control of nonlinear systems with unknown structure. Universal approximation capabilities of NNs [29], [30] have been employed to parameterize uncertainties in the system with unknown structure. The NN approximation approach of [31] allowed use of a finite number of delayed values of available input/output data to approximate observable uncertainties. Further improved in [32], the NN approximation scheme led to a major progress in adaptive output feedback control. The adaptive output feedback controllers of [12] and [13] utilized the NN approximation approach of [31] and [32] to stabilize nonlinear non-affine in control systems having unknown dimensions in a dynamic inversion setting. One drawback of these controllers that limits their usage on practical problems is that unless the existing control architecture is already based on inversion, it must be replaced with one that is. The adaptive algorithms of [12] and [13] have later been implemented in a model-following context to augment more general fixed gain linear controllers [16] − [23]. A common requirement in [16] − [22] is that a linear model of the plant be available. It is further assumed that the closed-loop system consisting of the plant model regulated by the existing controller meets the performance specifications. This is often not the case, particularly when the existing controller gains are tuned in an operational environment.

In [16] − [18], the reference model is defined as the linear plant model controlled by the existing controller as illustrated in Figure 1. Since the input to the reference model is the linear control signal driven by the error signal based on the true system output y_m rather than the reference output, this architecture is referred to as the open loop reference model-following adaptive augmenting architecture. The PCH technique for treating actuator nonlinearities in a dynamic inversion based controller was modified for the open loop reference model adaptive augmenting approach in [17], [18] and simply called control hedging.

In [19] − [21] the reference model is formed by closing the loop around the linear system model with the existing linear controller, as shown in Figure 2. We refer to this architecture as the closed loop reference model-following adaptive augmenting architecture. An important feature of this architecture is that it does not rely on feedback linearization, and thus it can be applied to non-minimum phase systems. It is assumed that the linear model of the system represents the non-minimum zeros of the true plant to a sufficient accuracy, and that the linear controller takes into account the presence of these zeros. The approach has also been extended to MIMO systems in [20], [21].

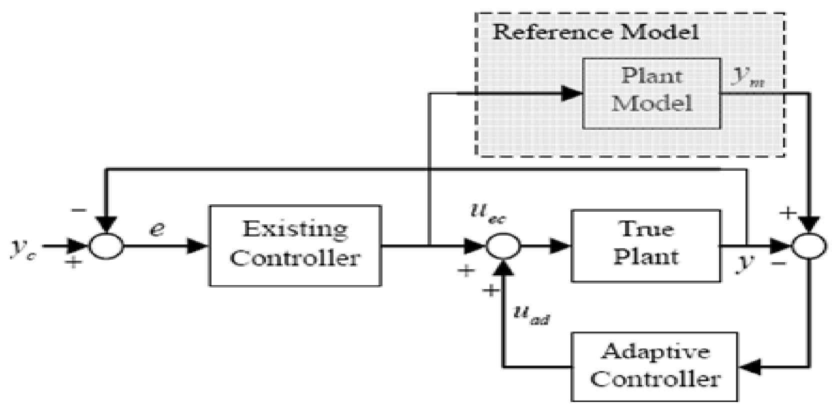

Fig 1: The open loop reference model following adaptive augmenting architecture [16]

The open loop and closed loop augmenting approaches assume that the existing controllers have been designed for the linear model of the system to achieve satisfactory dynamics. For systems where the controller has been designed by other means, for example by a tuning process while in operation with the true plant, and not by a model based design approach, these two approaches cannot be applied. No matter how accurate the available model is, when a model based controller is implemented in a real world application, it almost always requires further tuning on the system. If the linear model does not represent the true dynamics with sufficient accuracy, the model based controller tuned on the true system may no longer yield satisfactory dynamics when applied to the model.

An adaptive augmenting approach that addresses the limitations of the open loop and closed augmenting approaches mentioned above has been proposed in [23] where a simple stable linear model is introduced as the reference model as depicted in Figure 8. Since selection of the reference model is not restricted by the dynamics of the true system, except

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that its relative degree has to match that of the regulated output, we refer to this architecture as the arbitrary reference model-following adaptive augmenting architecture.

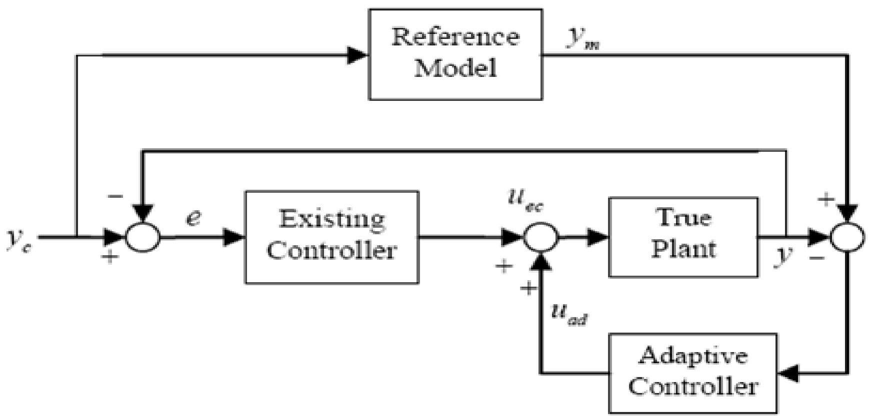

Fig 2: The arbitrary reference model following adaptive augmenting architecture [23]

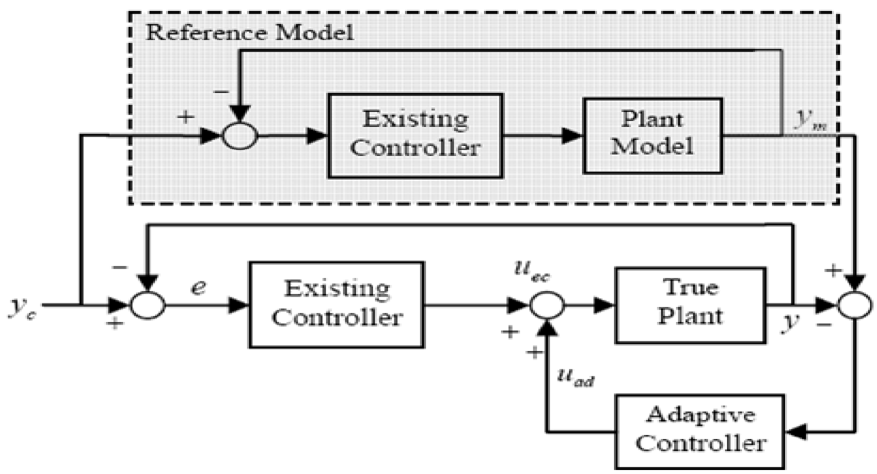

Fig 3: The closed loop reference model following adaptive augmenting architecture [19]

The presence of time delay has much effect on system performance and may destroy the stability of system [33]. Therefore, the study for time-delay systems has important practical significance. Some interesting results were obtained [33-39]. According to whether the designed controller depends on the time delay or not, the control approaches for time-delay systems may be classified into two categories: delay-dependent [34, 35] and delay-independent [36-39]. In both of them, the choice of Lyapunov-Krasovskii functional is decisive for showing stability. Recently, some research efforts have also been made in the controller design for nonlinear time-delay systems by mean of backstepping technique [38, 39]. In [38], a stabilization algorithm for a class of output feedback nonlinear time-delay systems was presented. In [39], adaptive tracking for a class of output-feedback nonlinear time-delay systems was addressed by using a delay-dependent output-feedback controller. However, the uncertainties from completely unknown nonlinear functions in system equation were not discussed in these papers [38, 39].Motivated by previous works on adaptive NN control uncertain nonlinear systems and robust control of nonlinear time-delay systems, several adaptive NN control schemes[40-42] were presented for classes of strict-feedback nonlinear time-delay systems, where NNs were only used to approximate delay-independent nonlinear functions, while delay-dependent nonlinear functions were assumed to have known upper bound functions. The assumption is difficult to be satisfied due to uncertainty of systems. To the

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best of our knowledge, it is merely considered that NNs are used to approximate unknown delay-dependent nonlinear functions in adaptive NN control.

It has been well established that hysteretic behavior is not specific to structural materials, as electrical circuits, electro-magnets, bio-physical processes, and other engineering phenomena also demonstrate such behavior under certain conditions. For instance, if a magnetizing current in the winding of an un-magnetized ring sample is steadily increased from zero, a magnetic response is observed such that even when the current is brought back to zero, the material stays as a permanent magnet. Therefore, plots of flux density versus magnetic intensity show a hysteretic response. In early 1970s, with the introduction of hysteresis models for electrical circuits [43] attempts were made to generalize such models for structural applications [44]. Studies, however, indicated that complexities arise when one tries to seek physical meanings for various parameters of such models for structural engineering applications. Various analytical models for hysteretic behavior of steel members or reinforcing steel have been developed, primarily to predict the earthquake-induced forces using a moment-curvature analysis. A comprehensive literature review of such models has been provided by Bate and Wilson [45]. The performance of these models depends on whether they include the Bauschinger effect as well as strain hardening or softening in the member. Most recently, Dodd and Restrepo-Posada [46] proposed a model for cyclic response of reinforcing steel. The model is based on the natural coordinate system, i.e., natural strain and true stress, and incorporates the Bauschinger effect by a simple expression. The advantage of the model is that the cyclic stress} strain response is symmetrical in tension and compression in the natural co-ordinate system. The model is, however, calibrated for certain grades of steel and is not generalized.

Historically, the simplest model used for steel has been the idealized elastic-perfectly plastic model. Figure 4(a) shows a representative load-detection curve for an elastic-perfectly plastic material. The model is characterized by a yield load Q:, its corresponding yield displacement X:,and the elastic stiffness ($K_e Q_y/X_y$). Recent studies by Nakashima [47] have shown that if this model is used for simulating the hysteretic behavior of tested shear panels, it will inevitably fail to trace the apparent hardening associated with those panels. He also reported that such model underestimates the cumulative dissipated energy by as much as 50 per cent depending on the maximum drift angle observed in the panel. To account for the strain hardening of steel, a generalbi-linear model has also been proposed (see Figure 4(b)). While some authors such as Housner[48] have reported that the bi-linear model tends to overestimate the energy absorption of the system, others such as Nakashima [47] have reported otherwise. Nakashima [47] indicated that the bi-linear model underestimates the dissipated energy more so than the elastic-perfectly plastic model, when the two models go through the same deformation cycle. He attributed his finding to the fact that the bi-linear model only incorporates kinematic and not the isotropic hardening, while the presence of the latter was evidenced in his experiments on shear panels.
In recent years, researchers are inclined towards the augmentation of adaptive tools with conventional control strategies for designing inverse operator for systems preceded with hysteresis. Significant contributions in this field are cited in this report. BeibeiRen et.al. [49] and in it's extended version[50] proposed an adaptive control scheme for delayed systems subjected to hysteresis. Proposed scheme employs Prandtl-Ishlinskii model for hysteresis and effectively mitigate it using neural based controller and assures the semi global ultimate upper bounded stability of closed loop signals. Qu et.al.[51] proposed an adaptive dynamic error surface control based scheme for delayed systems subjected to hysteresis. In [52],Mousavi et.al. proposed a fuzzified output feedback tracking controller for delayed uncertain systems subjected to nonlinearities like hysteresis. Notes discussing techniques to avoid singularities due to adaptation are referred in the article however no such technique and it's effect on system performance are discussed. Zhang and Lin [53] proposed a dynamic surface based neural control for delayed nonlinear systems assuring semi global ultimate upper bounded stability of the system under consideration.

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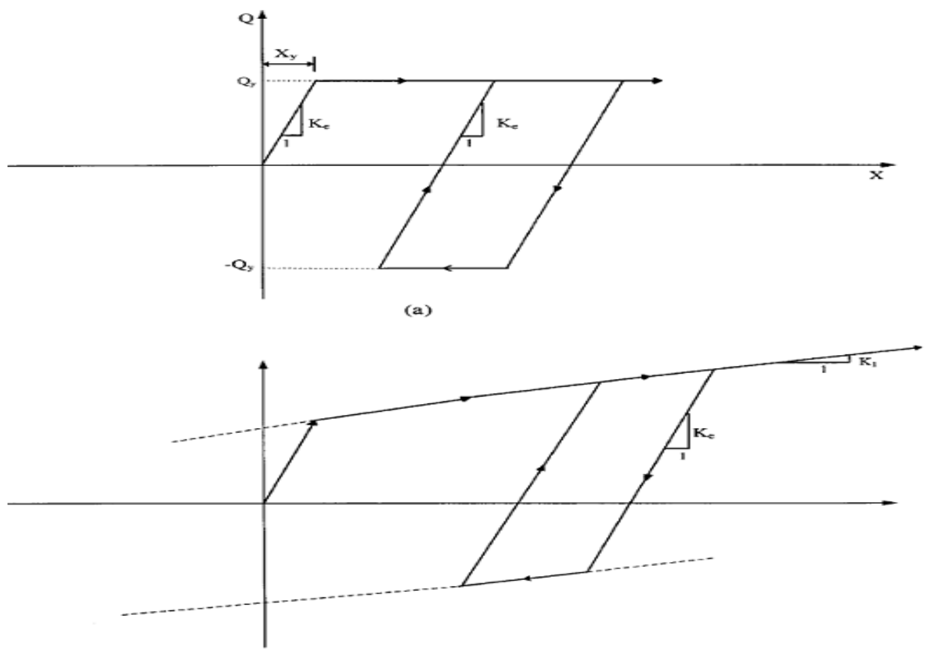

Fig 4: (a) Elastic-perfectly plastic model; (b) General bilinear model

III. CONCLUSION

Above literature reveals the advances in the field of controller design for delayed nonlinear systems with actuator hysteresis. Recent finding indicates the application of tools like neural networks for approximating system nonlinearities as well as nonlinearities due to hysteresis. Application of neural network greatly relaxes the model dependencies for hysteresis. Based on the above review it has been observed that the research findings mainly emphasis on single input systems and this work can be extended to multi input systems. Secondly, performance of the system can be improved by using some advance neural network architecture like recurrent neural network or neuro fuzzy networks for system approximation.

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