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# Adaptive sliding mode control of a class of nonlinear systems with artificial delay

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**Abstract**

In this paper, an adaptive-robust control (ARC) strategy, christened as Adaptive Time-delayed Sliding Mode Control (ATSMC) is presented for trajectory tracking control of a class of uncertain Euler-Lagrange systems. The proposed control framework brings together the best features of the switching control logic and time-delayed logic. ATSMC uses artificial time delay to approximate the unknown dynamics through time-delayed logic, and the switching logic provides robustness against the approximation error. The adaptation law for the switching gain of the conventional ARC methodologies suffer from over- and under-estimation problems. The novel adaptive law of ATSMC alleviates the over- and under-estimation problems of switching gain. Moreover, a new design methodology and stability criterion for time-delayed control is proposed which provides an upper bound on the allowable delay time. Experimental results of the proposed methodology using a nonholonomic wheeled mobile robot (WMR) is presented and improved tracking accuracy of the proposed control law is noted compared to time-delayed control and conventional adaptive sliding mode control.


## 1. Introduction

Adaptive control and Robust control are the two popular control strategies to deal with uncertain nonlinear systems. In general, adaptive control uses predefined parameter adaptation laws which adjusts the parameters of the controller online according to the pertaining uncer-

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tainties [1]. However, online computation of the unknown system parameters and controller gains for complex systems is intensive [2]. Whereas, robust control reduces computation complexity for complex systems compared to adaptive control as exclusive online estimation of uncertain parameters is not required [3]. Robust control tackles the uncertainties of the system within a predefined uncertainty bound. However, defining a prior uncertainty bound is not always possible in practice. Further, to increase the operating region of the controller, often higher uncertainty bounds are assumed. This in turn leads to problems like higher controller gain and consequent possibility of chattering for the switching law based robust controller like Sliding Mode Control (SMC). This in effect reduces controller accuracy [4]. Higher order sliding mode [5] can alleviate the chattering problem but prerequisite of uncertainty bound still exists.

Time-Delayed Control (TDC) is utilized in [6,7,15,31,37] to provide robustness against uncertainties. In this process, all the uncertain terms are represented by a single function which is then approximated using control input and state information of the immediate past time instant. The advantage of this robust control approach is that it is easy to implement and reduces the burden of tedious modelling of complex systems to a great extent. In spite of this, the unattended approximation error, commonly termed as time-delayed error (TDE) causes detrimental effect to the performance of the closed loop system and its stability. In this front, a few works have been carried out to tackle TDE which include internal model [8], gradient estimator [9], ideal velocity feedback [11], nonlinear damping [12] and sliding mode based approach [13,14]. The stability of the closed loop system, as proposed in [8,11,31,37], depends on the boundedness of TDE as shown in [6]. An auto-tuning algorithm is proposed in [10] so that the nominal mass/inertia matrix can follow the perturbed mass/inertia matrix to maintain the system stability as outlined in [6]. Stability of the system in [13] is established in frequency domain, which makes the approach difficult to analyse the stability of complex nonlinear systems. Moreover, the controllers designed in [12] and [14] require nominal modelling and upper bound of the TDE respectively which is not always possible in practical circumstances. In the field of TDC based controllers, to the best knowledge of the authors, controller design issues such as selection of controller gains and sampling interval to achieve efficient performance is still an open problem for Euler–Lagrange (EL) systems. In contrast to TDC, works reported in [16–18] use low pass filter to approximate the unknown uncertainties and disturbances. However, frequency range of system dynamics and external disturbances are required to determine the time constant of the filter. Furthermore, the order of the low pass filter needs to be adjusted according to the order of disturbance to maintain stability.

Considering the constraints of adaptive and robust control, recently global research is re-oriented towards adaptive-robust control (ARC). The series of publications [2,19–25] estimate the uncertain terms online based on projection function which requires predefined bound of individual uncertain system parameters. The works reported in [26–30] attempt to estimate the maximum uncertainty bound but the integral adaptive law makes the controller susceptible to very high switching gain and consequent chattering [31]. Recently, researchers have applied ARC in quantization process for industrial networked control systems [32]. The adaptive sliding mode control (ASMC), as presented in [33,34], evaluates the switching gain depending on a predefined threshold value. However, until the threshold value is achieved, the switching gain will be increasing (resp. decreasing) even if tracking error decreases (resp. increases) and this creates overestimation (resp. underestimation) problem of switching gain [35].