Implementation Issues and Experimental Studies of Adaptive Robust Controllers for Robot manipulators

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Abstract

This paper summarizes recent advancements on the adaptive robust control (ARC) of robot manipulators. Some of the critical implementation issues are discussed. These issues include (i) the selection of suitable ARC controller structures for reducing on-line computation time and the effect of noisy velocity measurement, (ii) on-line desired trajectory generation and initialization for a better transient performance, (iii) the tuning of controller parameters in implementation for achieving high performance, and (iv) the selection of the bounds of physical parameters and controller parameters to alleviate the effect of control saturation. Comparative experimental studies done on a SCARA type direct-drive robot are presented to illustrate the advantages and the drawbacks of qualitatively different adaptive and robust control algorithms.

1 INTRODUCTION

Practically, parameters of a robot manipulator such as gravitational load vary from a task to another, and, may not be precisely known in advance. The manipulator may also be subjected to uncertain nonlinearities such as external disturbances and joint friction. To handle these uncertainties, numerous robust control algorithms have been proposed, such as adaptive control [1, 2], deterministic robust control (DRC) or sliding mode control (SMC) [3, 4], and, recently, adaptive robust control [5, 6, 7, 8].

The adaptive robust control (ARC) [5, 6, 7, 8] proposed by Yao and Tomizuka effectively combines adaptive control with deterministic robust control (DRC). It uses both means — *certain robust controller structure and parameter adaptation* — to reduce tracking errors. Departing from the model-based adaptive control [1, 2], the approach puts more emphasis on the selection of robust controller structures as in DRC to attenuate the effect of model uncertainties as much as possible. Thus, the main practical problem of adaptive control [9]–unknown transient performance and non-robustness to uncertain nonlinearities–can be solved painlessly and a guaranteed transient performance can be obtained. Contrary to DRC, the approach discriminates the difference between parametric uncertainties and uncertain nonlinearities and uses parameter adaptation to reduce the model uncertainties. As a result, an improved performance can be obtained–*asymptotic tracking* is achieved without using discontinuous or infinite-gain feedback [10] in the presence of parametric uncertainties. The approach differs fundamentally from the existing robust adaptive control approaches [9, 11] in that it emphasizes robust performance in addition to robust stability. In return, a much stronger performance robustness–guaranteed transient and final tracking accuracy in the presence of both parametric uncertainties and uncertain nonlinearities–can be achieved; in robust adaptive control schemes [9, 11], steady state tracking error can be shown to stay within an unknown ball whose size depends on the disturbances only and nothing can be said about the transient performance. Comparative experimental results for the trajectory tracking control of robot manipulators [7, 8] and the high-speed/high-accuracy motion control of machine tools [12] have shown the effectiveness of the proposed ARC and the improvement of performance. A general theoretical framework is recently formalized by Yao in [13].

2 PRACTICAL IMPLEMENTATION ISSUES

Some of the critical practical issues in implementing ARC controllers are briefly outlined in the following.

2.1 Controller Complexity

In contrast to the conventional adaptive controllers [1, 2], the proposed ARC can handle both parametric uncertainties and uncertain nonlinearities effectively. This advantage enables us to take a practical approach in designing ARC controllers *without making a comprise between the rigorous theoretical development and the simplicity of the resulting controller*. The exact full nonlinear model of a robot manipulator is normally too complicated to be used for model compensation. Instead, only the essential part of the model will be used for the model compensation design and only the major unknown parameters (e.g., payload) which affect the tracking performance heavily will be adapted on-line to achieve a better model compensation for high performance. The rest terms of the robot dynamic model will be treated as uncertain nonlinearities and will be handled effectively by the robust control terms in ARC controllers. The design process is briefly outlined as follows.

A rigid manipulator having n degrees of freedom in free space can be described by

$$M(q,\beta)\ddot{q} + C(q,\dot{q},\beta)\dot{q} + G(q,\beta) + \tilde{f}(q,\dot{q},t) = u \quad (1)$$

where $\beta \in R^p$ is the vector of a suitably selected set of the unknown robot parameters and $\tilde{f}(q,\dot{q},t) \in R^n$ is the vector of unknown nonlinear functions such as external disturbances and unmodeled joint friction. Conventionally, since adaptive control deals with parametric uncertainties only, it is assumed [1, 2] that the system has no uncertain nonlinearity ($\tilde{f} = 0$) and all other terms can be linearly parametrized in terms of β:

$$M(q,\beta)\ddot{q}_r + C(q,\dot{q},\beta)\dot{q}_r + G(q,\beta) = f_0(q,\dot{q},\dot{q}_r,\ddot{q}_r) + Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\beta \quad (2)$$

where $\dot{q}_r$ and $\ddot{q}_r$ are any reference vectors. Since the resulting controllers utilize f_0 and the regressor Y for model compensation and parameter adaptation, the expressions of f_0 and Y have to be perfectly known so that they can be calculated on-line, which may need a tremedous amount of off-line work and on-line computation time.

Under the general framework of ARC [13], we are *not* restricted to the above procedure for model compensation and parameter adaptation. If controller complexity represents an issue for implementation, instead of using f_0 and Y in the design, we can use simple $\hat{f}_0$ and $\hat{Y}$ for model compensation and adapt major unknown parameters such as payload only. Sure, to be effective, $\hat{f}_0$ and $\hat{Y}$ should capture major portions of f_0 and Y respectively. The resulting differences $\tilde{f}_0 = f_0 - \hat{f}_0$ and $\tilde{Y} = Y - \hat{Y}$ can then be lumped with the original uncertain nonlinearity $\tilde{f}$ to create a fictitious uncertain nonlinearities $\tilde{f}_l$:

$$\tilde{f}_l = \tilde{f} + \tilde{f}_0 + \tilde{Y}\beta \quad (3)$$

An ARC controller can then be synthesized so that only simple $\hat{f}_0$ and $\hat{Y}$ will be used for model compensation and adaptation, and the lumped uncertain nonlienarities $\tilde{f}_l$ will be effectively handled by a simple robust feedback term. By doing so, we obtain a simpler ARC controller without losing theoretical rigorous and sacrificing performance much.

The above idea has been successfully tested in the high-speed/high-accuracy motion control of machine tools [12]. In [12], by lumping all model uncertainties into one term and adapting only one parameter, a very simple ARC controller was obtained. The experimental results show that when tracking a circle with a radius of 2cm with a feedrate of 6 meter/minute, the maximum tracking errors of both X and Y-axes are within 3 microns, which is in the same scale as the encoder resolution of 1 micron.

2.2 Desirable ARC Controller Structures

Because of the relatively transparent dynamics of robot manipulators, several options exist in the design of the needed ARC robust control law and the parameter adaptation law. Some desirable ARC controller structures should be identified so that one can select the most appropriate one. One of them is the desired compensation structure–f_0 and Y in (2) are calculated based on reference trajectory $q_d(t)$ only, i.e., use $f_0(q_d,\dot{q}_d,\dot{q}_d,\ddot{q}_d)$ and $Y(q_d,\dot{q}_d,\dot{q}_d,\ddot{q}_d)$ in the model compensation and the adaptation law. The idea of using the desired compensation adaptation law was first proposed by Sadegh and Horowitz [2] and was experimentally demonstrated by Whitcomb, et al. [14] that it achieves a superior tracking performance among those tested adaptive schemes. In [7, 8], we generalized the idea for ARC designs and a desired compensation ARC (DCARC) controller having the following nice features was proposed: (i) The regressor can be calculated off-line and thus on-line computation time can be reduced; (ii) The interaction between the parameter adaptation and the robust control law is minimized, which leads to an almost total separation of the robust control law design and parameter adaptation design; and (iii) The effect of measurement noise is minimized since the regressor does not depend on actual measurements. As a result, a fast adaptation rate can be chosen in implementation to speed up the transient response and to improve overall tracking performance. These claims have been verified by the comparative experiments reported in [7, 8].

2.3 Desired Trajectory Initialization and Generation

It is shown in [6] that on-line trajectory initialization can be used to minimize transient performance to achieve a guarantee performance even for a high "relative degree" nonlinear system. For ARC of robot manipulators, which is essentially a "relative degree" one design, trajectory initialization can be performed easily. Thus, it can be used to minimize transient error whenever the system experiences large tracking errors due to certain sudden changes of operating conditions. Furthermore, by suitably choosing parameters used for on-line trajectory generation, we may also alleviate the control saturation problem. In [15], this method is used to indirectly regulate intermediate variables such as working pressures of swing motors to meet certain practical constraints.

2.4 Alleviating Control Saturation Problem

All parameter adaptation laws proposed in the literature are of integration type. Thus, it may suffer from the common integration windup problem when control saturation occurs due to the appearance of some unexpected large disturbance for a short period. It was illustrated in [12] that one of the nice features of the proposed ARC design is that the resulting ARC controller has a built-in anti-integration windup mechanism. This mechanism comes from the fact that ARC utilizes the available prior information on the bounds of physical parameters in the design and switches off parameter adaptation automatically when extreme cases such as the appearance of large disturbances arise. Furthermore, by combining the control saturation bounds with the prior information on the bounds of the parametric uncertainties, we can also decide the extent of the disturbance that the system can handle so that the resulting ARC controller has a better built-in anti-windup mechanism.

3 COMPARATIVE EXPERIMENTAL STUDY

To compare qualitatively different algorithms to understand their underlining theoretical working mechanisms and practical limitations, comparative study was carried out on a SCARA type direct-drive robot. The study compared several typical controllers in each of the following categories:

Robust Control Algorithms: A very simple nonlinear PID scheme (NPID) and a model based robust control algorithm (DCRC) were proposed in [7] and implemented.

Physical Parameter (or Model) Based Adaptive Algorithms: Two benchmark adaptive control schemes, SLAC proposed in [1] and DCAL in [2], were implemented.

Gain Based Adaptive Algorithms: Performance-based (or gain-based) adaptive control use adaptation laws to adjust controller gains instead of physical parameter estimates. By adjusting feedback gains on-line, a simple gain-based adaptive algorithm (PIDAC) was proposed in [7] to remove the requirements in choosing feedback gains.

Adaptive Robust Control Algorithms: Three ARC controllers–ASMC in [5], DCARC in [16], and DCARC with adjustable gains (ARCAG) in [7]-were implemented.

The detailed experimental set-up, performance indexes, controller gain tuning processes, and control algorithms compared can be found in [8] and some of the preliminary results were published in [7]. Some of the experimental results are shown in the following table (unit is rad for tracking errors and Nm for control input torques):

Table 1: Experimental Results

Controller	e_M	e_F	$L[e_f]$	$L[u_1]$	$L[u_2]$	c_u
NPID	0.020	0.020	0.007	30.5	6.4	0.41
DCRC	0.026	0.023	0.008	30.3	6.3	0.42
SLAC	0.052	0.033	0.016	32.8	6.2	0.55
DCAL	0.035	0.020	0.009	30.3	6.3	0.43
PIDAC	0.071	0.016	0.006	30.4	6.3	0.44
ASMC	0.030	0.017	0.006	32.1	6.2	0.54
DCARC	0.020	0.013	0.004	30.6	6.4	0.41
ARCAG	0.036	0.012	0.004	30.2	6.3	0.42

In the table, transient performance is measured via e_M, the sum of the maximal absolute value of tracking errors of each joint. Final tracking accuracy is measured via e_F and $L[e_f]$, the maximal absolute value and the average tracking errors during the last three seconds of each run. The degree of control chattering is measured via $c_u = \sum_{i=1}^{2} \frac{L[\Delta u_i]}{L[u_i]}$, the sum of the normalized control variations of each joint, where $L[\Delta u_i]$ is the average of control input increments of each joint.

Based on the experimental data, the following can be concluded: (i) **Parameter Adaptation Improves Tracking Accuracy**; (ii) **Dynamic Compensator Improves Tracking Accuracy**; (iii) **Desired Compensation Improves Tracking Accuracy**; (iv) **Gain-based Adaptive Controllers via Fixed-gain Robust Controllers:** in practice, gain-based adaptive controllers do not offer much advantage in improving tracking performance. They may be used in the initial gain-tuning process to obtain the lower bound of the stabilizing feedback gains instead of using a conservative theoretical formula. However, because of their gain adaptation nature, caution should be taken to prevent possible instability which may be induced by the excessive large gain estimates during adaptation process.

4 CONCLUSION

The proposed DCARC possesses all the desirable good qualities –parameter adaptation, dynamic compensator, and desired compensation. Experimental results show that it achieves the best tracking performance by using the same amount of control effort and control chattering. These facts show again the importance of using the both means, parameter adaptation and certain controller structure, in designing high performance controllers–the main theme of the proposed ARC. Using either one of them alone may not be enough –in fact, in these experiments, probably because the effect of link dynamics is not so severe and the disturbances and measurement noise are not so small, the proposed simple NPID robust controller out-performs DCAL, the best tracking performance adaptive controllers tested in [14].

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