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A Survey of Adaptive Control Technology in Robotics

S. Tosunoglu and D. Tesar
University of Texas at Austin
Austin, TX 78712

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ABSTRACT

This paper reviews the previous work on the adaptive control of robotic systems. Although the field is relatively new and does not yet represent a mature discipline, considerable attention for the design of sophisticated robot controllers has occurred. In this presentation, adaptive control methods are divided into model reference adaptive systems and self-tuning regulators with further definition of various approaches given in each class. The similarity and distinct features of the designed controllers are delineated and tabulated to enhance comparative review.

1. INTRODUCTION

Control of robotic manipulators is a challenging problem mainly due to the nonlinear and coupled nature of the system dynamics. A considerable amount of valuable work has been produced in the dynamic formulation and the control of these systems within the last two decades. Since the pioneering works of Uicker [1], Hooker and Margulies [2], and Kahn and Roth [3] on the formulation of dynamics, researchers have concentrated on the efficient computer implementation and numerical construction of the dynamic equations. While the work on the efficient dynamic equation algorithms is still going on, control of manipulators has also received significant attention. Over the years, literature on the manipulator control methods using optimization, linearization, nonlinearity compensation, and recently, adaptive techniques has become quite rich.

This paper reviews the accumulated work in the area of adaptive control as applied to robotics. The reader should note that adaptive control in itself is not yet a mature discipline in systems theory. Also, since some of the existing tools in adaptive control are strictly for linear and/or time-invariant systems, their application to robotics deserves special attention. The immaturity of adaptive control is best demonstrated by the lack of a definition of adaptive control agreed to by the leading researchers [4].

According to Webster's dictionary, to adapt means "to adjust (oneself) to new circumstances". Adaptive control, then, in essence, is used to mean a sophisticated, flexible control system relative to the conventional fixed feedback system. An adaptive system will assure quality system performance when large and unpredictable variations in the plant dynamics or loading occur. Although our aim is by no means to establish the missing definition, since the robotics community seems to have reached a consensus on what is meant by adaptive control, we will give our definition to illustrate our interpretation of adaptive control.

Definition: A feedback control system is adaptive if the gains are selected with the on-line information of plant outputs and/or plant state variables.

This definition is depicted in block diagram format in Figure 1. The above definition encompasses all the previous work on the adaptive control of manipulators currently available to us.

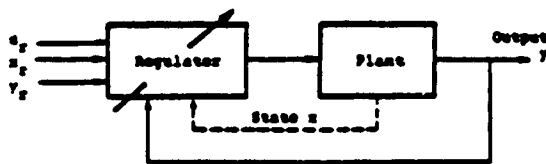


Figure 1. Block Diagram Representation of an Adaptive Control System

Although the early work on adaptive control dates back to the 1950s, its first extensive application to robotics was given by Dubowsky and DesForges in 1979 [5]. Since then a variety of different methods has been developed. So far, the existing adaptive control methods applied to robotics may be categorized under the design of

- i. Model Reference Adaptive Systems (MRAS)
- ii. Self-tuning Regulators (STR)

The following methods are used in the design of MRAS:

- i. Local parametric optimization
- ii. Lyapunov's second method
- iii. Hyperstability theory
- iv. Sliding control theory

The STR design procedure may be divided into three steps:

- i. Selection of a parametric structure to represent the robotic system via discrete-time modeling
- ii. On-line estimation of system parameters using the least squares, extended least squares or maximum likelihood methods
- iii. On-line controller design based on the estimated system parameters via extended minimum variance or pole-zero placement techniques

Block diagrams of MRAS and STR are illustrated in Figures 2 and 3. Note that the dotted boxes in these figures may be reduced to the regulator block in Figure 1. After a brief review of system dynamics, the related background work is presented below.

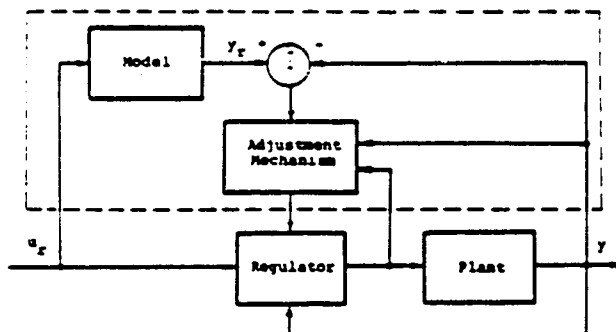


Figure 2. Block Diagram of Model Reference Adaptive System

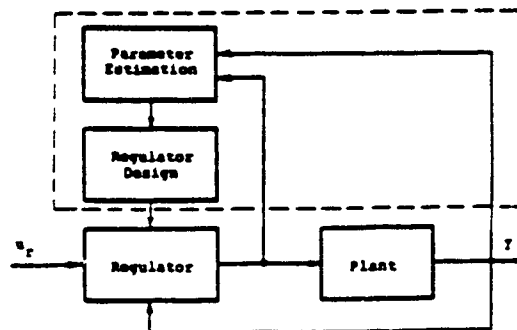


Figure 3. Block Diagram of Self-tuning Regulator

2. SYSTEM DYNAMICS

Dynamic equations of an n-link, n-degree-of-freedom, spatial, serial robot arm with rigid links are given by

$$A(\theta)\ddot{\theta} - F(\theta, \dot{\theta})\dot{\theta} - G(\theta)\theta = u \quad (1)$$

where $\theta \in \mathbb{R}^n$ is the relative joint displacement vector ($x = [\theta^T \ \dot{\theta}^T]^T \in \mathbb{R}^{2n}$), $A(\theta) \in \mathbb{R}^{n \times n}$ is the generalized inertia matrix, $-f = -F(\theta, \dot{\theta})\dot{\theta} \in \mathbb{R}^n$ represents the inertia torques due to centrifugal and Coriolis accelerations, $-g = -G(\theta)\theta \in \mathbb{R}^n$ is the gravity loads as seen at the joints where $G(\theta) \in \mathbb{R}^{n \times n}$ is non-unique, and $u \in \mathbb{R}^n$ is the control. In state-space representation, Eq. (1) can be given by

$$\dot{x} = \begin{bmatrix} 0 & I \\ A^{-1}G & A^{-1}F \end{bmatrix} x + \begin{bmatrix} 0 \\ A^{-1} \end{bmatrix} u \quad (2)$$

Note that functional dependencies are dropped for clarity. If each actuator (D.C. motor) is modeled as a second-order, linear, time-invariant subsystem (neglecting the armature inductance), and is coupled with the manipulator dynamics, the previously defined state vector, x , will be preserved and the control will be the actuator input voltage. In this case, Eq. (2) takes the following form

$$\dot{x} = \begin{bmatrix} 0 & I \\ A^{-1}(G-E_1) & A^{-1}(F-E_2) \end{bmatrix} x + \begin{bmatrix} 0 \\ A^{-1}E_3 \end{bmatrix} u \quad (3)$$

where $\Lambda = A + J$ is the combined inertia matrix with $J = \text{diag}[J_k]$, J_k is the rotor inertia of the k^{th} actuator referred to output shaft, E_1 , E_2 and E_3 are diagonal, positive definite constant matrices and functions of various actuator/gear train parameters.

Although most of the works do not include the actuator dynamics, the above, simplified form may be substituted, since the form of the equations remains the same. Depending on the adaptation algorithm, these constant actuator parameters may either be included in the on-line identification scheme or assumed known. In our presentation, the generic u will represent the suitable control (either the effective input torques or the voltages). The only exception is [6] where third-order actuator dynamics is studied in addition to the above simplified form. The dynamic equations, Eq. (2) or (3), may be given in terms of the robot-hand coordinates expressed in a fixed reference frame (task-oriented coordinates) and adaptive controllers may be designed for this system [6,7,8].

3. MRAS-BASED CONTROLLERS

In MRAS design, usually a second-order, linear, time-invariant, continuous-time reference model is selected for each link of the serial robot. Then, a control law is derived to force the robot to behave like the selected model. As mentioned earlier, local parametric optimization [5,9], Lyapunov's second method [10], hyperstability [11,12,13], or the sliding control theory [14,15,16] is usually employed to achieve the goal.

In 1979, Dubowsky and DesForges [5] implemented the local parametric optimization technique on a robot arm. In their formulation, each servomechanism is modeled as a second-order, single-input, single-output system, neglecting the coupling between system degrees of freedom. Then for each degree-of-freedom, position and velocity feedback gains are calculated by an algorithm which minimizes a positive semi-definite error function utilizing the steepest descent method. Stability is investigated for the uncoupled, linearized system model. This work represents the first implementation of adaptive control to robotics.

The recent works have concentrated on the designs based on the Lyapunov's second method and the hyperstability theory. In the most general case, these control methods yield the following control structure u_p :

$$u_p = \delta_1 f_1(A_p, F_p, G_p, x_p) + \delta_2 f_2(K_i, x_p, x_r, u_r) + \delta_3 f_3(m_j, x_p, x_r, \dot{x}_r) \quad (4)$$

where subscripts p and r represent the plant and reference model, respectively, δ_i is either 0 or 1, $f_1 \in R^n$, $K_i \in R^{n \times n}$ nonlinear or constant gain matrix, $i=1,2$, or 3, $m_j \in R^1$ represents an unknown system parameter like the payload, link mass content, center of gravity location, etc., where a combination of these constant parameters or a nonlinear term is to be estimated in the adaptation process, and $j=1,2,\dots,k$, where k depends on the specific controller design. Although some controllers call for plant joint accelerations, they are not shown in Eq. (4).

The first term f_1 in Eq. (4) describes the nonlinearity compensation. It may represent the complete manipulator dynamics as in [17,18], or only the gravity terms and the Jacobian as in [7]. A controller with $\delta_1 = 1$ and $\delta_2 = \delta_3 = 0$ indicates only a nonlinearity compensation. The second term in u_p represents the feedback portion of the controller. The gain matrices K_i may either be nonlinear or constant. Now $\delta_1 = \delta_3 = 0$ and $\delta_2 = 1$ represent the control structures of [16,19,20,21] among others. The third term in u_p includes the portion of the control where system parameters are estimated [17,18,22]. Slotine [18], for example, includes all the components into his controller, therefore, $\delta_1 = \delta_2 = \delta_3 = 1$. Takegaki and Arimoto's control strategy [7] may be summarized by $\delta_1 = \delta_2 = 1$ and $\delta_3 = 0$. Horowitz and Tomizuka's [22] $\delta_1 = 0$, $\delta_2 = \delta_3 = 1$, etc.

Various MRAS control structures are summarized in Table 1. This table differentiates the methods which require explicit calculation of dynamic equations (Nonlinearity Compensation) from the methods which adaptively estimate the plant parameters on-line (Incorporation of Plant Parameter Estimation). However, further distinction is needed in the latter group, since while one approach explicitly identifies the nonlinear terms (as in A, G, and F with reference to Eq. (2)), and estimates them on-line, the recent methods treat the constant robot parameters as unavailable, estimate and compensate them in their algorithms. Some methods choose nonlinear feedback matrices in their controllers (H, L, S in Table 1) without incorporating the explicit system parameter estimations.

The early works presented in Table 1 have generally avoided the nonlinearity compensation and opted for the assumption that the nonlinear system parameters vary slowly in time. On this basis, a stability analysis is given for the system. This assumption almost certainly is too restrictive, since the nonlinear manipulator system parameters are functions of the joint position and velocities. The faster the robot movement is, the more rapidly the system parameters will vary. The objective on the other hand, for the more sophisticated control methods is to enable fast robot movements with high precision. As a result of revolutionary advances in the microprocessor industry with prices steadily coming down, the possibility of real-time implementation of computation intensive algorithms is steadily improving. Recently, Wander and Tesar [23,24] have implemented the complete dynamic equations [25] of a 6-link, general architecture robot arm in 6.5 milli sec. (150 Hz) in explicit form without using recursion. Their algorithm is able to treat an n-degree-of-freedom (DOF) serial system of completely general parameters (43 milli sec. for 12-DOF). They have implemented the algorithm on an Analogic AP-500 array processor. Further work on the comparative analysis of various computer architectures is underway at the University of Texas at Austin.

Some of the most recent works include nonlinearity compensation along with a feedback portion and parameter identification features [6,17,18]. Once the control has the form $u_p = \bar{A}_p^{-1}(s_p)u_p'$, where subscript p denotes the plant, \bar{A}_p is the on-line calculated generalized inertia matrix and u_p' is yet to be selected, generally, global stability of the closed-loop system can be shown provided that $\bar{A}_p^{-1}\bar{A}_p = I$, where I is the identity matrix of order n, is maintained [6]. Otherwise, in reference to Table 1, all methods without nonlinearity compensation need to assume system parameters stay constant during the adaptation.

Table 1. Summary of MRAS Controllers in the Literature

	CONTROLLER CHARACTERISTICS			
	NONLINEARITY COMPENSATION ¹	LINEAR / NL FEEDBACK / METHOD	INCORPORATION OF PLANT PARAMETER ² ESTIMATION	ASSUMED SYS. PARAMETERS STAY CONST. DURING ADAPTATION ³
Dubowsky and DesForges 1979 [5]	--	O	--	√
Horowitz and Tomizuka 1980 [22]	--	C	N	√
Takegaki and Arimoto 1981 [7]	G	L	--	√
Balestrino et al. 1983 [19]	--	H	--	√
Stoten 1983 [21]	--	H	--	√
Balestrino et al. 1984 [16]	--	H,S	--	√
Nicosia and Tomei 1984 [27]	--	H	--	√
Vukobratovic et al. 1985 [30]	--	H	--	√
Landau 1985 [36]	--	C	N	√
Whyte 1985 [28]	--	L,C	--	√
Lim and Estami 1985 [20]	--	L	--	√
	√	L	--	--
Hsia 1986 [29]	--	L	--	√
	--	H,C	--	√
	--	C	N	√
Craig, et al. 1986 [17]	√	--	√	--
Slotine 1986 [18]	√	L,C,S	√	--
Tosunoglu and Tesar 1986 [6]	A	L,H,C	√	--
	√	L,H,C	√	--

Key to Remarks:

1 : Calculates complete or partial nonlinear dynamics on-line.

2 : Robot link lengths, mass contents, actuator parameters, etc., if not otherwise specified.

3 : If "yes", stability analysis based on this assumption.

G : Gravity load compensated; also requires on-line Jacobian calculation.

A : Requires only the on-line calculation of the inertia matrix.

O : Nonlinear-gain feedback using local parametric optimization.

C : Constant-gain feedback.

L : Nonlinear-gain feedback using Lyapunov's second method.

H : Nonlinear-gain feedback using hyperstability theory.

S : Nonlinear-gain feedback using sliding theory.

N : Structure of nonlinear system parameters (functions of state variables) are explicitly assumed known and are adaptively estimated; stability analysis based on hyperstability theory.

√ : Yes.

-- : No.

Balestrino, et al. [19] have developed an adaptive controller which produces discontinuous control signals leading to chattering. Stability analysis is presented using hyperstability theory. In [16], Balestrino, et al. present three methods; the first is based on the theory of variable-structure systems, the second on the hyperstability and the third is a combination of the first two methods. Designed controllers produce high-frequency chatter which is highly undesirable since higher order dynamic modes may be excited. Numerical simulations show an extremely high frequency of sign switches in the plant input, prohibiting its physical realization. Stoten [21] formulates the MRAS problem closely following the procedures in [9] and simulate the algorithm for a 1-link manipulator.

Horowitz and Tomizuka [22] study the adaptive control of a 3-link arm. Gravity effects and the mass and inertia of the first link are neglected. Each nonlinear term in the dynamic equations is identified a priori, treated as unknown, and estimated by an adaptation algorithm. For the modeled system and the designed controller, stability analysis is given by Popov's hyperstability theory. Later, Anex and Hubbard [26] have experimentally implemented this algorithm with some modifications. System response to high speed movements is not tested, but practical problems encountered during the implementation are addressed in detail.

Takegaki and Arimoto [7] propose an adaptive method to track desired trajectories which are described in the task-oriented coordinates. The suggested controller compensates gravity terms, calculates the Jacobian and the variable gains, but does not compensate the manipulator dynamics completely. System stability is assured if the manipulator hand velocity is sufficiently slow, i.e., nonlinear system parameters change slowly.

Nicosia and Tomei [27] derive control laws using the hyperstability theory to follow a linear, time-invariant reference model. The plant (manipulator) parameters and the payload are assumed known and are not identified. Their controller does not produce chattering and is relatively easy to implement. Lim and Eslami [20] propose controller designs based on Lyapunov's second method. The author's objective is to control the linearized dynamic equations with the developed controllers; hence, assuring the stability of the linearized system. Later, nonlinearity compensation is suggested to enhance the system response. Whyte [28] designs an adaptive controller via Lyapunov's second method. The algorithm does not require any knowledge of the manipulator dynamics and selects nonlinear gains in the feedback loop to follow the reference model. System stability is shown, provided that the parameter changes are slow. Hsia [29] reviews the current methods used in adaptive control and gives brief formulations for each method. Vukobratovic, et al. [30], review local parametric optimization and hyperstability-based methods and choose not to include the approaches based on Lyapunov's second method in their book on the non-adaptive and adaptive control of manipulators.

Tosunoglu and Tesar [6] select a generalized nonlinear reference model which represents ideal robot dynamics. The plant, the actual robot whose system parameters may not be exactly known, is then forced to behave like the reference model to follow the desired trajectory. The advantage of the nonlinear reference model is that the adaptation process ceases once the nominal trajectory is recovered. (Such is not the case when linear models are selected.) Error-driven dynamics is derived and the system is augmented to include the integral feedback feature to eliminate the parameter discrepancies between the plant and the reference model, and the disturbances acting on the system. It is shown that the controllers designed in this work via Lyapunov's second method also produce hyperstable systems. Simulations demonstrate successful trajectory tracking on 3- and 6-link, spatial manipulators under unknown payloads and estimated system parameters (link lengths, masses, inertia components, payload, etc.). The authors also provide comparative analyses of the effect of integral feedback and various controller update rates, 60 to 200 Hz.

Craig, Hsu and Sastry [17] take an interesting approach in designing an adaptive controller using the Lyapunov's second method. In this work, the structure of the terms in the dynamic equations is assumed known, but their numerical values remain unknown. They partition the dynamics into known and unknown portions and estimate the unknown parameters along with compensation for the nonlinearities. Global stability is proved by assuming that a matrix function of the plant joint position, velocity and accelerations is bounded. Although all the terms which are functions of positions are bounded, velocity and accelerations may increase without bounds; thus, making the matrix unbounded. However, modifications in the controller structure may alleviate this problem. Their numerical simulations identify link masses and Coulomb friction coefficients for a two-link manipulator with encouraging results.

Slotine and Li [18] derive a control law with full feedforward dynamics compensation, PD feedback and on-line payload and manipulator parameter estimation using Lyapunov's second method. Since this control scheme does not eliminate the steady-state errors, the authors restrict the steady-state position errors to lie on a sliding surface. This modification, in turn, causes the loss of numerical efficiency where, interestingly, the authors make use of the recursive computation feature of the manipulator dynamics. Later, an approximate implementation is suggested to improve the numerical efficiency. Payload parameter identification is simulated on a two-link manipulator.

Once these current methods are refined, application to manipulators with higher degrees of freedom will naturally follow. Determination of the structure of the constant terms (for identification) for manipulators with higher number links may be achieved with symbolic generation of dynamic equations, but the effect of increased number of terms will require further investigation.

4. SELF-TUNING REGULATOR (STR) BASED CONTROLLERS

In this method, typically, nonlinear manipulator dynamics is linearized about a nominal trajectory and then discretized. The discretized model gives the structure of the parametric model whose parameters need to be estimated on-line. The parametric model is given by the following multivariable difference equation

$$y(k) = \theta^T \phi(k-1) + e(k) \quad (5)$$

where $y(k) \in \mathbb{R}^n$ is the system output, k is the sampling time counter, $\theta \in \mathbb{R}^{n \times (2nm+1)}$ contains the parameters to be identified, $\phi \in \mathbb{R}^{(2nm+1)}$ represents the combined system input and output vector, $e \in \mathbb{R}^n$ is a random, zero-mean Gaussian white noise, and m is the order of the estimation model.

Parameter estimation is based on the system identification techniques using the sampled input-output data. Although such techniques include the least squares, extended least squares and maximum likelihood methods; the recursive least squares method is extensively used because of its lower computational requirements [8,25,29-36]. The recursive least squares estimation is given by

$$\hat{\theta}_i(k) = \hat{\theta}_i(k-1) + P(k) \phi(k-1) [y_i(k) - \hat{\theta}_i^T(k-1) \phi(k-1)] \quad (6)$$

where

$$P(k) = \frac{1}{\lambda} \left[P(k-1) - \frac{P(k-1) \phi(k-1) \phi^T(k-1) P(k-1)}{\lambda + \phi^T(k-1) P(k-1) \phi(k-1)} \right]$$

$\hat{\theta}_i(k)$ represents the estimate of the i^{th} row of θ defined in Eq. (5), $P(k)$ is a square symmetric matrix of order $(2nm+1)$, and $0 < \lambda < 1$ is an exponential forgetting factor.

Once the parameters are identified at each sampling time, regulator parameters are estimated using the extended minimum variance [8,30,32], or pole-zero placement techniques [29,33,35]. The method described above is known as explicit or indirect STR. If the regulator parameters are estimated directly by a reparameterization of the process model, the model is called implicit or direct STR. Usually implicit STR algorithms cancel all process zeros making them suitable only for minimum phase systems.

Koivo and Guo [32] assume an autoregressive model and identify system parameters using the recursive least squares technique. They design an extended minimum variance controller for the estimated model. The method chooses a quadratic performance index in terms of the state error vector and the system control vector and minimizes it relative to admissible controls while satisfying Eq. (5). Their simulations include decoupled and partially coupled parametric model structures. They report that the parameter convergence is faster in the decoupled case, and that no significant improvement in the system response is observed for the coupled model. This is rather interesting, because the amount of on-line calculations is considerably reduced for the decoupled case. Also reported is the fact that the model and the controller parameter identifications may not converge fast enough while the robot motion takes place.

Lee [8] derives the perturbation equations, discretizes them and estimates the system parameters using the recursive least squares method. Then an adaptive controller is designed using the extended minimum variance technique. The parameter identification requires the estimation of $6n^2$ parameters on-line (216 for a 6-link manipulator). Lee provides a detailed breakdown of the computational requirements and concludes that for a 6-link manipulator the control scheme can be updated at about 56 Hz on a PDP-11/45.

Hsia [29] reviews the STR formulation on a decoupled model. Karnik and Sinha [35] develop an STR based on a non-minimum phase model which assigns the system poles while retaining all the zeros. This algorithm is developed for a UNIMATE-2000 robot. Landau [9,36] and Vukobratovic, et al. [30] review various STR designs in detail.

In general, discrete-time formulation is especially suitable for computer control. However, on-line estimation of all system parameters and the control design make STR computationally intensive. Astrom [4] reports that numerical estimation techniques tend to be numerically unstable as the number of parameters increases in the system model. In this case, the complete system is parameterized. However, the papers reviewed in this work do not raise the question with regard to numerical instability although they do indicate the importance of initial parameter selections. In STR methods, convergence of estimated parameters in the adaptation process is guaranteed if the system parameters are constant. Since the actual robot model parameters are nonlinear functions of the state vector, the question of system parameters varying slowly in time again arises in the STR methods.

5. CONCLUSIONS

Adaptive control of robotic systems has received significant attention within the past few years. A class of control laws based on the MRAS design realize the adaptation through signal synthesis with a completely known parameter structure, while some methods select a subclass of the parameters for identification for reduced computational burden. All adaptive controllers via STR design and some MRAS-based methods estimate the complete (nonlinear) system parameters on-line.

Stability analysis usually relies on the condition that the nonlinear system parameters vary slowly. This condition is removed if a nonlinearity compensation component is also incorporated in the controller. The most recent works, which exploit the special structure of manipulator dynamics, seem to favor this feature. The use of state-of-the-art microprocessor technology along with the sophisticated dynamic formulation algorithms strongly indicate that real-time implementation of dynamic compensation is rapidly becoming feasible.

Further research to perfect the existing algorithms and to provide rigorous stability proofs, which will improve the maturity of the adaptive control, is still needed. Although today's industrial robots employ linear controllers to accomplish a number of useful tasks, fast and precise robot movements remain to be implemented. Development of laboratory test beds and implementation of the developed adaptive controllers on robotic manipulators are also crucial, since only after successful demonstrations will technology transfer be possible.

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