5-23-1990

Survey of the robust control of robots

Chaouki T. Abdallah

Peter Dorato

M. Jamshidi

SURVEY OF THE ROBUST CONTROL OF ROBOTS

C. Abdallah, P. Dorato, and M. Jamshidi
CAD Laboratory for Systems and Robotics
Electrical and Computer Engineering Department
University of New Mexico
Albuquerque, NM 87131.

ABSTRACT

In this survey, we discuss current approaches to the robust control of the motion of robots and summarize the available literature on the subject. The three major designs discussed are the "Linear-Multivariable" Approach, the "Passivity" approach and the "Variable-Structure" approach. The survey is limited to rigid robots and nonadaptive controllers.

I. INTRODUCTION

There are basically two underlying philosophies to the control of uncertain systems : the adaptive control approach, and the robust control approach. In the adaptive approach, one designs a controller which attempts to "learn" the uncertain parameters of the particular system and, if properly designed will eventually be a "best" controller for the system in question. In the robust approach, the controller has a fixed-structure which yields an "acceptable" performance for a given plant-uncertainty set. In general, the adaptive approach is applicable to a wider range of uncertainties , but robust controllers are simpler to implement and no time is required to "tune" the controller to the plant variations.

We review here different robust control designs used in controlling the motion of robots. A discussion of adaptive controllers may be found in [1]. The techniques discussed in this survey belong to one of three categories. The first is the linear-multivariable or feedback-linearization approach [2] where the inverse dynamics of the robot are used in order to globally linearize and decouple the robot's dynamics. Since one does not have access to the exact inverse dynamics, the linearization and the decoupling will not be exact. This will be manifested by uncertain feedback terms that may be handled using multivariable linear robust control techniques [3]. The methods based on computed-torque, or inverse-dynamics such as those of [4-11] fall under this heading. This approach will be described in section II of the paper. The second category contains methods that exploit the passive nature of the robot [12]. These techniques try to maintain the passivity of the closed-loop robot/controller system despite uncertain knowledge of the robot's parameters. Although not as transparent to linear control techniques as the computed-torque approach is, passivity-based methods can nontheless guarantee the robust stability of the closed-loop robot/controller system. The works described in [13,14] fall under this category and will be discussed in section III. In the third category we include methods that can not be easily deduced from either the computed-torque nor the passivity approaches. These include variable-structure and switching controllers [15] which attempt to robustly control the nonlinear robot. Section IV will present the works of [16,17,41] which provide a sample of these techniques. A general survey of existing robust control theory may be found in [3, 18].

Let the rigid robot dynamics be given in joint space by the Lagrange-Euler equations [19]

$$D(q)\ddot{q} + h(q,\dot{q}) = \tau \tag{1.1}$$

where q is the generalized coordinate n vector representing the joints positions, and τ is the generalized n torque input vector. The matrix $D(q)$ is a symmetric positive-definite inertia matrix and $h(q,\dot{q})$ is a vector containing the Coriolis, centrifugal, and gravity terms. In general, (1.1) arises as a solution to the Lagrange equations of motion for natural systems [20]. In this paper, we survey methods which deal primarily with designing controllers that will make q and $\dot{q}$ track some desired q_d and $\dot{q}_d$ when the some entries of $D(q)$ and $h(q,\dot{q})$ are uncertain. This will exclude the important case when the robot comes in contact with the environment.

II. LINEAR MULTIVARIABLE APPROACH

In this section we review approaches which use linear or saturating linear multivariable design techniques for design of robust robot controllers. In the early days of robot control, the idea of linearizing the nonlinear robot equations about their desired trajectory was popular, and many controllers were designed that way [21,23,42,43]. Later, however, the special structure of equations (1.1), and the fact that the control τ provides an independent input for each degree of freedom [2,12] , has led to the use of "global" linearization of the nonlinear system. It is this later approach that is stressed in this section. For an excellent description of the exact linearization of robots see [2]. By defining the trajectory error vector, $e_1 = q-q_d$, $e_2 = \dot{e}_1$, one is able to globally linearize the nonlinear error system, to the following

$$\dot{e} = Ae + Bv \tag{2.1}$$

where

$$v = D(q)^{-1}[\tau-h(q,\dot{q})] - \ddot{q}_d. \tag{2.2}$$

and

$$A = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} , \; B = \begin{bmatrix} 0 \\ I \end{bmatrix} , \; e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$$

The problem is then reduced to finding a linear controller v which will achieve a desired closed-loop performance i.e.

$$\dot{z} = Fz + Ge,$$
$$v = Hz, \tag{2.3}$$

or,

$$v(t) = H(sI-F)^{-1}Ge(t) \equiv C(s)e(t)$$

The following static state-feedback controller is often used

$$v = -K_1e_1-K_2e_2 \equiv -Ke \tag{2.4}$$

to lead to the following nonlinear controller

$$\tau = D(q)[\ddot{q}_d+v]+h(q,\dot{q}) \tag{2.5}$$

which gives the following closed-loop system

$$D(q)[\ddot{e}_1+K_2\dot{e}_1+K_2e_1] = 0. \tag{2.6}$$

Unfortunately, the control law (2.5) can not usually be implemented due to its complexity or to uncertainties present in $D(q)$ and $h(q,\dot{q})$. Instead, one applies

$$\tau = \hat{D}[\ddot{q}_d+v]+\hat{h} \tag{2.7}$$

where $\hat{D}$ and $\hat{h}$ are estimates of D and h . This in turn leads to (Figure 1)

$$\dot{e} = Ae + B(v+\eta) \tag{2.8}$$

where

$$\eta = E(v+\ddot{q}) + D^{-1}\Delta h$$
$$E = D^{-1}\hat{D} - I_n \;,\; \Delta h = \hat{h} - h \tag{2.9}$$

The vector η is a nonlinear function of both e and v and can not be treated as an external disturbance. It represents a disturbance of the globally linearized error dynamics which is caused by modeling uncertainties, parameter variations and maybe even noisy measurements [4]. The linear multivariable approaches then revolve around the design of linear controllers $C(s)$ (which may be dynamical) that will give a control law v such that the complete closed-loop system (Figure 1) is stable in some suitable sense, e.g. uniformly ultimately bounded, globally asymptotically stable, etc. for a given class of nonlinear perturbation η i.e.

$$\dot{e} = Ae + B(v+\eta) \tag{2.10}$$

$$v(t) = C(s)e(t) \tag{2.11}$$

The following reasonable assumptions [24] are often made

$$\|D^{-1}\| \le a, \tag{2.12}$$

$$\|E\| \le \alpha \tag{2.13}$$

$$\|\Delta h\| \le \delta_0\|e\|^2 + \delta\|e\| + \rho_0 \tag{2.14}$$

where a , α , δ_0 , δ , and ρ_0 are nonnegative finite constants which depend on the size of the uncertainties.

In general, the small-gain theorem [25], or the total stability theorem [26] are applied in order to find $C(s)$. The most general of these controllers have been designed using Youla parametrization and H^∞ control theory [27,28] and will be discussed first.

Spong and Vidyasagar [4] used the factorization approach [27] to design a class of linear compensators $C(s)$, parametrized by a stable transfer matrix $R(s)$, and which guarantee that the solution $e(t)$ to the nonlinear system (2.2) has a bounded L_∞ norm. The authors actually assumed that the bound on Δh is linear, i.e. $\delta_0 = 0$ in (2.14) and found the family of all L_∞ stabilizing compensators of the nominal plant. A particular compensator may then be obtained by choosing the parameter R(s) to satisfy other design criteria such as surpressing the effects of η. As was discussed in [24], including the more reasonable quadratic bound will not destroy the L_∞ stability result, but will exclude any L_2 results unless the problem is reformulated and more assumptions are made. In particular, noisy measurements are no longer tolerated. Craig [29] discussed the L_2 problem and under certain conditions, was able to show the boundedness of the error signals.

Static feedback compensators such as the ones given in (2.3) have also been used extensively starting with the works of Freund [30], and Tarn et.al. [6], where

$$v = C(s)e = -Ke \tag{2.15}$$

such that

$$\dot{e} = Ae + B(v+\eta) = (A-BK)e + B\eta = A_c e + B\eta. \tag{2.16}$$

In these papers, the authors use the state-feedback to either place the poles sufficiently far in the left-half-plane [9], therefore guaranteeing stability in the presence of η (by the total stability theorem for example), or an extra control loop [6] to correct for the effects of η. In Kuo and Wang [31], the internal model principle developed by Francis and Wonham [32] is used to design a linear controller which minimizes the effects of the disturbance term η. However, since η is a nonlinear function of e and v, minimizing its effects does not necessarily guarantee closed-loop stability. In Gilbert and Ha [10], Proportional-Integral-Derivative control is applied in order to obtain some sensitivity improvements. Cai and Goldenberg [33] use Proportional-Integral control to improve the robustness properties of the controller. Arimoto and Miyazaki [34] use Proportional-Integral-Derivative feedback control to robustly stabilize robot manipulators. Ha and Gilbert [5] use a saturating type feedback control derived from Lyapunov function theory in order to guarantee the ultimate boundedness of the error vector $e(t)$. Their solution is parametrized with certain constant matrices which make it possible to design for ultimate error bound, rate of approach to the ultimate bound, size of the saturating zone, and feedback gains in the unsaturated region. In Spong et. al. [8], Lyapunov function theory was used to guarantee the ultimate boundedness of the error vector in (2.2). The controller is saturating and was obtained from the results of Cvetkovic and Vukobratovic [35] and a linear "high-gain" controller based on the theory of Barmish et.al. [36], Gutman [37], and Corless and Leitman [38]. A similar approach was discussed by Chen [39]. Finally, in Samson [11], Lyapunov theory was used to obtain a "High-gain" controller which guarantees ultimate boundedness.

The feedback-linearization approach has been popular (under different names) in the robotics field. Its main advantage is obviously the wealth of linear techniques which may be used in the linear outer loop. In the presence of contact forces however, this approach becomes much more involved as was discussed in [14]. In some cases, the local linearization approach was combined with other techniques in order to guarantee robust stability [21,23,42]. In particular, Desa and Roth [23] used the internal model principle to minimize the effects of disturbances for a robot model linearized over segments of the total operating time. Here also, closed-loop stability is not guaranteed.

III. PASSIVITY - BASED APPROACH

In this section, we review approaches which rely on the passive structure of rigid robots as described in the following

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \tag{3.1}$$

where $h(q,\dot{q}) = C(q,\dot{q})\dot{q} + g(q)$, and $\dot{D}(q)-2C(q,\dot{q})$ is skew symmetric by an appropriate choice of $C(q,\dot{q})$ [12]. As a result of that, the following theorem is obtained.

Theorem 3.1 [1]:

The Lagrange-Euler dynamical equations of a rigid robot (1.1) define a passive mapping from τ to $\dot{q}$ i.e.,

$$<\dot{q} \mid \tau>_T \equiv \int_0^T \dot{q}^T \tau dt \ge -\beta \tag{3.2}$$

for some $\beta > 0$ and all T finite.

Based on that property, if one can close the loop from $\dot{q}$ to τ with a passive system (along with l_2 bounded inputs) as in Figure 2, the closed-loop system will be stable using the passivity theorem [25]. This however, will only show the asymptotic stability of $\dot{e}_1$ and not of e_1. On the other hand, if one can show the passivity of the system which maps τ to a new vector r which is a filtered version of e_1, then a controller which closes the loop between $-r$ and τ will guarantee the asymptotic stability of both e_1 and $\dot{e}_1$. This approach has been used in the adaptive control literature to define passive controllers [1]. Consider then the following control law

$$\tau = D(\ddot{q}_d - K_v F_v(s)\dot{e}_1) + C\dot{q} + g \tag{3.3}$$

where $F_v(s)$ is an SPR transfer function, K_v is a positive-definite gain matrix. Unfortunately, the inclusion of an integrator which reconstructs the error e_1 will destroy the SPR condition. Substituting the above control law into equation (3.2), one gets from Figure 2

$$r = [C - DK_v F_v(s)]\dot{e}_1$$

$$r = \Lambda(s)\dot{e}_1 \tag{3.4}$$

and

$$u_2 = D\ddot{q}_d + C\dot{q}_d + g \tag{3.5}$$

where $DK_v F_v(s) - C$ is SPR with an SPR inverse by an appropriate choice of K_v and $F_v(s)$. Using the passivity theorem, one deduces that $\dot{e}_1$ and r are bounded in the L_2 norm, and since

$$\dot{e}_1 = \Lambda(s)^{-1} r \tag{3.6}$$

is SPR, one deduces that $\dot{e}_1$ is asymptotically stable. Unfortunately, as discussed above, this will only imply that the position error e_1 is bounded and not its asymptotic stability.

On the other hand, since one does not have the exact knowledge required to implement controller (3.3), one usually uses

$$\tau = \hat{D}[\ddot{q}_d - K_v F_v(s)\dot{e}_1] + \hat{C}\dot{q} + g \tag{3.7}$$

Notice that the gravity term g is being exactly canceled. Applying this controller to equation (3.1) results in Figure 2, with

$$r = [\hat{C} - \hat{D}K_v F_v(s)]\dot{e}_1 \tag{3.8}$$

and

$$u_2 = \hat{D}\ddot{q}_d + \hat{C}\dot{q}_d \tag{3.9}$$

and the stability of the closed-loop system is still guaranteed using the passivity theorem if one chooses $DK_vF_v(s)-\hat{C}$ to be SPR with an SPR inverse.

The passivity approaches described so far have been modified versions of the feedback-linearization approaches. In [13,14] however, Anderson demonstrated using network-theory concepts, that even in the absence of contact forces, a feedback-linearization-based controller is not passive and may therefore cause instabilities in the presence of uncertainties. His solution to the problem consisted of using Proportional-Derivative (PD) controllers with variable gains i.e.

$$\tau = -K_1e_1 - K_2e_2 + g, \tag{3.10}$$

where K_1 and K_2 are time-varying and dependent on the inertia matrix $D(q)$. Even though, $D(q)$ is not exactly known, the stability of the closed-loop error is guaranteed by the passivity of the robot and the feedback law. The advantage of this approach is that contact forces may now be accommodated and that larger uncertainties may now be accomodated. Its main disadvantage is that its performance depends on the knowledge of $D(q)$ whose singular values are needed in order to find K_1 and K_2. In [40], a combination of feedback-linearization and passivity results was used to show the stability of the closed-loop error response under the assumption that the h terms are known or small.

IV. VARIABLE - STRUCTURE CONTROLLERS

In this section, we group designs that use variable-structure controllers [15] and other designs which may not be easily deduced from either previous approaches. The VSS theory has been applied to the control of many nonlinear processes. One of the main features is of this approach is that one only needs to drive the error to a "switching surface", after which the system is in "sliding mode" and will not be affected by any modeling uncertainties and/or disturbances [15,16]. The first application of this theory to robot control seems to be in the work of Young [16] where the set point regulation problem ($\dot{q} = 0$) was solved using the following controller

$$\tau_i = \begin{cases} \tau_i^+ & \text{if } s_i(e_{1i},\dot{q}_i) > 0 \\ \tau_i^- & \text{if } s_i(e_{1i},\dot{q}_i) < 0 \end{cases} \tag{4.1}$$

where i=1, $\cdots$,n for an n - link robot, and

$$s_i(e_{1i},\dot{q}_i) = c_ie_i + \dot{q}_i, \quad c_i > 0. \tag{4.2}$$

are the switching planes. It is then shown using the hierarchy of the sliding surfaces $s_1,s_2, \cdots ,s_n$ and given bounds on the uncertainties in the manipulators model, that one can find τ^+ and τ^- in order to drive the error signal to the intersection of the sliding surfaces after which the error will "slide" to zero. This controller eliminates the nonlinear coupling of the joints by forcing the system into the sliding mode. Unfortunately, the control effort as seen from (4.1) is discontinuous and will therefore create "chattering" which may excite unmodeled high-frequency dynamics.

More recently, Slotine has modified [17,41] the original VSS controllers using the so-called "suction control". In this approach, the sliding surface $s(t)$ is allowed to be time-varying and the control procedure consists of two steps. In the first, the control law forces the trajectory towards the sliding surface while in the second step, the controller is smoothed inside a possibly time-varying boundary layer, in order to achieve optimal trade-off between control bandwidth and tracking precision, therefore eliminating chattering and the sensitivity of the controller to high-frequency unmodeled dynamics. The controller structure in this case is given by

$$\tau = \hat{D}[\ddot{q}_d - 2\Lambda\dot{e}_1 - \Lambda^2e_1 - \Phi(q,\dot{q},t)] + \hat{h} \tag{4.3}$$

where, Λ is a diagonal matrix of positive elements λ_i (which may be time-varying) and $\Phi(.,.,.)$ is a nonlinear term determined by the extent of the parametric uncertainties and the suction control modifications [17].

V. CONCLUSIONS

The robust motion control of rigid robot was reviewed. Three main areas were identified and explained. All controllers were robust with respect to a range of uncertain parameters although some of them could only guarantee the boundedness of the position error rather than its asymptotic convergence. A combination of these approaches may be useful as we try to include force control, and flexibility effects in our current and future research.

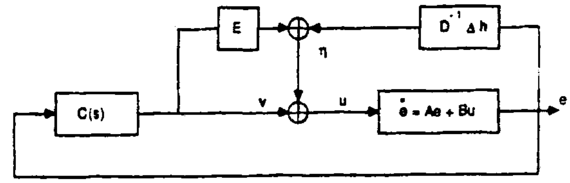

Figure 1

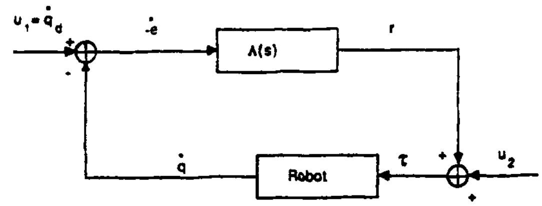

Figure 2

REFERENCES

[1] R. Ortega, and M.W. Spong, "Adaptive Motion Control of Rigid Robots: A Tutorial," *Proc. IEEE Conf. Dec. & Contr.*, pp. 1575-1584, Austin, TX, Dec. 1988.

[2] K. Kreutz, "On Manipulator Control by Exact Linearization," *IEEE Trans. Auto. Cont.*, Vol. 34, No. 7, pp. 763-767, July 1989.

[3] P. Dorato, Ed., *Robust Control*, IEEE Press, 1987.

[4] M.W. Spong, and M. Vidyasagar, "Robust Linear Compensator Design for Nonlinear Robotic Control," *IEEE J. Rob. and Autom.*, Vol. RA-3, No. 4, pp.345-351, Aug. 1987.

[5] E.G. Gilbert, and I.J. Ha, "An Approach to Nonlinear Feedback Control with Applications to Robotics," *IEEE Trans. Sys., Man, and Cyber.*, Vol. SMC-14, No. 6, pp. 879-884, Nov./Dec. 1984.

[6] T.J. Tarn, A.K. Bejczy, A. Isidori, and Y. Chen, "Nonlinear Feedback in Robot Arm Control," *Proc. IEEE Conf. Dec. and Contr.*, Las Vegas, NV, Dec. 1984.

[7] E.J. Davison, and A. Goldenberg, " The Robust Control of a General Servomechanism Problem: The Servo Compensator," *Automatica*, Vol. 11, pp. 461-471, 1975.

[8] M.W. Spong, J.S. Thorp, and J.M. Kleinwaks, "Robust Microprocessor Control of Robot Manipulators, *Automatica*, Vol. 23, No. 3, pp. 373-379, 1987.

[9] M.S. Fadali, M. Zohdy, and B. Adamczyk, "Robust Pole Assignment for Computed Torque Robotic Manipulators Control," *Proc. IEEE Amer. Contr. Conf.*, June 1989, pp. 37-41.

[10] E.G. Gilbert and I.J. Ha, "Robust Tracking in Nonlinear Systems," *IEEE Trans. Autom. Contr.*, Vol. AC-32, No. 9, pp. 763-771, 1987.

[11] C. Samson, "Robust Nonlinear Control of Robotic Manipulators," *Proc. 22nd IEEE Conf. Dec. Contr.*, San Antonio, TX, Dec. 1983, pp. 1211-1216.

[12] M.W. Spong, "Control of Flexible Joint Robots: A Survey," *Report UILU-ENG-90-2203, DC-116*, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Feb. 1990.

[13] R.J. Anderson, "Passive Computed Torque Algorithms For Robots," *Proc. IEEE Conf. Dec. & Contr.*, pp.1638-1644, Tampa, Fl, Dec. 1989.

[14] R.J. Anderson, *A Network Approach to Force Control in Robotics and Teleoperation*, Ph.D. Thesis, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 1989.

[15] V.I. Utkin, "Variable Structure Systems with Sliding Modes," *IEEE Trans. Auto. Contr.*, Vol. AC-22, pp. 212-222, Apr. 1977.

[16] K-K.D. Young, "Controller Design for A Manipulator Using Theory of Variable Structure Systems," *IEEE Trans. Sys., Man, and Cyber.*, Vol. SMC-8, No. 2, pp. 210-218, Feb. 1978.

[17] J-J.E. Slotine, "The Robust Control of Robot Manipulators," *Int. J. Rob. Res.*, Vol. 4, No. 2, pp.49-64, Summer 1985.

[18] P. Dorato, and R.K. Yedavali, *Recent Advances in Robust Control*, IEEE Press, New York, 1990.

[19] M.W. Spong, and M. Vidyasagar, *Robot Dynamics and Control*, John Wiley & Sons, Inc., New York, 1989.

[20] L. Meirovitch, *Methods of Analytical Dynamics*, McGraw-Hill, New York, 1970.

[21] P. Misra, R.V. Patel, and C.A. Balafoutis, "A Robust Servomechanism Control Scheme for Tracking Cartesian Space Trajectories," *Preprint*

[22] L.R. Hunt, R. Su, and G. Meyer, "Global Transformations of Nonlinear Systems," *IEEE Trans. Autom. Contr.*, Vol. AC-28, No. 1, pp. 24-31, 1983.

[23] S. Desa, and B. Roth, "Synthesis of Control Systems for Manipulators Using Multivariable Robust Servo Mechanism Theory," *Int. J. Robotic Res.*, Vol. 4, pp. 18-34, Fall 1985.

[24] N. Becker, and W.M. Grimm, "On L_2 and L_∞ Stability Approaches for the Robust Control of Robot Manipulators," *IEEE Trans. Automa. Contr.* , Vol. 33, No. 1, pp. 118-122, Jan. 1988.

[25] C. Desoer, and M. Vidyasagar, *Feedback Systems: Input-Output Properties*, Academic press, New York, 1975.

[26] B.D.O. Anderson et.al., *Stability of Adaptive Systems: Passivity and Averaging Techniques*, Prentice-Hall Inc., Englewood Cliffs, NJ, 1989.

[27] M. Vidyasagar, *Control Systems Synthesis: A Factorization Approach*, MIT Press, Cambridge, MA, 1985.

[28] B.A. Francis, *A Course in H_∞ Control Theory*, Springer-Verlag, Berlin, 1987.

[29] J.J. Craig, Adaptive Control of Mechanical Manipulators, Addison-Wesley, Massachusets, 1988.

[30] E. Freund, "Fast Nonlinear Control with Arbitrary Pole-Placement for Industrial Robots and Manipulators," *Int. J. Rob. Res.* , Vol. 1, No. 1, pp. 65-78, Spring 1982.

[31] C.Y. Kuo, and S.P.T. Wang, "Nonlinear Robust Industrial Robot Control," *Trans. ASME J. Dyn. Syst. Meas. Control*, Vol. 111, No. 1, pp. 24-30, March 1989.

[32] B. A. Francis, and W.M. Wonham, "The Internal Model Principle of Control Theory," *Automatica*, Vol. 12, pp. 457-465, 1976.

[33] L. Cai, and A.A. Goldenberg, "Robust Control of Position and Force for a Robot Manipulator in Non-Contact and Contact Tasks," *Proc. Amer. Contr. Conf.*, Pittsburgh, PA, June 1989, pp. 1905-1911.

[34] S. Arimoto, and F. Miyazaki, "Stability and Robustness of PID Feedback Control for Robot Manipulators of Sensory Capability," *Proc. 1st Int. Symp. Robotics Res.*, pp.783-799, 1983.

[35] V. Cvetkovic, and M. Vukobratovic, "One Robust, Dynamic Control Algorithm for Manipulation Systems," *Int. J. Robotics Res.*, Vol. 1, pp. 15-28, 1982.

[36] B. R. Barmish, I.R. Petersen, and A. Fever, "Linear Ultimate Boundedness Control of Uncertain Dynamical Systems," *Automatica*, Vol. 19, pp. 523-532, 1983.

[37] S. Gutman, "Uncertain Dynamic Systems - A Lyapunov Min-Max Approach," *IEEE Trans. Autom. Contr.*, Vol. AC-24, pp. 437-443, 1979.

[38] M.J. Corless, and G. Leitman, "Continuous State Feedback Guaranteeing Uniform Ultimate Boundedness for Uncertain Dynamic Systems," *IEEE Trans. Autom. Contr.*, Vol. AC-26, pp. 1139-1144, 1981.

[39] Y.H. Chen, "On the Deterministic Performance of Uncertain Dynamical Systems," *Int. J. Contr.*, Vol. 43, No. 5, pp. 1557-1579, 1986.

[40] C. Abdallah, and R. Jordan, "A positive-Real Design for Robotic Manipulators," *Proc. IEEE Amer. Contr. Conf.*, San Diego, CA, May 1990.

[41] J.J. Slotine, and S.S. Sastry, "Tracking Control of Nonlinear Systems Using Sliding Surfaces with Applications to Robot Manipulators," *Int. J. Contr.*, Vol. 38, pp. 465-492, 1983.

[42] M. Whitehead, and E.W. Kamen, "Control of Serial Manipultors with Unknown Variable Loading," *Proc. IEEE Conf. Dec. & Contr.*, Ft. Lauderdale, Fl, Dec. 1985.

[43] J.Y.S. Luh, "Conventional Controller Design for Industrial Robots: A tutorial," *IEEE Trans. Sys., Man, & Cyber.*, Vol. SMC-13, No. 3, pp. 298-316, May/June 1983.