'92 KACC 1992. 10. 19~21

External Force Control for Two Dimensional Contour Following ; Part 2. Analysis and Implementation of Adaptive Control

Young Chil Park and Sungkwun Kim

Control R/D Team, Production Engineering Division
Consumer Electronics Business, Samsung Electronics
Suwon City, Kyungki-Do, Korea, 441-742

Abstract

Control of tool-environment interaction force to comply the robot system to an environment is of vital in many automated process. This paper presents the implementation of an adaptive force control with commercial robot system in two dimensional contour following task. A model reference adaptive control system, combined with the linear compensators, is implemented. That is, a use of adaptive control is to provide an auxiliary control system so that the contour following performance can be improved from that of using linear control system only. Hyperstability is used to derive the adaptive control law. Experimental verification of the proposed control system is obtained using PUMA 560 robot system. Data obtained experimentally shows that the use of additional adaptive control system improves the contour following performance about 30 % in RMS contact force errors upon that of the system controlled by the linear compensators only.

1. Introduction

Control of tool-environment interaction force to comply the robot system to an environment is of vital for the successful task accomplishment in many automated process. Classical examples of tasks required such compliant motions are peg-in-hole assembly, contour following, crank turning etc. Robot force control, which has historically received much attention, provides a fundamental means of relating manipulator compliant motion to the force which it causes.

This paper presents the analysis and implementation of an adaptive force control with the commercial robot system. It is designed to use a commercially available robot system in two dimensional contour following task for the surface scanning purpose, where the exact shape and location of the contour are previously unknown. While commercially available robot systems are very capable in many tasks, use of such robot systems to the task which requires a compliant motion is often limited since they are usually functioning as pure position controlled devices. There is usually no means of controlling the force directly. Also accessing the internal structure of the controller may not be possible. While the modification of the controller to achieve a direct force control capability is not an impossible task, such modification may not be allowed in many situations.

External force control by accommodation, so that the commercially available robot system can be used without any modification, in two dimensional contour following task with a constant tool orientation is implemented by Park and Kim[1]. In there, the linear, decoupled model of two dimensional contour following system is derived first. Then the lead compensators are obtained using root locus method. While a good contour tracking is obtained using a linear control system, experimental data shows that the contour following system performance is highly depending on the large and high bandwidth noise, where the effect of system model inaccuracy is also considered as a noise. Thus an adaptive control is considered to compensate such unmodeled system dynamics.

Many different adaptive control schemes have been proposed in the literature, but the most of them are not quite mature for the practical use, as pointed by Astrom[2]. Especially under the influence of a disturbance acting on the system which is very typical in an industrial environment, only a few successful use of them has been reported. There are much discussions on the practical implementation issues in the literature, for instance Wittenmark[3]. Nevertheless the adaptive control will be very useful if the care is taken.

The main use of adaptive control system in this work is to improve the system performance upon that of the system using the linear compensators only (See Park and Kim[1] for the contour tracking performance using linear control system). Due to the difficulties in implementation as well as a design constraint (use of position controlled robot system) imposed in our work, an adaptive control system is used to complement the linear control system. That is, an adaptive controller combined with the linear control system has been implemented as a final control law.

The brief preview of this work is as follows. In Section 2, an appropriate adaptive control mechanism for this work is selected first. Then the adaptive control law is derived using hyperstability. We also discuss many practical issues on the implementation of an adaptive control in a noisy environment (which is not an unusual situation for the force control problem). Experimental verification of the proposed control structure is presented in Section 3 using a PUMA 560 robot system. Finally the results obtained in this work as well as discussions are summarized in Section 4.

2. Adaptive Control System

To improve the contour following system performance upon that of the system using linear compensators only, a model reference adaptive control system is added. This section first presents the selection of an appropriate adaptive control mechanism. Then the adaptive control law is derived.

2.1 Selection of Adaptive Control Structure

The main use of adaptive control in this work is to improve the system performance in the contour following upon that of the system using the linear compensators only. As pointed out earlier, experimentally obtained data using linear compensators only shows that the system is affected by a relatively large and high bandwidth noise. It is well known that the adaptive control system developed with idealized system model will mostly be unstable under the influence of disturbance, even for the bounded and small disturbance[4]. Much progress is made toward the robust adaptive control[4,5], but the preliminary experimental test results show that it is not quite adequate yet for the practical use.

To select an appropriate adaptive control structure for our work, first consider the role of linear compensators H_x and H_θ in the contour following system. One way to implement the adaptive control is adjustments of H_x and H_θ directly. But it is not feasible because of the following reason. Whatever the adaptive control mechanism is, the only available information we can use to adjust the control system is a force error. Thus if H_x and H_θ are going to be adjusted directly, there are two controllers to be adjusted from a single information and we do not know how this single information can be resolved. Returning to the discussion of the role of compensators H_x and H_θ in the linear contour following system, they are used to provide different control inputs to x and θ-paths from a common information, which is force error (See Figure 3 in [1]). In other words, the linear compensators provide the way of resolving a single information to invoke two different motions. This consideration provides the following requirement in the selection of an adaptive control mechanism. (1) We need to consider two linear compensators as a part of the robot system. (2) Then, whichever the adaptive control mechanism is selected, it should be the one working only on the force error signal. (3) Finally, the modified force error by adaptive mechanism will be fed into the linear compensators.

With the interpretation of H_x and H_θ as command generators from a common signal, consider a selection of adaptive control structure. Model reference adaptive control system and self-tuning regulators are two main structures used. Self-tuning regulator type adaptive control[6] uses the system model identified by the on-line type estimator. It is indirect control method. Successful implementation of a self-tuning adaptive controller has been reported, for example the works by Fortescue, Kershenbaum and Ydstie[7] and Dumont[8]. But for this work, any indirect adaptive control method cannot be used due to the following reason. When the system is identified from the measured information (which is a contact force), the identified system model has a completely different dynamic characteristics from the one obtained in the linear model. We think that the reason of why not to fit the proper model is that the order of magnitude of the noise is almost the same of that of the system output itself. We tested this noise effect on the identification of system model extensively using computer simulated data. This consideration fixes the model reference adaptive control system[9] as an adaptive control structure to be used in our work.

Successful implementation of model reference adaptive control structure requires an appropriate reference model representing the actual system. It is very important especially under the large disturbance which makes the implementation of adaptive control very hard[10]. To find a reference model, consider the linear model of contour following system again. In the linear model, an assumption was made such that the contact force f_x was independent from θ-path motion. Thus the following 5th order reference model can be the one representing the relation between the input (which is a force error) and the output (a contact force).

$$\frac{f_x}{f_{err}} = H_x \bullet \left[\frac{T(z+1)}{2(z-1)} \right] \bullet ARM_x \tag{2.1}$$

In equation (2.1), H_x is the first order force regulator, ARM_x is the third order robot system x directional Cartesian dynamics and the integrator is approximated by the trapezoid rule. In general, a use of high order reference model raises many problems. As pointed out by Ortega[11], the model reference adaptive control system with high order reference model carries serious practical and numerical difficulties. Also it is well known that the control system having a low order is less sensitive to the uncertainties than that having a high order[12,13]. Another difficulty in using a system model given by equation (2.1) is that it is a nonminimum phase system. This fact makes the application of adaptive control very difficult since many adaptive control methods are derived based on the explicit assumption of stable zeros. For example, unified adaptive control by Landau and Lozano[14] was developed with the system model which has only stable zeros. While the adaptive control system developed for the minimum phase system shows a good parameter convergence property, many problems have been reported when such control algorithm is applied to the nonminimum phase system[15]. Unbounded input is a typical problem. While there are many works to deal with the nonminimum phase system[16,17], they use an explicit on-line system identification procedure, thus cannot be used for this work.

Consideration of the problems caused by the high order reference model requires a selection of lower order reference model. Besides, in practical engineering problem, any model is only an approximation of the original system, where the order of system model is usually lower than that of the actual system. To find a simpler reference model, consider contour following system as a force regulator. As we discussed before, when there is a force error, the force error is going to be removed by the actual robot motion. Also recall that the robot motion (as a mechanical device) can well be described by the second order differential equation. Thus if we characterize the contour following system as a pure mechanical system, then the second order reference model can adequately describe the input and output relations. This consideration asks the use of reference model by an artificially constructed, a second order model, but having very similar dynamic characteristics with the linear contour following system.

Figure 1 presented in next section shows the adaptive control system used in this work. As shown in Figure 1, the implementation of a model reference adaptive control system is to tune the input. Even though the linear compensators are not shown explicitly, the modified force error by adaptive control mechanism is fed into them so that two different motions from a single information can be generated.

2.2 Adaptive Control Law

Based on the discussions of the previous section, a reference model and the actual system including linear compensators are assumed to be second order systems. Consider the reference model given by the following one step ahead form of discrete transfer function.

$$y(k+1) = a_{1m}y(k) + a_{2m}y(k-1) + b_{1m}f_{err}(k) + b_{2m}f_{err}(k-1) \tag{2.2}$$

Equation (2.2) describes the time invariant reference model, where $y(k)$ is the output and $f_{err}(k)$ is the input to the reference model (which is a force error). It is assumed that the reference model is stable. For the actual system, consider the following second order discrete equation.

$$x(k+1) = a_1x(k) + a_2x(k-1) + b_1u(k) + b_2u(k-1) \tag{2.3}$$

In equation (2.3), $x(k)$ is the output of the actual system and $u(k)$ is the control input to the actual system. The actual system is also assumed as a time invariant system. This implies that all a_i and b_i in equation (2.3) are constant, but unknown. One further assumption required is that we know the sign of b_1. The sign of b_1 can easily be identified from the step response of the contour following system, thus does not introduce any difficulty in the design of adaptive control law. Subtracting equation (2.3) from

(2.2), the generalized error equation is obtained as follows,

$$\begin{aligned} e(k+1) &= a_{1m}e(k) + a_{2m}e(k-1) + (a_{1m} - a_1)x(k) \\ &+ (a_{2m} - a_2)x(k-1) + b_{1m}f_{err}(k) + b_{2m}f_{err}(k-1) \\ &- b_1 u(k) - b_2 u(k-1) \end{aligned} \tag{2.4}$$

where $e(k) = y(k) - x(k)$ (a generalized error).

Design of adaptive control mechanism implementing a signal synthesis approach is finding an appropriate input $u(k)$ so that the error dynamics defined by equation (2.4) is asymptotically stable. To achieve this design objective, consider the following form of input $u(k)$,

$$\begin{aligned} u(k) &= \alpha_1(k)x(k) + \alpha_2(k)x(k-1) + \alpha_3(k)f_{err}(k) \\ &+ \alpha_4(k)f_{err}(k-1) + \alpha_5(k)u(k-1) \end{aligned} \tag{2.5}$$

where $\alpha_i(k)$, $i = 1, \ldots, 5$ are adjustable parameters. Then the error dynamics given by equation (2.4) can be rewritten as follows.

$$\begin{aligned} e(k+1) &= a_{1m}e(k) + a_{2m}e(k-1) \\ &+ [a_{1m} - a_1 - b_1\alpha_1(k)]x(k) + [a_{2m} - a_2 - b_1\alpha_2(k)]x(k-1) \\ &+ [b_{1m} - b_1\alpha_3(k)]f_{err}(k) + [b_{2m} - b_1\alpha_4(k)]f_{err}(k-1) \\ &+ [-b_2 - b_1\alpha_5(k)]u(k-1) \end{aligned} \tag{2.6}$$

Equation (2.6) shows the evolution of generalized error $e(k)$ in terms of adjustable parameters $\alpha(k)$. If $\alpha(k)$ are going to be adjusted properly so that the error dynamics of equation (2.6) is asymptotically stable, the design objective has been achieved.

To find adaptive control law using hyperstability [18], convert equation (2.6) into the following equivalent feedback system.

$$e(k+1) = a_{1m}e(k) + a_{2m}e(k-1) + w_1(k+1) \tag{2.7}$$

$$v(k+1) = e(k+1) + d_0 e(k), \quad -1 < d_0 < 1 \tag{2.8}$$

$$\begin{aligned} w(k+1) &= -w_1(k+1) \\ &= [b_1\alpha_1(k) + a_1 - a_{1m}]x(k) + [b_1\alpha_2(k) + a_2 - a_{2m}]x(k-1) \\ &+ [b_1\alpha_3(k) - b_{1m}]f_{err}(k) + [b_1\alpha_4(k) - b_{2m}]f_{err}(k-1) \\ &+ [b_1\alpha_5(k) + b_2]u(k-1) \end{aligned} \tag{2.9}$$

Equations (2.7) and (2.8) define a linear time invariant feedforward block, where d_0 in equation (2.8) will be defined later. Equation (2.9) defines a nonlinear time varying feedback block. For the equivalent feedback system defined by equations (2.7) to (2.9), if the following transfer function is a strictly positive real (SPR) function,

$$H(z) = \frac{z^2 + d_0 z}{z^2 - a_{1m}z - a_{2m}} \tag{2.10}$$

and the equivalent feedback system satisfies the following inequality,

$$\eta(0,k_1) = \sum_{k=0}^{k_1} w(k+1)v(k+1) \geq -\gamma_0^2 \quad \text{for all } k_1 \geq 0 \tag{2.11}$$

the system is hyperstable. Consider first a transfer function of equation (2.10). Since the reference model is a stable system, the poles of transfer function of equation (2.10) are located within the unit circle in z plane. So if the following condition is satisfied, the transfer function of equation (2.10) is SPR.

$$Re[H(s)] \geq 0 \quad \text{for all } w, \text{ where } s = jw \tag{2.12}$$

This can be proven as follows. Since the reference model is stable, the following relation, which can be easily obtained by Jury's test, is satisfied.

$$1 + a_{1m} - a_{2m} > 0 \text{ and } 1 - a_{1m} - a_{2m} > 0 \tag{2.13}$$

Also, the real part of $H(s)$ can be obtained by a simple transformation of $z=(1+s)/(1-s)$ from equation (2.10), to have an equivalent continuos time domain transfer function $H(s)$, and then replace s by jw in $H(s)$. In $Re[H(s)]$ obtained, we can see easily using equation (2.13) that, if we select d_0 as follows,

$$-1 < d_0 < \frac{1 + 3a_{2m}}{a_{1m}} \tag{2.14}$$

with a positive a_{1m}, which is the case for this work, equation (2.12) is satisfied. That is, the first condition required for the system described by equations (2.7) to (2.9) to be hyperstable is satisfied with d_0 given by equation (2.14). To prove the second condition specified by equation (2.11), rewrite it using $w(k+1)$ defined in equation (2.9) as follows, where the adaptation starts from $k=0$.

$$\begin{aligned} \eta(0,k_1) &= \sum_{k=0}^{k_1} v(k+1)x(k)[b_1\alpha_1(k) + a_1 - a_{1m}] \\ &+ \sum_{k=0}^{k_1} v(k+1)x(k-1)[b_1\alpha_2(k) + a_2 - a_{2m}] \\ &+ \sum_{k=0}^{k_1} v(k+1)f_{err}(k)[b_1\alpha_3(k) - b_{1m}] \\ &+ \sum_{k=0}^{k_1} v(k+1)f_{err}(k-1)[b_1\alpha_4(k) - b_{2m}] \\ &+ \sum_{k=0}^{k_1} v(k+1)u(k-1)[b_1\alpha_5(k) + b_2] \end{aligned} \tag{2.15}$$

In equation (2.15), if each term of the right hand side satisfies the inequality given by equation (2.11), $\eta(0,k_1)$ in equation (2.15) will satisfy the condition required by (2.11). To obtain this, consider the following parameter adaptation scheme,

$$\alpha_i(k) = \alpha_i(k-1) + \phi_i[v(k)] = \sum_{l=0}^{k} \phi_i[v(l)] + \alpha_i(-1) \tag{2.16}$$

where $\alpha_i(-1)$ represents the initial values of parameters and $\phi_i[v(k)]$ represents a function of $v(k)$. Then the first term of the right hand side of equation (2.15) can be written as follows.

$$\begin{aligned} \eta_1(0,k_1) &= \sum_{k=0}^{k_1} v(k+1)x(k)[b_1\alpha_1(k) + a_1 - a_{1m}] \\ &= \sum_{k=0}^{k_1} v(k+1)x(k)[b_1 \sum_{l=0}^{k} \phi_1[v(l)] + b_1\alpha_1(-1) + a_1 - a_{1m}] \end{aligned} \tag{2.17}$$

If we select

$$\phi_1[v(k)] = sgn(b_1)g_1 x(k)v(k+1), \quad g_1 > 0 \tag{2.18}$$

where $sgn(b_1)$ is +1 for $b_1 > 0$ or -1 for $b_1 < 0$ and g_1 is a positive constant gain, then the equation (2.17) can be rewritten as follows.

$$\begin{aligned} \eta_1(0,k_1) &= \tfrac{1}{2}b_1 sgn(b_1)g_1[\sum_{k=0}^{k_1} v(k+1)x(k) + \tfrac{b_1\alpha_1(-1)+a_1-a_{1m}}{b_1 sgn(b_1)g_1}]^2 \\ &+ \tfrac{1}{2}b_1 sgn(b_1)g_1[\sum_{k=0}^{k_1} v(k+1)x(k)]^2 - \tfrac{1}{2b_1 sgn(b_1)g_1}[b_1\alpha_1(-1) + \\ &a_1 - a_{1m}]^2 \geq -\tfrac{1}{2b_1 sgn(b_1)g_1}[b_1\alpha_1(-1) + a_1 - a_{1m}]^2 = -\gamma_0^2 \end{aligned} \tag{2.19}$$

That is, if the following parameter adaptation law is used to adjust $\alpha_i(k)$,

$$\alpha_1(k) = \alpha_1(k-1) + sgn(b_1)g_1 x(k)v(k+1) \tag{2.20}$$

the first term of right hand side of equation (2.15) will satisfy the inequality of equation (2.11). Using exactly the same argument, if all the other parameters are adjusted as follows,

$$\alpha_2(k) = \alpha_2(k-1) + sgn(b_1)g_2 x(k-1)v(k+1) \tag{2.21}$$

$$\alpha_3(k) = \alpha_3(k-1) + sgn(b_1)g_3 f_{err}(k)v(k+1) \tag{2.22}$$

$$\alpha_4(k) = \alpha_4(k-1) + sgn(b_1)g_4 f_{err}(k-1)v(k+1) \tag{2.23}$$

$$\alpha_5(k) = \alpha_5(k-1) + sgn(b_1)g_5 u(k-1)v(k+1) \tag{2.24}$$

then equation (2.15) so as the equation (2.11) will be satisfied. This proves that the equivalent feedback system given by equations (2.7) to (2.9) is hyperstable.

Equations (2.20) to (2.24) provide the adaptive control laws. To implement those control laws, one further consideration is required. When the parameters $\alpha_i(k)$ are updated at instant k, $v(k+1)$, which is not an available information at instant k yet, is required. Thus $v(k+1)$ needs to be estmated from the information available at instant k and it can be done as follows. The output of the actual system of equation (2.3), when $\alpha_i(k-1)$ is used instead of $\alpha_i(k)$, is given as follows.

$$x^0(k+1) = a_1 x(k) + a_2 x(k-1) + b_1 u^0(k) + b_2 u(k-1) \tag{2.25}$$

In equation (2.25), the control input at instant k is computed using $\alpha_i(k-1)$ which is available at instant k as follows.

$$u^0(k) = \alpha_1(k-1)x(k) + \alpha_2(k-1)x(k-1) + \alpha_3(k-1)f_{err}(k) + \alpha_4(k-1)f_{err}(k-1) + \alpha_5(k-1)u(k-1) \quad (2.26)$$

Since the output $x^0(k+1)$ is a measurable information at instant k, we can define a new generalized error and a new output of linear compensator of equation (2.8) using $x^0(k+1)$ as follows.

$$e^0(k+1) = y(k+1) - x^0(k+1) \quad (2.27)$$

$$v^0(k+1) = e^0(k+1) + d_0 e(k) \quad (2.28)$$

When the equation (2.28) is expanded using equation (2.25) to (2.27), $v^0(k+1)$ can be expressed as follows.

$$\begin{aligned} v^0(k+1) &= a_{1m}(k) + a_{2m}e(k-1) + d_0 e(k) \\ &+[a_{1m} - a_1 - b_1\alpha_1(k-1)]x(k) \\ &+[a_{2m} - a_2 - b_1\alpha_2(k-1)]x(k-1) \\ &+[b_{1m} - b_1\alpha_3(k-1)]f_{err}(k) + [b_{2m} - b_1\alpha_4(k-1)]f_{err}(k-1) \\ &+[-b_2 - b_1\alpha_5(k-1)]u(k-1) \end{aligned} \quad (2.29)$$

Also using equations (2.7), (2.8) and adaptive control laws, $v(k+1)$ can be rewritten as follows, where $p(b_1) = b_1 sgn(b_1)$.

$$\begin{aligned} v(k+1) &= a_{1m}e(k) + a_{2m}e(k-1) + d_0 e(k) \\ &+[a_{1m} - a_1 - b_1\alpha_1(k-1) - p(b_1)g_1 x(k)v(k+1)]x(k) \\ &+[a_{2m} - a_2 - b_1\alpha_2(k-1) - p(b_1)g_2 x(k-1)v(k+1)]x(k-1) \\ &+[b_{1m} - b_1\alpha_3(k-1) - p(b_1)g_3 f_{err}(k)v(k+1)]f_{err}(k) \\ &+[b_{2m} - b_1\alpha_4(k-1) - p(b_1)g_4 f_{err}(k-1)v(k+1)]f_{err}(k-1) \\ &+[-b_2 - b_1\alpha_5(k-1) - p(b_1)g_5 u(k-1)v(k+1)]u(k+1) \end{aligned} \quad (2.30)$$

Subtracting equation (2.30) from (2.29) and rearrange it, the following relation between $v^0(k+1)$ and $v(k+1)$ can be obtained.

$$v(k+1) = \frac{v^0(k+1)}{1 + p(b_1)[g_1 x(k)^2 + g_2 x(k-1)^2 + g_3 f_{err}(k)^2 + g_4 f_{err}(k-1)^2 + g_5 u(k-1)^2]} \quad (2.31)$$

Equation (2.31) makes $v(k+1)$ as an available information at instant k so as to make the computation of control input $u(k)$ possible. One may notice from equation (2.31) that the value of b_1 is required to compute $v(k+1)$, which is unknown. We only know the sign of b_1, not the value of b_1 itself. A good approximation can be the value of b_{1m} used in the reference model. A very similar case has been studied by Bothoux and Courtiol[19] and the test results show a good control performance when b_1 is replaced by b_{1m}.

Figure 1 shows the implementation of adaptive control mechanism derived in this section, where z^{-1} represents a unit step delay operator.

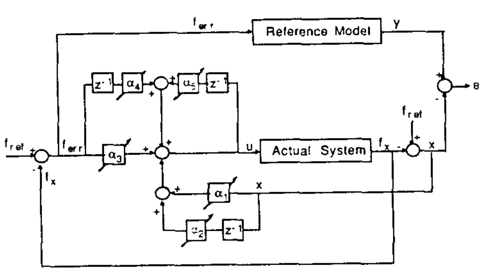

Figure 1. The Adaptive Control System

3. Experimental Verification

Adaptive control system proposed in Section 2 is experimentally verified in this section. The robot system involved is a PUMA 560 manipulator controlled by the standard Unimation controller. An Astek FS6-120A six axis wrist force sensor is used to measure the contact force. The external force control loop is closed by LSI-11/73 microcomputer.

3.1 Adaptive Control System

To implement the adaptive control derived in Section 2, a selection of reference model is required. Consider the following second order discrete transfer function as a reference model.

$$H(z) = \frac{0.4288(z-1)}{z^2 - 1.1424z + 0.3263} \quad (3.1)$$

This second order reference model is obtained using the following criteria. (1) A reference model provides the way of removing force error to the actual system. (2) Thus the step response of open loop transfer function starts from zero. (3) Also the steady-state output of it is zero. (4) Finally the steady-state settling times of a unit step response for the reference model and the robot system are almost identical. The reference model of equation (3.1) satisfies all those conditions. Its step response starts from zero and the final value is zero. The bandwidth of reference model is about 20 *rad/sec*, which is almost the same with that of the robot system itself.

The next step in implementation of adaptive control is defining the adaptive gains g_i in equations (2.20) to (2.24). Theoretically any positive values of g_i can be used. In general, a fast adaptation can be accomplished by using a higher gain, even though it usually asks a large input magnitude. For our application, it should be low enough since it is being used in the very noisy environment. Otherwise the stability of the overall system cannot be guaranteed. A good advise in defining the magnitude of gain is given by Rohrs et al[20], quoted here as follows. "*Keep the adaptation gain small and let the adaptation proceed slowly.*" The actual values of g_i used in this work is $g_i = 0.01$, $i = 1, \ldots, 5$. Also the initial values of parameters $\alpha_i(k)$ used are $\alpha_1(-1) = \alpha_2(-1) = \alpha_4(-1) = \alpha_5(-1) = 0.0$ and $\alpha_3(-1) = 1.0$.

So far many practical issues as well as some remedies to resolve the difficulty in implementation of adaptive control to the actual system have been discussed. But it still requires one further modification in the adaptive control laws given by equations (2.20) and (2.24). To explain this, consider the equation (2.20). As shown in equation (2.20), the parameter $\alpha_1(k)$ is begin updated from its value at instant $k-1$ by $sgn(b_1)g_1 x(k)v(k+1)$. Since $x(k)$ and $v(k+1)$ include the noise in it, the effect of disturbance in the parameter $\alpha_1(k)$ is being accumulated continuously. This is very unwanted characteristics of an integration type adaptive control algorithm. To prevent such noise summing process, the adaptive control law given by equation (2.20) is modified as follows,

$$\alpha_1(k) = \delta\alpha_1(k-1) + sgn(b_1)g_1 x(k)v(k+1) \quad (3.2)$$

where δ is a forgetting factor and has a value of less than 1. A use of forgetting factor will slow down the adaptation process. Also its use does not guarantee the perfect model following. But the slower adaptation process is a lot better than unstable system. In addition, a perfect model following was not the objective of using an adaptive control system for this work. If a very small value of δ is used, equation (3.2) approaches the proportional type adaptive control law. In general, there is no rigorous stability proof for the proportional type adaptive control system. A use of additional forgetting factor requires further mathematical analysis. While such analytical work is being under investigation, modified parameters for all $\alpha_i(k)$ by the exactly same form of equation (3.2) are used in this work with $\delta = 0.33$.

3.2 Experimental work

Two different tasks were selected to test the adaptive control system. The constant tracking speed $v_y = 10$ *mm/sec* is used. Also reference contact force f_{ref} was set by 10 *N*. Figure

2 shows the force error recorded, while the robot is following a straight edge. Compared the contour following performance with that of using only linear compensators (See Figure 9 of [1].), the performance improvement, when the additional adaptive control is added, is small. Following straight edge with linear compensators only already shows a good contour tracking. Thus there is not much room left for the performance improvement when the adaptive control is added.

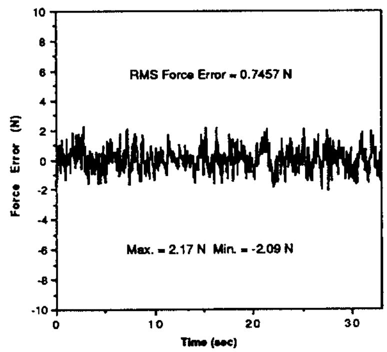

Figure 2. Following a Straight Edge

Figure 3 shows the contact force error recorded when the adaptive control system is following a 40 mm radius curvature. (See Figure 8 of [1].) Compared with the contour tracking performance of linear system (See Figure 7 of [1].), the adaptive control tries to put the force error close to zero, which is the main objective of the use of adaptive control in this work. Finally the experimentally obtained data shows that the use of additional adaptive control system improves the contour following performance in terms of RMS contact force error about 30 % upon that of the system using linear compensators only.

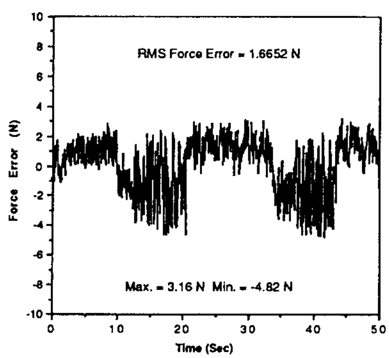

Figure 3. Following a Curved Contour

4. Discussion and Conclusion

This paper presents an implementation of adaptive force control with a commercial robot system in two dimensional contour following task for the surface scanning purpose.

An adaptive control is used in this work as an auxiliary control system. That is, with the linear control system as a main control of the contour following system, the adaptive control is added to improve the performance upon that of using linear control system only. A model reference adaptive control system with a signal synthesis approach has been used.

The proposed control system is experimentally verified with the PUMA 560 robot system. While there are many difficulties in implementation of adaptive control due to the large noise, experimentally obtained data shows that additional adaptive control system improves the contour tracking performance about 30 % upon that of using a linear control system only.

Many practical issues with regard to the application of adaptive control in the very noisy environment have been discussed. Some attempts are also made to provide the remedies. Nevertheless we feel that we only brought the problems rather than gave any clear answer. More rigorous mathematical analysis, including a nonlinear effect of the contour following system, is required and this is currently under investigation.

References

[1]. Park, Y.C. and Kim, S., "External Force Control for Two Dimensional Contour Following : Part 1. A Linear Control System Approach," Proc. the 1992 Korean Automatic Control Conference, Seoul, Korea, 1992

[2]. Astrom, K.J., "Theory and Applications of Adaptive Control - A Survey", Automatica, Vol. 19, No. 7, 1983, pp. 471-486

[3]. Wittenmark, B., "Adaptive Control : Implementation and Application Issues", Lecture Notes in Control and Information Sciences, Adaptive Control Strategies for Industrial Use, Proc. of a Workshop, Canada, 1988, pp. 103-120

[4]. Rohrs, C.E. et al, "Robustness of Continuous Time Adaptive Algorithm in the Presence of Unmodeled Dynamics", IEEE Trans. on Automatic Control, Vol. AC-30, 1985, pp. 881-889

[5]. Narendra, K.S. and Annaswamy, A.M., *Stable Adaptive System*, Prentice Hall, Englewood Cliffs, New Jersey, 1989, pp. 291-358

[6]. Astrom, K.J., Borisson, U., Ljung, L. and Wittenmark, B., "Theory and Application of Self-Tuning Regulators", Automatica, Vol. 13, 1977, pp. 457-476

[7]. Fortescue, T.R., Kershenbaum, L.S. and Ydstie, B.E., "Implementation of Self-Tuning Regulators with Variable Forgetting Factors", Automatica, Vol. 17, 1981, pp. 831-835

[8]. Dumont, G.A., "Self-Tuning Control of a Chip Refiner Motor Load", Automatica, Vol. 18, 1982, pp. 307-314

[9]. Landau, I.D., *Adaptive Control, The Model Reference Approach*, Marcek Dekker Inc., 1979

[10]. Kreisselmeier, G. and Anderson, B., "Robust Model Reference Adaptive Control", IEEE Trans. on Automatic Control, Vol. AC-31, 1986, pp. 127-133

[11]. Ortega, R., "Assessment of Stability Robustness for Adaptive Controllers", IEEE Trans. on Automatic Control, Vol. AC-28, 1983, pp. 1106-1109

[12]. Anderson, B.D.O. and Liu, Y., "Controller Reduction : Concepts and Approaches", IEEE Trans. on Automatic Control, Vol. 34, 1989, pp. 802-812

[13]. Goodwin, G.C. and Ramadge, P.J., "Design of Restricted Complexity Adaptive Regulators", IEEE Trans. on Automatic Control, Vol. AC-24, 1979, pp. 584-588

[14]. Landau, I.D. and Lozano, R., "Unification of Discrete Time Explicit Model Reference Adaptive Control Designs", Automatica, Vol. 17, 1981, pp. 593-611

[15]. M'saad, M., Ortega, R. and Landau, I.D., "Adaptive Controllers for Discrete-Time Systems with Arbitrary Zeros: An Overview", Automatica, Vol. 21, 1985, pp. 413-423

[16]. Goodwin, G.C. and Sin, K.S., "Adaptive Control of Nonminimum Phase Systems", IEEE Trans. on Automatic Control, Vol. AC-26, 1981, pp. 478-483

[17]. Trulsson, E. and Ljung, L., "Adaptive Control Based on Explicit Criterion Minimization", Automatica, Vol. 21, 1985, pp. 385-399

[18]. Popov, V.M., *Hyperstability of Control Systems*, Springer -Verlag, 1973

[19]. Bethoux, G. and Courtiol, B., "A Hyperstable Discrete Model Reference Adaptive Control Systems", Proc. The Third IFAC Symposium on Sensitivity, Adaptivity and Optimality, Ischia, 1973, pp. 282-289

[20]. Rohrs, C.E., Athans, M., Valavani, L. and Stein, G., "Some Design Guide Lines for Discrete-Time Adaptive Controllers", Automatica, Vol. 20, 1984, pp. 653-660