External Force Control for Two Dimensional Contour Following ; Part 1. A Linear Control Approach

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Abstract

The ability of a robot system to comply to an environment via the control of tool-environment interaction force is of vital for the successful task accomplishment in many robot application. This paper presents the implementation of external force control for two dimensional contour following task using a commercial robot system. Force accommodation is used since a constraint imposed in our work is not to modify the commercial robot system. A linear, decoupled model of two dimensional contour following system in the discrete time domain is derived first. Then the experimental verification of linear control is obtained using a PUMA 560 manipulator with standard Unimation controller, Astek FS6-120A six axis wrist force sensor attached externally to the arm and LSI-11/73 microcomputer. Experimentally obtained data shows that the RMS contact force error is 0.8246 N when following the straight edge and 2.3768 N when following 40 mm radius curved contour.

1. Introduction

The ability of a robot system to comply to an environment via the control of tool-environment interaction force is of vital for the successful task accomplishment in many robot application. Classical examples of tasks which require such compliant motion by the force control are peg-in-hole assembly, contour following (for deburring, welding or surface scanning), crank turning etc. Robot force control has historically received much attention, with an excellent summary of different force feedback architectures by Whitney[1].

This paper presents an implementation of external force control by force accommodation method. It is designed to use a commercial 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. Not like a simple deburring with the rotary tool which does not require any specific tool orientation with respect to the part surface, following a contour to scan the surface requires the tool (which is an inspection sensor) to maintain a constant orientation with respect to the contour. Thus the task presented in this work requires that (1) the robot needs to move its tool in the contour normal direction to maintain contact and (2) simultaneously to rotate it to maintain a constant tool orientation with respect to the contour (3) while it is moving with constant speed in the contour tangential direction.

Commercially available robot systems are very capable in many simple tasks, like pick and place type tasks. But the use of such robot systems in a task which requires a compliant motion has often a significant limitation because the most of them are usually functioning as pure position controlled devices. There is usually no means of controlling the force directly. Of course a modification of an existing controller so that a direct force control can be done is not an impossible task. But in many application, it may not be allowed.

One of the constraints imposed in our work is not to modify the standard robot system. Thus it limits the availability of variables used inside of the controller and several force control methods cannot be used, for example the hybrid position/force approach of Raibert and Craig[2]. Many different experimental results of the contour following are reported in the literature, but they are based on either a hybrid control method[1,3,4,5,6] which requires a measurement of position or a substantially modified robot controller[7]. However, the force accommodation method proposed by Whitney[8] can be implemented since it does not require any position measurement to be fed back.

Figure 1 shows the implementation of force control by accommodation with the commercial robot system, where the force control loop is closed externally. As shown in Figure 1, the internal position control loop which represents the standard robot system is preserved. Whenever the contact force F_{con} is different from the predefined reference force F_{ref}, the force regulator will generate either a velocity or a position command from the force error F_{err} so that the force error is going to be removed.

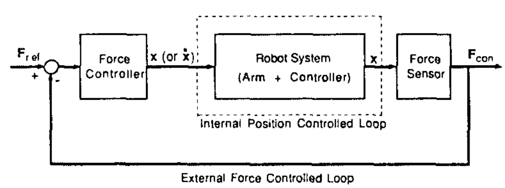

Figure 1. External Force Control

The brief preview of this work is as follows. A liner, decoupled model of two dimensional contour following system in the discrete time domain is derived in Section 2. A linear model obtained in this paper shows that two dimensional contour following can be accomplished using only a force in the x direction of tool coordinates. A design procedure to obtain the linear force compensators is also discussed in Section 2. Experimental verification of the linear model of the contour following system is presented in Section 3 using PUMA 560 manipulator with the standard Unimation controller, Astek FS6-120A six axis wrist force sensor attached externally to the arm and LSI-11/73 microcomputer. Finally the results obtained as well as discussions are summarized in Section 4.

2. Analysis of Two Dimensional Contour Following System

In this section, a linear, decoupled model of two dimensional contour following system by force accommodation is derived. Then we discuss how to find the linear compensators for each direction.

2.1 Linear Model of Two Dimensional Contour Following System

Contour following is a problem of force regulation. While the robot tool is moving in one direction with constant speed, it is also going to be driven, if necessary, in other directions to maintain the contact force at the predefined level. Thus a design of contour following system is a design of force regulator such that, when the actual contact force F_{con} differs from the predefined reference force F_{ref}, the robot is going to make compensatory motions to remove the force error defined by $F_{err} = F_{ref} - F_{con}$.

To get a more detailed insight of contour following with constant tool orientation relative to the contour, consider three different tool-contour contact geometries shown in Figure 2, where the coordinates are fixed to the tool and the robot is continuously moving in the positive y direction with a constant velocity.

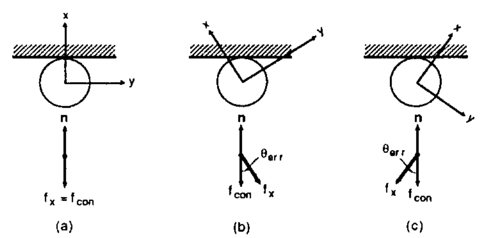

Figure 2. Tool-Contour Contact Geometries

For the first contact configuration as shown in Figure 2 (a), the actual contact force f_{con} (which is also the force in the x direction f_x) will not be changed from the initially defined reference contact force, while the robot is moving in y direction. The force error defined by $f_{err} = f_{ref} - f_{con}$ will be zero and no compensatory motions will be required. When the robot tool coordinates are as shown in Figure 2 (b) and the robot is trying to move in positive y direction, f_{con} and f_x will be increased and the force error f_{err} will be negative. In this situation, the robot needs to move in the negative x direction. Also the rotation around the positive z axis is required. Finally when the tool makes contact to the contour as shown in Figure 2 (c), f_{con} and f_x will be decreased as the tool moves in the positive y direction. Here the force error will be positive and the translation in the positive x direction and a rotation about a negative z axis are required. Thus when the force accommodation approach is used to follow a contour with a constant tool orientation with respect to the contour, the following type of control law should be used.

$$x_c \text{ (or } \dot{x}_c \text{)} = H_x f_{err} \quad (2.1)$$

$$\theta_c \text{ (or } \dot{\theta}_c \text{)} = H_\theta f_{err} \quad (2.2)$$

In equations (2.1) and (2.2), H_x has a positive steady-state gain and H_θ has a negative steady-state gain. Also x_c (or $\dot{x}_c$) represents the translation (or linear velocity) in the x direction and θ_c (or $\dot{\theta}_c$) represents the rotation (or an angular velocity) with respect to the z axis.

To find the relations among f_{con} , f_x , actual(absolute) robot displacement in the x direction x_a , and the actual (absolute) tool rotation about z axis θ_a , consider the tool-contour contact geometries shown in Figure 2 again.. When the contact geometry is as shown in Figure 2 (a), the following relation between x_a and f_{con} (which is equal to f_x) can be obtained.

$$f_{con} = f_x = k_x(x_a - x_{con}) \quad (2.3)$$

In equation (2.3), $x_{err} = x_a - x_{con}$ represents the relative displacement of the tool in the x direction with respect to the contour and k_x represents the contour following system x directional stiffness. Thus the force error in the control law of equations (2.1) and (2.2) can be directly replaced by the force error in the x direction for this case. The relative tool displacement in the x direction will directly affect the contact force through the system stiffness k_x . When the tool has an orientation as shown in Figure 2 (b) and (c), f_x is related to f_{con} as follows,

$$f_x = f_{con} \cos(\theta_a - \theta_{con}) \quad (2.4)$$

and x_{err} will cause the relative tool displacement d_n along the contour normal direction as follows,

$$d_n = x_{err} \cos(\theta_a - \theta_{con}) \quad (2.5)$$

where $\theta_{err} = \theta_a - \theta_{con}$ is an actual angle between the tool x axis and the contour normal vector. If the tool orientation is remained constant with represent to the global reference frame (means there is no tool rotation), θ_{err} will be an absolute angle difference between the x axis of the tool coordinates and the contour normal vector, thus cannot be assumed as a small angle. But when we maintain a constant tool orientation with respect to the contour, the tool orientation will be continuously adjusted to align the x axis of tool coordinates with the contact normal vector. If the contour following system is working correctly, θ_{err} in equations (2.4) and (2.5) should be small all the times. Thus equations (2.4) and (2.5) can be approximated as follows.

$$f_x \approx f_{con} \text{ and } d_n \approx x_{err} \quad (2.6)$$

Equation (2.6) shows that maintaining constant contact force when the tool orientation is constant with respect to the contour is equivalent to maintaining constant force in x direction. Also equations (2.6) and (2.3) show that only the displacement along the x direction of tool coordinates will have an effect in the contact force.

The first order approximation discussed so far results in the linear, decoupled model of contour following system shown in Figure 3. In the block diagram of Figure 3, ARM_x and ARM_θ represent the robot system x directional linear and rotational with respect to the z axis Cartesian dynamics respectively. Also the force regulators will generate the linear and angular velocities respectively from the force error in the x direction, where the integrators (which are actually a part of the robot system) are approximated by the trapezoid rule and T is a robot system sampling period.

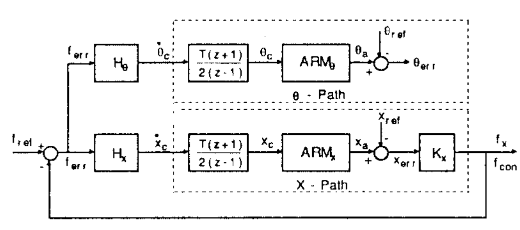

Figure 3. Block Diagram of Two Dimensional Contour Following System

Since the linear, decoupled model obtained is only an approximation of the actual system, there will be a difference between the actual system and the linear model. While consideration of the coupling effect will yield a better model (although nonlinear), we adopt the linear, decoupled model due to the simplicity in design and implementation.

2.2 Design of H_x and H_θ

The x-path controller H_x can be obtained independently from the θ-path since they are decoupled in the linear model of Figure 3. To obtain H_x, first delete the complete θ-path in Figure 3 to obtain a single channel external force control as shown in Figure 4 (a). Then, consider the following. When there is a force error caused by robot motion, the force error is going to be removed by the tool displacement along the x axis of tool coordinates. Since the adjustment of f_x to f_{ref} is going to be done by the actual robot motion, H_x should be designed such that the closed loop system shown in Figure 4 (a) has a similar dynamic behavior to the position response of the robot system itself. That is, H_x should be obtained using the following three steps. (1) Identify the robot system Cartesian dynamics in the x direction (ARM_x). (2) Then using the identified system transfer function, find the robot system step response so as the dynamic characteristics of the robot system. (3) Finally, with the measured x directional system stiffness k_x, H_x is found such that the step response of the closed loop system shown in Figure 4 (a) has almost the same dynamic characteristics with that of the robot system itself.

While the linear, decoupled model of two dimensional contour following system gives an opportunity to find H_x and H_θ independently from each other, it leaves the output of θ-path independent from the contact force f_x. In addition, since the value of θ is not available (constraint imposed in this work), it is not possible to close the θ-path externally by either a force or a position. This cause some difficulties in design of H_θ since only the input of θ-path is available.

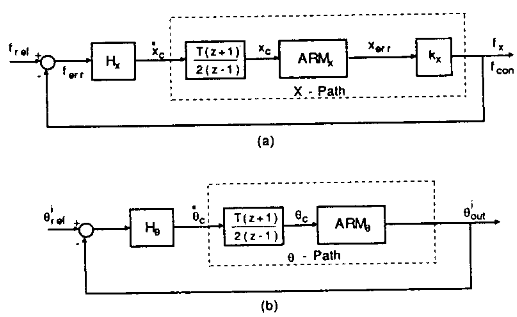

Figure 4. Design of H_x and H_θ

To find H_θ with this constraint, consider the following. First the actuating signal of θ-path in the linear model of Figure 3 is the force error which is exactly the same one used in the x-path. Secondly when H_x is designed, it is done such that the closed loop system response shown in Figure 4 (a) is similar to the response of the robot system itself. With this in mind, consider the closed loop system shown in Figure 4 (b). If H_θ is obtained such that the step response of the closed loop system shown in Figure 4 (b) has a similar dynamic characteristics to that of the robot system rotational step response about the z axis, H_θ obtained will satisfy the requirement exactly the same one used to find H_x.

These design procedures to obtain H_x and H_θ will be clarified further in next section when we discuss the experimental verification of the linear model of contour following system.

3. Experimental Verification

The design procedures presented in Section 2 are verified experimentally using a commercial robot system in this section. The robot system involved is PUMA 560 manipulator with standard Unimation controller. An Astek FS6-120A six axis wrist force sensor, attached externally to the arm, is used to measure the contact force. The external force control loop is closed by the LSI-11/73 microcomputer.

3.1 Identification of Robot System

The first step in the design of force regulators was a representation of robot system Cartesian dynamics by the discrete transfer functions. These were found by a simple system identification procedure. To find x directional robot system Cartesian model ARM_x, the robot system was driven by a randomly generated position command, while the actual position of the robot end effector was acquired. Also, to obtain the Cartesian model of system rotational dynamics with respect to the z axis ARM_θ, actual angular position of the end effector was measured, while the robot was driven by a randomly generated angular position input. The input-output relations of the x directional linear displacement and the angular displacement about z axis, expressed by the discrete transfer function, were obtained using a least square algorithm as follows.

$$ARM_x = \frac{0.0037z^2 + 0.0711z + 0.5234}{z^3 - 0.2807z^2 - 0.0359z - 0.0853} = \frac{0.0037\,(z + 9.6058 + j7.0169)}{(z - 0.5881)(z + 0.1537 \pm j0.3483)} \tag{3.1}$$

$$ARM_\theta = \frac{-0.0092z^2 + 0.2191z + 0.6869}{z^3 + 0.2376z^2 - 0.2583z - 0.0823} = \frac{-0.0092\,(z - 26.7298)(z + 2.8056)}{(z - 0.5343)(z + 0.3859 \pm j0.0716)} \tag{3.2}$$

There are two things we need to be aware of in the system models expressed by the discrete transfer functions of equations (3.1) and (3.2). The first one is that there are unstable zeros in both transfer functions. When a physical system is being identified from the sampled input and output data and if the original system has a continuous transfer function with pole excess larger than two, unstable zeros will always come out in the discrete transfer function, regardless of whether the continuous transfer function actually has unstable zeros or not [9]. Unstable zeros limit the closed loop system performance in many respects. They also impose limitations on the design of controller. For example, any pole-zero cancellation either explicitly or implicitly should not be done. The second thing we need to be aware of in the system model is that the leading coefficient of the numerator in ARM_θ is negative. Thus, if the closed loop system characteristic equation of Figure 4 (b) is written in Evans form, it will have negative variable parameter. This must be noted when the force regulator H_θ is designed using the root locus method.

3.2 Design of H_x and H_θ

The second step in the design of H_x and H_θ is a computation of step responses of ARM_x and ARM_θ to provide the characteristics of H_x and H_θ. That is, H_x will be defined from the system of Figure 4 (a) such that the step response of it will be very similar to the step response of ARM_x. Also H_θ will be obtained using the closed loop system of Figure 4 (b) so that the step response of it is very close to the step response of ARM_θ. The step response of ARM_x and ARM_θ show that they are both critically damped system (as expected) and have almost the same characteristics.

The root locus design technique is used to find H_x and H_θ, even though the state-space method analytically has some advantages over the root locus method. We will discuss the reason of why the state-space design procedure is not used in this work later. We first tested the possibility of using constants of H_x and H_θ. While the use of constant gains is very straightforward, simulated responses of the closed loop systems of Figure 4 (a) and (b) show unsatisfactory results, with too much overshoot. Thus lead compensators were selected with the following considerations. (1) It will increase the system damping and reduce the rising time. (2) Use of lead compensator also increases the closed loop system bandwidth.

Using the block diagram of Figure 4 (a) with the measured x directional system stiffness k_x = 13.85 *N/mm* and the sampling period T = 28 *msec* for the PUMA 560 robot system, the following lead compensator for H_x was obtained by the root locus method.

$$H_x = \frac{1.668\,(z - 0.705)}{z - 0.148} \quad mm/N - \mathrm{sec} \qquad (3.3)$$

Figure 5 shows the step response of the closed loop system of Figure 4 (a). As shown in Figure 5, even though there is still about 7.8 % overshoot, the overall closed loop system step response has very similar dynamic characteristics to that of ARM_x .

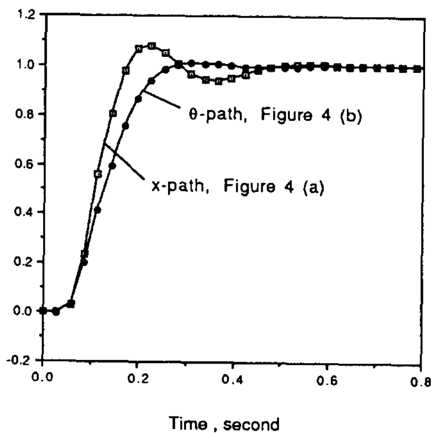

Figure 5. Closed Loop System Step Responses of x and θ-paths

Another lead compensator for H_θ was obtained with the artificial system of Figure 4 (b) as follows.

$$H_\theta = \frac{-11.9\,(z - 0.705)}{z - 0.148} \quad mm/N - \mathrm{sec} \qquad (3.4)$$

Figure 5 also shows the step response of the system of Figure 4 (b).

Unlike root locus method which requires several iterations to obtain H_x and H_θ , the state-space techniques allow us to assign the desired pole locations directly. Unfortunately the state-space design technique was not successfully used in this work. Among many plausible answers, the followings may be a partial explanation. As pointed out by Goodwin and Sin[10], while unmodeled output disturbances, parameter variations and unmodeled dynamics always exist in the actual system, the controller is usually designed with a model which does not include any of them. Thus the minor differences between the response of the model and that of the actual system are unavoidable. But the controller should be designed to minimize their effects. This can generally be accomplished by the controller that (1) has a wide bandwidth for the low frequency disturbance rejection and fast response time (high gain at low frequency) and (2) has a limited bandwidth to avoid problems due to the unmodeled dynamics and high frequency noise (low gain at high frequency). When the controller was obtained from the state-space method such that the closed loop system response was very similar to that of using a lead compensators, the state-space controller actually shows the lower gain at the lower frequency and the higher gain at the high frequency than those of the lead compensator controller. While the state-space method may be mathematically superior, we think that its use should be accompanied by a relatively accurate system model, which was not the case in our work.

3.3 Experimental Work

The force controllers, H_x and H_θ , of equations (3.3) and (3.4) were tested on three different tasks. The constant tracking speed (velocity in contour tangential direction, v_y) used for the experimental work is 10 *mm/sec* and the reference force f_{ref} is set by 10 *N*.

Figure 6 shows the recorded force error, while the robot is following a contour which has a step change in angle. As shown in Figure 6, the force developed after onset of the step is rejected within 1 second by the actual system,. According to the linear, decoupled model of Figure 3 with the closed loop system step response shown in Figure 5, the disturbance by the step encounter should be rejected within 0.5 second. This shows the inaccuracy of the linear model.

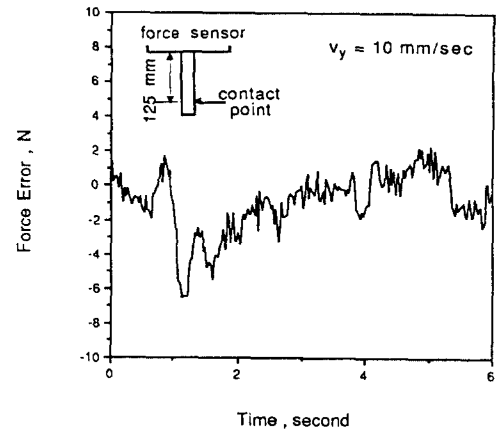

Figure 6. Following a Contour with Step Change in Angle of the Contour

Figure 7 shows the force error recorded while the robot is following a contour of 40 *mm* radius curvature shown in Figure 8. As shown in Figure 7, simple lead compensators well regulate the system to follow the contour.

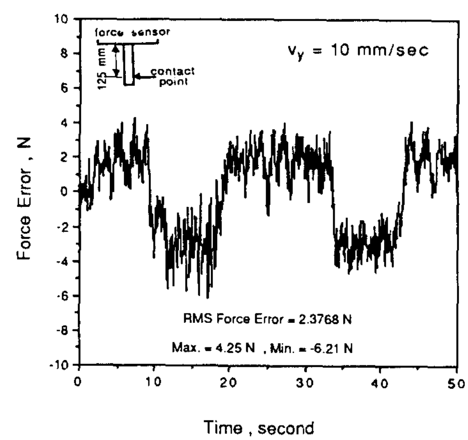

Figure 7. Following a Curved Contour

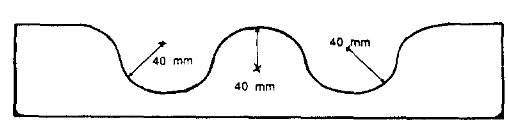

Figure 8. Curved Contour of 40 *mm* Radius

Finally, Figure 9 shows the system performance while following a straight edge.

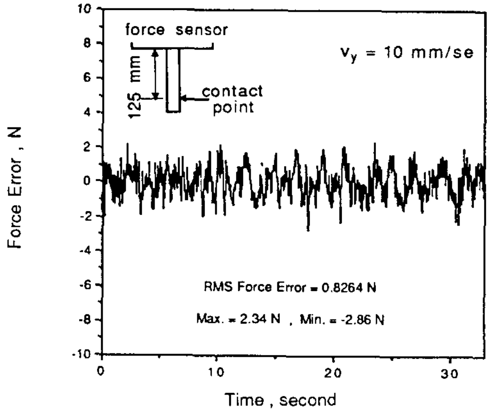

Figure 9. Following a Straight Edge

4. Conclusion and Discussion

This paper presents the implementation of force control using a commercially available robot system in two dimensional contour following task for the surface scanning purpose. While the commercially available robot systems are very capable, their applications are often limited since they are usually operated as pure position controlled devices.

The main constraint on our implementation of the force control was a use of commercially available system without any modification. Due to this constraint, only a force accommodation approach, where the force control loop is closed by the external computer, can be implemented.

A linear, decoupled model of two dimensional contour following system is derived first. Then the proposed design procedures are experimentally verified with the PUMA 560 robot system. Simple lead compensators obtained from the linear model of contour following system work quite well in regulating the contact force (so as to follow the two dimensional contour).

While the linear model of contour following system provides the simplicity in design and implementation, experimentally obtained data shows that the effects of inaccuracy of the linear model, unmodeled dynamics and the system performance dependency on the robot configuration are not negligible. Additional works should be accomplished to improve the system performance and this is being currently studied.

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