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Adaptive Compliant Control for Scara Manipulator

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ABSTRACT

In this paper, compliant motion control of a manipualator in manipulator is proposed by using the self-tuning adaptive controller. Compliant motion is needed in order to applicated to complicated and accurate fields such as assembly operation in which several parts are matched.

For a control method of compliant motion hybrid control is used so forces and position control are proposed selectively through a closed feedback loop.

By contacting with environment, the uncertainties higher. Self-tuning controller which adapts to variable dynamic response is applied to compliant motion control in order to satisfy the desired operation.

The applicability of the suggested algorithm was confirmed by simulation of the contour tracking task of four joint manipulator.

I. INTRODUCTION

Nowadays, manipulators are doing diverse tasks in various industrial fields. In general, they are used in simple and iterative tasks which can be performed for pure position control. However, there has gradually been rising necessity for controlling the task which contacts environment, such as the object of precise and complicated assembly operation and obstacles encountered during operation.

Compliant motion means a manipulation task whose manipulator has continuous contact with environment, and whose end-effector trace during task is modified by contact force. Compliant motion control is applicable to various fields as complex or precise work.

Among many kinds of controllers, PID controller is most widely used in general industry. In this application, adaptive controllers which correspond to dynamic characteristics can be realized by tuning control parameters optimally with data obtained from on-line measurement of process input/output.

This paper carries out compliant motion control using free-joint method and hybrid force/position control method, and designs self-tuner controller which estimates parameter values from on-line measurement of its manipulator and in turn calculates control parameter values so as to have desired system characteristics.

II. COMPLIANT MOTION CONTROL

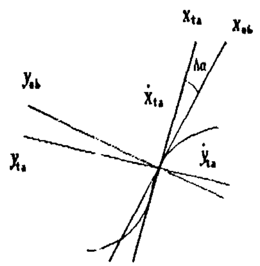
II. 1 Compliant Motion Control

In this part, we focus on a control configuration in case that the motion of the manipulator is partially restricted by contact surface. The subtask, defined by contact between manipulator end-effector and task environment, has natural constraints from the geometrical characteristics of task pattern, and artificial constraints from the decision of trajectory of position and force to execute the desired task. The variation of contact environment should be able to be detected to track the manipulator moving within natural constraints.

The contour of tracking is two-dimensional and position control is applied in tangential direction, and force control in normal direction.

The trajectory of the task frame should be generated so as to compensate the error by obtaining the difference between actual and computational task frame which is derived from the dynamic contact environment during manipulation. This can be realized by defining tracking direction at a common axis of two frames. In Fig. 2-1, the tracking direction of the contact point is that of z-axis, and error in the direction of rotation is $\Delta\alpha$.

$$\Delta\alpha = -\tan^{-1}\left|\frac{V_{yt}}{V_{xt}}\right| \tag{2-1}$$



$x_{ta}(v_d)$: direction of velocity control
$y_{ta}(f_d)$: direction of force control
$a_{zta}(\Delta\alpha)$: direction of tracking

Fig. 2-1. Direction of tracking and the error.

Once the velocity in the direction of position control is predefined, the problem reduces to obtain thevelocity in the direction of force control in order to generate trajectory for the task frame.The controller should generate adequate velocity of each axis at every moment of sampling, and the velocityin task frame generates the trajectory.In the contourtracking operation of Fig. 2-1, directions of each control axis in the task frame are as follows:

Ⅱ. 2 control in the direction of force control

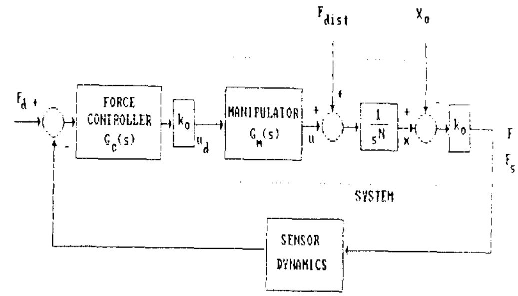
Fig. 2-2 is the general structure of force control axis. The characteristic Gm(s) of process is the manipulator system. Contact between manipulator and object (that is, environment) can be expressed as k_o, the stiffness at the contact point,

$$F = k_o(x - x_o) \tag{2-2}$$

where F is contact force, and x and x_o is the position of manipulator and environment, respectively.

Sensor dynamics is generally neglected, thus

$$F_s = F\ . \tag{2-3}$$



F_d: desired force
F : actual force
Fs: contact force measured by force sensor
N : number of free integration

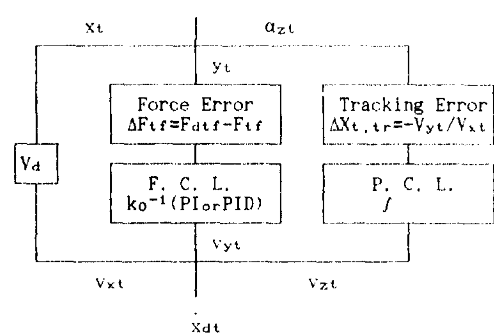
Fig. 2-2. Schematic diagram of active force control.

In the case of position control of a manipulator system, N equals zero and Gm(s) can be expressed as a second-order system. Commonly F_d is a constant. The force controller has compliance k_o^{-1} as its gain to have nothing to do with k_o. Neglecting F_{dist}, the closed-loop characteristic of Fig. 2-3 can be written as

$$\frac{F(s)}{Fd(s)} = \frac{Gc(s)Gm(s)}{s^N + Gc(s)Gm(s)} \tag{2-4}$$

To eliminate steady-state error, the following condition should be satisfied:

$$\lim_{s\to 0}\frac{F(s)}{F_d(s)} = \lim_{s\to 0}\frac{G_c(s)G_m(s)}{s^N + G_c(s)G_m(s)} = 1 \tag{2-5}$$



F.C.L. : Force Control Law
P.C.L. : Position Control Law

Fig. 2-4 Flowchart of compliant motion

As the open-loop characteristic $Gc(s)Gm(s)s^{-N}$ must include at least one integration term, the type should be at least 1 and the type of force controller 1-N and over.

Ⅲ. PARAMETER-ADAPTIVE CONTROLLER

Most industrial manipulators do not have control devices for compliant motion such as hybrid control, partly because it is hard to find out many necessary parameters of the dynamic model with accuracy in applications.

It is the self-tuning control method that designs appropriate feedback rules using on-line identification in order to estimate unknown system parameters. A parameter-optimized controller with short computation time is now designed.

Fig. 3-1 is a parameter-adaptive controller based on process identification.

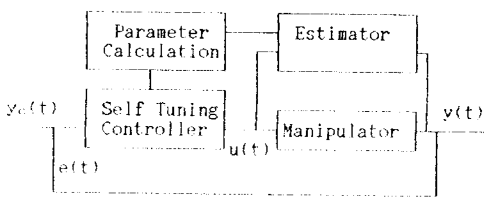


Fig. 3-1. Parameter-adaptive controller.

Ⅲ. 1 Process model

Expressing joint coupling each axis in the task frame as noise terms, we can model each axis independently. Control using AR model is as follows:

$$A(q^{-1})y(t) = B(q^{-1})u(t-d-1) + \xi(t) \qquad (3\text{-}1)$$

where $A(q^{-1}) = 1 + a_1q^{-1} + a_2q^{-2} + \ldots + a_Nq^{-N}$

$B(q^{-1}) = b_0 + b_1q^{-1} + b_2q^{-2} + \ldots + b_Mq^{-M}$

d = time delay.

Rewriting (3-1) becomes

$$y(t) = \phi^T\theta + \xi(t) \qquad (3\text{-}2)$$

$$\phi(t)=[-y(t-1)..-y(t-n+1)\ b0u(t-1)..b0u(t-m)]^T \qquad (3\text{-}3)$$

$$\theta(t)=[a_1\ a_2\ \ldots\ a_N\ b_0\ b_1\ \ldots\ b_M]^T \qquad (3\text{-}4)$$

ϕ stands for all the known values obtained form process input/output, and θ for unknown values to be estimated.

Ⅲ. 2 Self-Tuning Alogorithm

Solutions to model coefficients in (3-1) can be obtained as follows by the recursive least-square algorithm with variable forgetting factor. This algorithm enables the parameter estimates to follow both slow and sudden change in plant dynamics.

1. Prediction : $y(t)=\phi(t-d-1)\theta(t-1)+b0{*}u(t-k-1)$
2. Error : $\varepsilon(t)=y(t)-y(t)$
3. Gain

$$K(t)= \frac{P(t-1)\phi(t-d-1)}{1 + \phi^T(t-d-1)P(t-1)\phi(t-d-1)}$$

4. Estimate : $\theta(t)=\theta(t-1)+K(t)\varepsilon(t)$
5. Forgetting : $\lambda(t)=1-[1-\phi(t-d-1)^TK(t)]\varepsilon(t)^2/\Sigma_0$
6. Covariance : $P(t)=[I-K(t)\phi(t-d-1)^T]P(t-1)/\lambda(t)$

Here, $P(t)$ is the covariance matrix which is proportional to the variance of the estimated values.

Ⅲ. 3 Computation of controller parameters.

The transfer function of the total system having a controller and a process model is

$$\frac{y(t)}{y_c(t)} = \frac{\hat{R}(q^{-1})\hat{B}(q^{-1})}{\hat{S}(q^{-1})\hat{A}(q^{-1}) + q^{-d}\hat{R}(q^{-1})\hat{B}(q^{-1})} \qquad (3\text{-}7)$$

By defining desired closed-loop polls as a Cr polynomial, and from the process estimation polynomials $\hat{A}$ and $\hat{B}$, we can obtain coefficients of S and R polynomials satisfying the following equation

$$\hat{S}(q^{-1})\hat{A}(q^{-1}) + q^{-d}\hat{R}(q^{-1})\hat{B}(q^{-1}) = Cr(q^{-1}) \qquad (3\text{-}8)$$

where $S(q^{-1}) = 1 + s_1q^{-1} + s_2q^{-2} + \ldots + s_{Ns}q^{-Ns}$

$R(q^{-1}) = r_0 + r_1q^{-1} + \ldots + r_{Nr}q^{-Nr}$

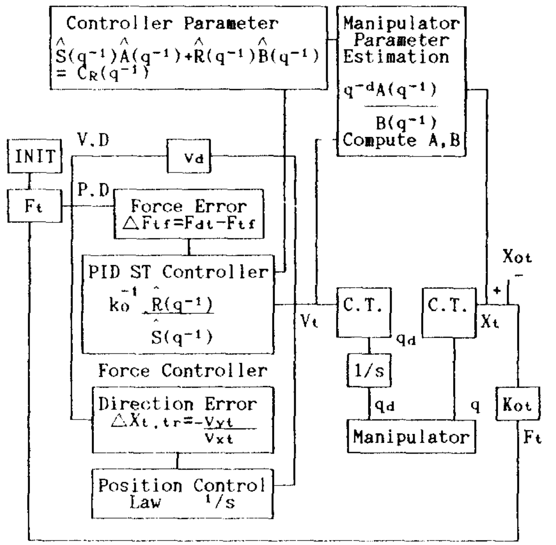
$$C_r(q^{-1}) = 1 + \sum_{i=1}^{n_c} c_iq^{-i}$$

The order of controller polynomials should have following relations with that of process polynomial.

$$Ns = M + d - 1$$
$$Nr = N - 1 \qquad (3\text{-}9)$$

Ⅳ. COMPLIANT SELF-TUNING CONTROLLERS

Fig. 4-1 shows multi-dimensional self-tuning



V.D : Direction of Velocity
P.D : Direction of Direction

Fig. 4-1. Multi-dimensional compliant motion control.

compliant motion control. Applying force control rule to force error, obtaining the velocity of force, tracking, and velocity direction, forming the desired velocity vector v_{dt}, obtaining the desired position vector x_{dt} by integrating v_{dt}, and finally from the AR model position vector x_t is obtained.

Estimating the process parameters from the input/output value of manipulator, the parameter-optimized self-tuning controller operating in the force control direction of compliant motion constitutes and produces dynamic trajectory of task at every moment of sampling.

V. SIMULATION AND THE RESULTS

The manipulator is expressed as a second-order system where N=2 and M=1 in (3-1). By setting the damping ratio 0.75, natural frequency 11 rad/s, and time delay d=1, then the ARMA model of the manipulator becomes as follows.

$$y(t) = 1.677y(k-1) - 0.720y(t-2) + 0.022u(k-1) + 0.019u(k-2) + \xi(k) \quad (5-1)$$

Here, $\xi(k)$ is the noise with zero mean and standard deviation of 0.005. The parameters estimated from the input/output values of the manipulator of (5-1) are updated at each and every contact point using recursive least-square algorithm.

Fig. 5-1 is the object of contour tracking task.

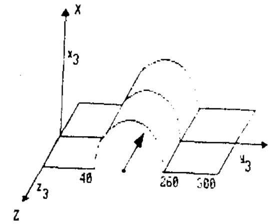


Fig. 5-1. The task model.

The task frame is constituted so that x_t axis is the direction of position control, z_t axis the direction of force control, and α_{yt} axis the direction of tracking.

Figs. 5-2 (a) and (b) show the results of parameter estimation based on (5-1), and that each parameter converges in 20 steps. Fig. 5-3 shows the values of self-turning PI controller coefficients composed of the estimated parameters in the direction

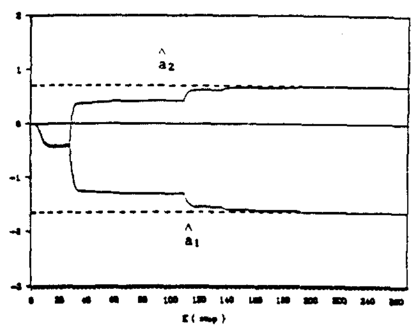


Fig. 5-2 (a). Estimated values of parameter a1,a2.

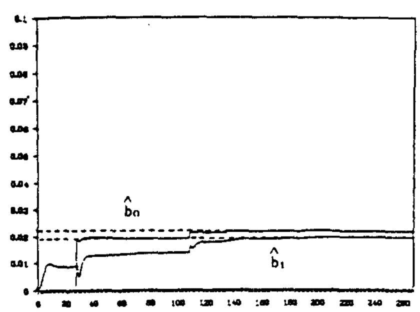


Fig. 5-2 (b). Estimated values of parameter b1,b2.

of force control. The value of $Cr(q^{-1})$ is determined to be $\xi = 0.7$ and $w_n = 5$.

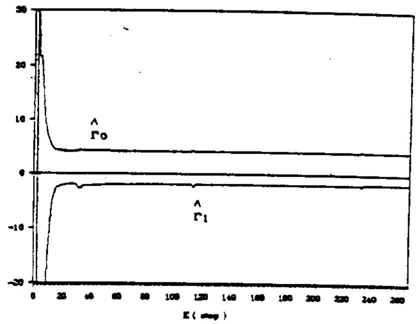


Fig. 5-3. Controller parameter r0,r1.

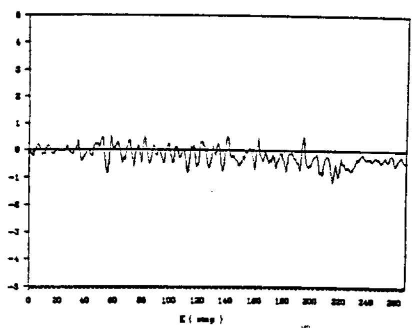


Fig. 5-4. Force error.

Fig. 5-4 shows the force error when v equals 20(mm/sec). Fd equals 15(N) and k_o is 3(N/mm).

Ⅵ. Conclusion

We have examined compliant motion control, which tracks desired trajectory by sensing contact force applied to the end-effector of the manipulator, in case of continuous contact with environment. It is noted that the hybrid method is efficient when the force and position control of the task has an external loop around the manipulator and maintain external force within desired value.

The simulation results show that the uncertain manipulator model, which is unable to recognize exact parameter values due to the variation of dynamic characteristics, controls the desired motion by the estimation of the system recognition.

In real cases, as the sensor dynamics cannot be neglected and the stiffness of contact surface is finite, the resulting error should be taken into consideration.

Ⅶ. REFERENCES

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