Control System Design

Implementation of the linear feedback control system with time varying feedback gains and command forces may be accomplished with a fairly simple analog controller. The feedback gains and command forces consist of well behaved sinusoidal functions, constants, and simple ramp functions. The difficulty caused by the gain fluctuation near the simulation final time may be overcome by cycling the control gain functions back to the beginning before the fluctuations take place. Cycling the control gain functions is not a problem because the control is in a feedback form. The effect of cycling the control gain functions may be interpreted in the analysis as restarting the nonlinear simulation with an initial state closer to the final state. Simulation of the nonlinear system within the region of operation always resulted in a stable response so the effect of restarting the simulation when the system state has moved closer to the final state is valid. A consequence of cycling the control is that the functional in Eq. (1) is not minimized in the exact sense for the entire time interval. The control gain functions are required to be synchronized such that they are properly phased with respect to each other.

Conclusions

This study has shown that the dynamic instability caused by sloshing fluid stores carried in the main rigid body of a spacecraft may be controlled by use of a linear quadratic regulator with the fluid modeled as an equivalent spherical pendulum and only the first mode of fluid oscillation included.

The control system presented stabilized a highly nonlinear system for a large deviation from the nominal operating point and uses easily measured state variables (only main body fixed angular rates and attitude) and was shown to be stable for a wide variation in fluid level. It was shown that sensing the dynamic state of the fluid was not necessary for the specific spacecraft under study. A pointing maneuver was also successfully accomplished by this control system and a control design based on the analysis was outlined for the specific spacecraft.

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Automated Cloth Handling Using Adaptive Force Feedback

R. Patton,[1] F. Swern,[2] S. Tricamo,[2] and A. van der Veen[2]

In this paper, a control loop for the handling of cloth is described and tested. The control loop is an adaptive force feedback controller which both provides correct tension on the cloth and straightens wrinkles in the cloth. The control loop was implemented and tested on a PUMA 560 robot with a LORD 15/50 force/torque sensor mounted on its wrist. Experiments demonstrate the ability of the control loop to straighten the cloth and to exert a specified tension on the cloth.

Introduction

An interesting problem in robotics is cloth handling. Applications include composite lay-up and apparel and upholstery manufacturing. Rebman (1986) describes an application of a tactile sensor to assembly of a flexible diaphram and a plastic cap. Hertzanu and Tabak (1986) described an adaptive controller for an industrial sewing machine. For most applications, cloth must be held taut and unwrinkled. It was postulated that this requires multi-axis force control, and a suitable control system was designed and constructed. The system chosen is an adaptive force feedback loop with position accommodation. Non-adaptive force feedback control schemes have been described and tested by many researchers, such as Whitney (1977). An adaptive force feedback loop for coordination of two robot arms was described by Seraji (1987).

Because cloth stiffness varies depending on whether the individual cloth fibers are taut or slack, a nonadaptive loop is unsuitable for cloth handling. An adaptive control loop was designed with cloth stiffness as the adaptive variable. The system design was constructed and tested using a PUMA 560 robot with a LORD 15/50 force/torque sensor mounted on its wrist.

Control System Description

Figure 1 shows the schematic diagram for one degree of freedom of the control system. The major blocks in the schematic are the plant and the parameter estimator. Tests run on the system showed that the x, y, and θ degrees of freedom were only weakly coupled; thus the stiffness matrix was assumed diagonal and the system degrees of freedom decoupled. The cloth handling problem was assumed to be planar, so that only 2-D control was necessary. The success of the experiments demonstrates the validity of these assumptions.

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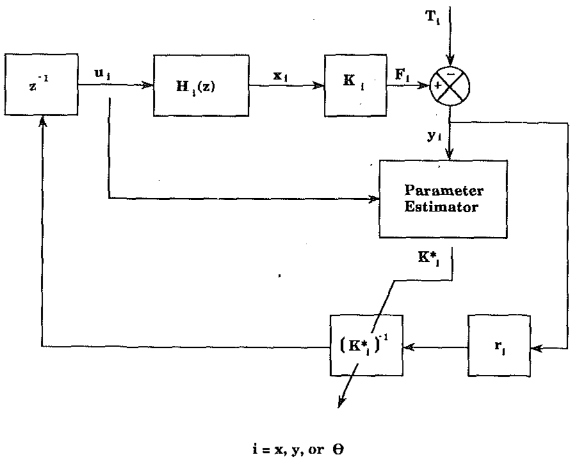

$H_i(z)$ = i^{th} DOF of the robot transfer function

K_i = cloth stiffness in the i^{th} direction

F_i = sensed force in the i^{th} direction

T_i = desired tension in the i^{th} direction

y_i = force error in the i^{th} direction

K^*_i = estimated stiffness in the i^{th} direction

r_i = feedback gain in the i^{th} direction

Fig. 1

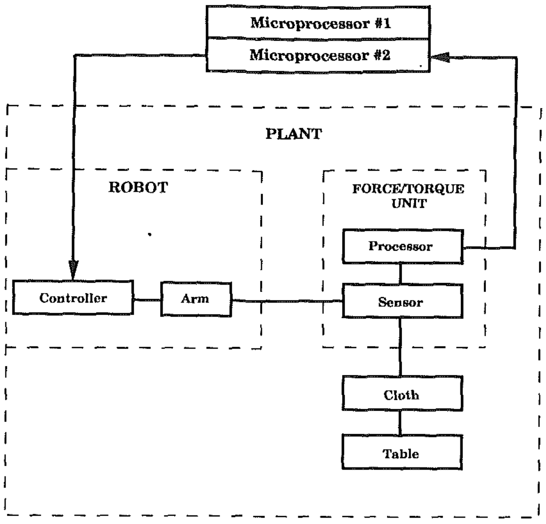

Fig. 2

CLOTH DRAPING
FORCES OR TORQUE VS TIME

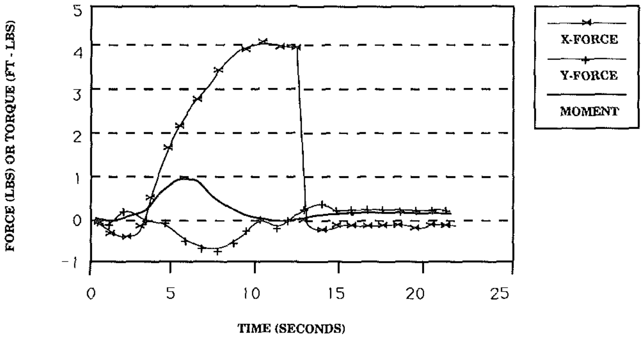

Fig. 3

The plant to be controlled is the robot-force/torque sensor combination; its inputs are robotic x, y and θ commands and its outputs are F_x, F_y and M_z. The PUMA controller translates positional commands into robot end effector motion. Because the PUMA controller has proprietary software it was not possible to determine the robot transfer function matrix directly; instead the transfer function matrix was identified experimentally using an ordinary least squares technique.

The parameter estimator is a least mean square (LMS) estimator. Let

$$y = KH(z)u = K\frac{a_1z^{-1} + \ldots + a_nz^{-n}}{1 + b_1z^{-1} + \ldots + b_nz^{-n}}u,$$

where $a_1, \ldots, a_n$ and $b_1, \ldots, b_n$ are found from the ordinary least squares plant identification, y is the error in the force, and u is the position command. Then the LMS estimator for K is

$$K^* = K^*_{-1} + r(y - y^*)w_{-1},$$

where K^* is the estimated stiffness,

$$y^* = -b_1y_{-1} - \ldots - b_ny_{-n} + K^*_{-1}(a_1u_{-1} + \ldots + a_nu_{-n}),$$

and

$$w_{-1} = a_1u_{-1} + \ldots + a_nu_{-n}.$$

The position control law is

$$u_i = \frac{y_i}{K_i^*},$$

where u_i is the change in the position of the ith degree of freedom (DOF), y_i is the force (or torque) error of the ith DOF, and K_i^* is the stiffness of the ith DOF.

Test Setup

Figure 2 shows the schematic for the cloth handling experiments. The test setup consisted of a PUMA 560 robot with both arm and controller which had a LORD 15/50 force/torque sensor and processor attached to its wrist. The robot controller and the sensor processor had proprietary software; no effort was made to reprogram them. The robot held one end of a cloth of dimensions 36 by 36 in., the other end of which was attached to a table. Both ends of the cloth were stapled to wooden rods; proper robot end effectors would eliminate the need for these rods. Two 8086 microprocessor cards were also built. The 1st microprocessor calculated the cloth stiffness and end effector position changes; the 2nd microprocessor was used for communication with the robot and the force/torque sensor.

Experimental Procedure

The experiments were run with one end of the cloth fixed. The initial slack and misalignments of the cloth were as follows:

Stretch (x) direction	6 to 10 in. of slack
Lateral (y) direction	2 to 4 in. of misalignment
θ direction	5° to 20° of misalignment

The robot straightened out the misalignments and pulled 4 lb of tension on the cloth. After it had done so the end effector was moved inward to produce 6 in. of slack in the x-direction. This movement draped the cloth over 2 boxes without wrinkling.

Experimental Results

The visual results showed consistency between the experiments. In all of them, the cloth was successfully draped over the boxes without wrinkles, the motion was smooth, and the times were approximately the same.

Figure 3 plots the x and y forces and the z-moment for one of the experiments. Starting at its initial slack, misaligned position, the robot pulls a 4 lb tension on the cloth and adjusts the lateral (y) force and the moment to zero. This requires approximately 12 s. At 14 s the robot drapes the cloth; at this point the tension (x-force) falls to zero. This experiment was successfully repeated several times.

Conclusions

A force feedback control loop implemented on a robot has been used successfully to straighten and draw a tension on a cloth. Further work will include using more sophisticated end effectors to grip the cloth, and applications in upholstery and composite manufacture.

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An Optimal Multivariable Controller With Application to Steam Temperature Control in a Boiler

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An optimal multivariable controller has been designed for superheater steam temperature control in a drum boiler. The controller takes the form of a linear quadratic regulator with supplementary states for added integral action. By means of a nonlinear model of the power plant, the performance of the controller is compared with that of the existing plant control system which consists of a set of PI controllers with feedforward action. The simulation results indicate that the superior performance of the digital controller justifies the expense of a control system retrofit.

1 Introduction

Several design techniques are available for multivariable controllers but many of them are judged impractical as they result in complex control laws that are difficult to implement. Evaluation of the optimal linear control problem with a quadratic performance index can avoid these difficulties. In the area of thermal power plants, field applications of Linear Quadratic (LQ) controllers have been made to marine boilers (Tysso and Brembo, 1978), drum boilers (Cori and Maffezzoni, 1984) and supercritical boilers (Nakamura and Akaike, 1981). In these and other applications it is not the "optimal" nature of the design alone that makes it attractive but the fact that it provides the control engineer with a straightforward technique to obtain a multivariable control law.

The LQ design works with a linear model of the process and involves a small number of tunable parameters. Though intended for application as a regulator in its classical form, manipulation of the cost function can extend its use to servo problems. The addition of integral action on the controlled variables can increase the robustness of the design through compensation of plant model mismatch and the elimination of steady-state errors.

A number of introspective reviews have been made that have examined the question of why more plants haven't been put under this type of advanced control (for example Rees and Bell, 1988). The key point appears to be one of economics. The digital implementation of an LQ controller costs more than the analog implementation of a Proportional plus Integral (PI) controller. Thus, the performance of a LQ controller must surpass that of a PI controller to the point that reduced operating costs will offset the higher capital costs of the former.

This paper sets out to reemphasize the practical features of an optimal multivariable LQ controller and illustrate its straightforward design. Application is made to steam temperature control in a power plant where economics clearly demonstrate the need for an advanced controller.

2 Design of a Practical Optimal Controller

The salient points of the design of a linear quadratic controller will be given in this section. Details can be found in a text such as Åström and Wittenmark (1984). The standard LQ regulator problem is to find the gain matrix K such that the control law:

$$u = -Kx \tag{1}$$

minimizes the cost function:

$$J = \int_0^{\infty} (x^T Q x + u^T R u)\,dt \tag{2}$$

subject to the constraint equations:

$$\frac{dx}{dt} = Ax + Bu \tag{3}$$

$$y = Cx \tag{4}$$

The optimal gain K is calculated from the related steady-state Algebraic Riccati Equation (ARE). The designer is required to select the weighting matrices Q and R.

For servo action and to increase the robustness of the controller in the face of modelling errors, the original system matrices are augmented as follows:

$$\begin{pmatrix} \dfrac{dx}{dt} \\ \dfrac{dz}{dt} \end{pmatrix} = \begin{pmatrix} A & 0 \\ C & 0 \end{pmatrix} \begin{pmatrix} x \\ z \end{pmatrix} + \begin{pmatrix} B \\ 0 \end{pmatrix} u \tag{5}$$

or

$$\frac{dx_a}{dt} = A_a x_a + B_a u$$

with

$$z = \int (y - y_{sp})\,dt$$

Equation (1) can now be rewritten as:

$$u = -K_1 x - K_2 \int (y - y_{sp})\,dt \tag{6}$$

where the expanded gain matrix $K = (K_1 \quad K_2)$ is obtained from the following ARE:

$$0 = SA_a + A_a^T S - SB_a R^{-1} B_a^T S + Q_a \tag{7}$$

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