TABULAR PULSE-WIDTH CONTROL OF A TWO DEGREE-OF-FREEDOM MANIPULATOR

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Abstract: Pulse-width control, when applied to single degree-of-freedom systems, is very effective in overcoming the deleterious effects of Coulomb friction and stiction. This paper applies pulse-width control to a multi-degree-of-freedom mechanism. Results are presented based both on simulations and on the performance of a two degree-of-freedom experimental manipulator developed at Bucknell University. A unique aspect of this research is the use of a table of pulse-width gain values rather than simply a single gain for each axis of motion. Results indicate that tabular pulse-width control produces responses that converge rapidly and achieve positioning accuracies equal to the precision of measurement sensors.

Keywords: Coulomb friction, pulse width, robot control, numerical simulation, robotic manipulators, control precision.

1. INTRODUCTION

This paper focuses on the development of pulse-width control methods for significantly improving positioning precision. High precision mechanical devices, such as assembly robots, micro-mechanisms, surgical tools, and disk drives are currently employed in a large variety of industrial, service, and commercial tasks. To function effectively, these mechanisms must typically be able to position a workpiece or component quickly and accurately. For optimum performance, two obstacles inherent to such systems must be overcome: stiction and structural flexibility. The performance of traditional controllers, such as proportional-integral-derivative (PID), is severely limited when confronted with significant amounts of either friction or flexibility. This is manifested by the occurrence of limit cycles, exceedingly long convergence times, or the degradation of performance as system parameters change.

As an alternative to traditional controllers for high precision applications, Yang and Tomizuka (1988) were the first to propose pulse-width control (PWC). Pulse-width control is particularly well suited to coping with the disparity between levels of static and kinetic friction and has been successfully applied to the control of robotic manipulators and other mechanisms in the presence of Coulomb friction and stiction. As originally proposed by Yang and Tomizuka, pulse-width control utilizes rectangular force pulses of fixed amplitude and variable duration. The duration of the force pulse required to move a rigid, single-mass, translational system a distance e was shown to be

$$t_p = \sqrt{\frac{2mf_c|e|}{f_a(f_a - f_c)}} = K\sqrt{|e|}\,, \qquad (1)$$

where t_p is the force pulse duration, m is the mass of the system, f_c is the Coulomb friction force acting on the mass, and f_a is the actuator force applied to the mass. Note that the amplitude of the actuator force pulse must be greater than the static friction force to ensure the initiation of motion. Using Eq. (1), a single pulse should suffice to move the mass to its desired final position. When the mass comes to rest at a position other than the desired one (due to uncertainties or variations in the values of the system parameters) additional pulses are applied, with the system coming to rest between successive pulses, until the desired position is achieved. To evaluate the performance of PWC, Yang and Tomizuka conducted experiments with a mass driven by a single lead screw. The experimental apparatus was specifically designed to be very rigid, with a low backlash lead screw and a non-compliant shaft. The results demonstrated high positioning accuracy and a rapid response. Moreover, an adaptive version of the pulse-width controller was robust and capable of tolerating significant variations in system parameters.

Rathbun, Berg, and Buffinton (2004a; 2004b) extended the theory of PWC and applied it to a truely industrial system, namely a large (14m x 7.5m x 3m workspace) gantry-style, prismatically jointed robot. For this system, a simple proportional-integral controller was used to move the end-effector relatively close to its desired position. When the PI controller no longer effectively moved the system closer to the desired position, PWC was implemented (PWC is intended to be applied only when a system is close to its desired position).

Wu and Tung (2004), using a nearly identical apparatus to that of Yang and Tomizuka, also significantly furthered the development of PWC. Instead of using predetermined durations for a force pulse, however, the force pulse was simply applied until the velocity of the mass rose above a predefined threshold, at which time the application of the pulse was terminated until the velocity was again below the threshold or within the specified tolerance.

The only documented investigations of the application of PWC to multi-link systems with dynamically coupled axes of motion have been done by Arif (2004), Beal (2005), and Perkins (2005) [an extension of the work of Perkins is presented by Buffinton *et al.* (2005)]. Arif developed simulations of both rigid and flexible manipulators with two revolute joints under PWC. She showed that a direct application of the controller developed by Yang and Tomizuka, without accounting for dynamic coupling, did not generally produce convergent results and in many cases lead to instability. Beal extended the work of Arif and investigated various other pulse-width control schemes and applied them in simulation to a two-link, revolute jointed manipulator. Beal established that for dynamically coupled, multiple degree-of-freedom systems, a direct application of Eq. (1) is inadequate and that the coupling between links must be explicitly taken into account in the determination of appropriate pulse durations. In his most successful scheme, Beal made direct use of the coupled equations of motion to develop lookup tables (in some ways similar to Armstrong-Hélouvry's tabular compensation method) for the pulse durations needed to produce a desired maneuver. This tabular method was shown not only to be effective and robust when subject to variations in system parameters, but also to require relatively small numbers of tabulated values even when simple linear interpolation was used to determine values between table entries. Beal's results additionally demonstrated that a tabular pulse-width controller developed with a rigid body model could be used to effectively control a corresponding flexible system by taking advantage of the piecewise linear gain method developed by Rathbun, Berg, and Buffinton.

The research described in this paper is a further extension of the work done by Perkins (2005) and specifically documents the results of simulations and experimental implementation of the tabular pulse-width controller developed by Beal (2005). In both simulations and experiments, the tabular controller is applied to a two degree-of-freedom manipulator with rigid links. The manipulator used for experiments was developed at Bucknell University and has one prismatic joint and one revolute joint. For the simulations, the tabular controller uses gain values calculated from a linearized system model. The gain values used during the experiments were determined empirically. Results indicate that the use of lookup tables in implementing PWC is a viable approach for systems with multiple degrees of freedom. Moreover, these results lay a foundation for the development of an adaptive method that updates the table entries and adapts to variations in friction and other parameters values.

2. SIMULATIONS

To initially evaluate effectiveness, simulations of tabular pulse-width control were conducted and compared to results obtained with a direct application of the approach used by Yang and Tomizuka. The system model used in the simulations is shown in Figure 1. The system has two joints, one revolute and one prismatic. To perform system maneuvers, a torque can be applied at point *O* and a force can be applied at point *P* to drive rotational and translational motions, respectively.

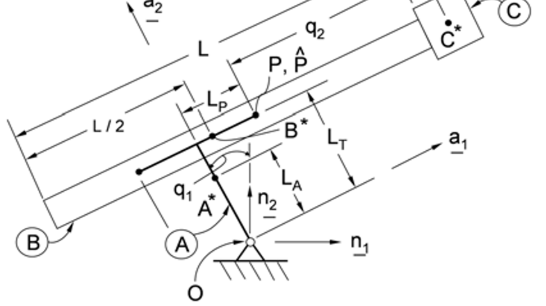

Fig. 1. Simulation System Model.

Values of the system parameters used in the simulations were L_A = 0.125 m, L_T = 0.25 m, L_P = 0.25 m, L = 1m, L_C = 0.125 m, m_A = 1 kg, m_B = 1 kg,