Adaptive Friction and Inertia Compensation of a High Performance Voice Coil Manipulator

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I. INTRODUCTION

Voice coil manipulator is widely used in modern industry. Due to its direct drive actuation characteristic, it can provide fast and accurate motions. In semiconductor manufacturing and packaging industry, accurate positioning and fast operating speed are essential criteria in ensuring production rate and product quality. Position accuracy and travelling speed are two conflicting requirements, and a compromise between them is required. To realise a high performance manipulator for accurate positioning necessitates the use of intelligent variable-speed drives with power electric actuators and advanced control algorithms.

In this study the voice coil manipulator shown in figure 1 consists of a PC-hosted DSP-based controller, a driver, feedback devices and an actuator together with associated moving arm and mechanism.

As end point accuracy, tracking accuracy and repeatability are important, it is necessary for the manipulator to keep track on a pre-defined trajectory at all times to minimise any potential stress on its electrical and mechanical systems.

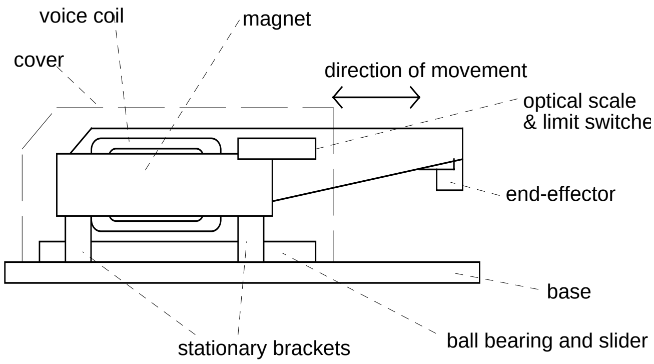

Figure 1 A voice coil manipulator

For the present system, performance will degrade due to variation of physical parameters, which include moment of inertia and viscous friction. These parameters vary during the operation of the manipulator. It is essential for the controller to compensate the effect of varying friction and inertia to ensure the consistence overall performance of the process. An adaptive controller is a suitable solution to provide such kind of on-line compensation.

A survey on friction and its control and compensation techniques has been published [1]. As friction and inertia characteristics are different on different mechatronic systems, it is not possible to develop an unique way to model the friction and inertia characteristics in different systems. An adaptive friction control system for high precision positioning tables has been published [2]. In this paper, Lyapunov stability theory is used in friction estimation instead of traditional parameter estimation algorithms. However, viscous friction is assumed to be constant during motion. Such assumption is not applicable to our target manipulator.

In this paper, the proposed control algorithm has been simulated preliminary in a general servo manipulating system [3]. This algorithm is further extended and implement on a voice coil manipulator

II. SYSTEM MODELLING

A simple experiment was carried out to test the characteristics of both coulomb and viscous friction. The force required to compensate the coulomb friction is determined by injecting an open-loop constant control signal to the motor until it just starts to move. For the measurement of viscous friction, a closed loop control signal is used. The required force is the signal level which can drive the motor to run at a particular constant velocity.

Result of the experiment is shown in figure 2.

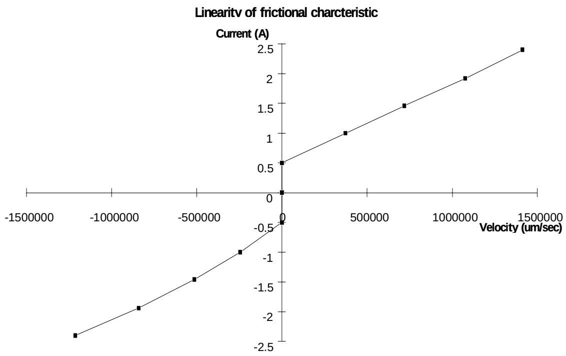

Figure 2 Measured column and viscous friction of the voice coil manipulator

It can be seen from figure 2 that the value of coulomb friction is nearly constant in both positive and negative directions. Also, the level of viscous friction can be approximated as a linear curve within the working velocity range in both positive and negative directions. Under this situation, a second order model can used to describe the dynamics of the manipulator. Figure 3 shows the electro-mechanical model of the manipulator in block diagram form.

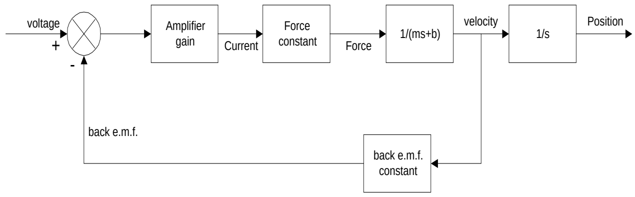

Figure 3 : Electro-mechanical model of the manipulator

The block diagram shown in figure 3 can summarise as equations (1)-(3).

$$G(s) = \frac{K}{s(T_m s + 1)} \tag{1}$$

in which

$$K = \frac{K_a K_f}{b + K_a K_f K_{bemf}} \tag{2}$$

and

$$T_m = \frac{m}{b + K_a K_f K_{bemf}} \tag{3}$$

where
- m moving mass inertia
- b viscous friction coefficient
- K_a Current Amplifier Gain
- K_f Force Constant
- K_{bemf} Back e.m.f. constant

From equation (1), the equivalent discrete model of the manipulator is obtained:

$$G(z) = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \tag{4}$$

From equation (4) and equation (1), the value of K and T_m can be found.

III. ON-LINE PARAMETERS ESTIMATION

Standard Recursive Least Squares Estimation (RLSE) with exponential forgetting factor is commonly used for model parameter estimation. However, the parameters estimated by RLSE will be asymptotic biased [4], unless the following condition is satisfied:

$$E[\phi(k)v(k)] = 0 \qquad (5)$$

where *v(k)* stochastic disturbance term of the system

$\phi(k)$ matrix of input and output components

It can show that equation (5) can be satisfied if and only if *v(k)* is white noise. In practice it is difficult to ensure that the system disturbance is always white noise.

In order to obtain a stable and robust parameter estimator, a Recursive Instrumental Variable Estimation (RIVE) algorithm is used. The RIVE algorithm can summarise as equations (6)-(8):

$$\varepsilon(k) = y(k) - \phi^T(k)\hat{\theta}(k-1) \qquad (6)$$

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{P(k-1)z(k)}{\left[1+\phi^T(k)P(k-1)z(k)\right]}\varepsilon(k) \qquad (7)$$

$$P(k) = \frac{P(k-1) - P(k-1)z(k)\phi^T(k)P(k-1)}{1+\phi^T(k)P(k-1)z(k)} \qquad (8)$$

Equations (6)-(8) show that RIVE algorithm is similar to RLSE algorithm, except that $\phi(k)$ is changed to *z(k)* and $\phi^T(k)$ is kept the same. In equations (7)-(8), *z(k)* is the instrument matrix. There are many possibilities for choosing an instrument matrix, but *z(k)* can be interpreted in the following form :

$$z(k) = \left[-\hat{x}(k-1) \quad -\hat{x}(k-2) \quad u(k-1) \quad u(k-2)\right]^T \qquad (9)$$

$$\hat{x}(k) = z^T(k)\hat{\theta}(k) \qquad (10)$$

where $\hat{x}(k)$ is the estimated noise-free output of the process using the estimated parameter vector $\hat{\theta}(k)$. The initialisation procedure of RIVE is similar to RLSE. From equation (4), the estimated parameter vector $\hat{\theta}(k)$ and delayed input and output vector $\phi(k)$ are expressed in the form :

$$\hat{\theta}(k) = \left[a_1 \quad a_2 \quad b_1 \quad b_2\right]^T \qquad (11)$$

$$\phi(k) = \left[-y(k-1) \quad -y(k-2) \quad u(k-1) \quad u(k-2)\right]^T \qquad (12)$$

IV. CONTROLLER DESIGN

a). Inertia and Friction Compensation

In order to achieve high accuracy and fast dynamic response with consistence performance, an inertia compensator and a friction compensator are added to the control algorithm. The inertia term is proportional to the acceleration and provides an immediate force to overcome the inertia effect. Since friction exists all the time, a friction compensator based on velocity information is used to provide a control force for a higher manipulator performance. Both inertial and frictional characteristics are time-varying as well.

b). Tracking Controller

The main task of the tracking manipulator is to maintain the system's response and accuracy during position, velocity, or force tracking. In our application, a discrete PID controller with anti-windup is employed

Figure 4 shows the block diagram of the proposed servo control loop with adaptive compensation.

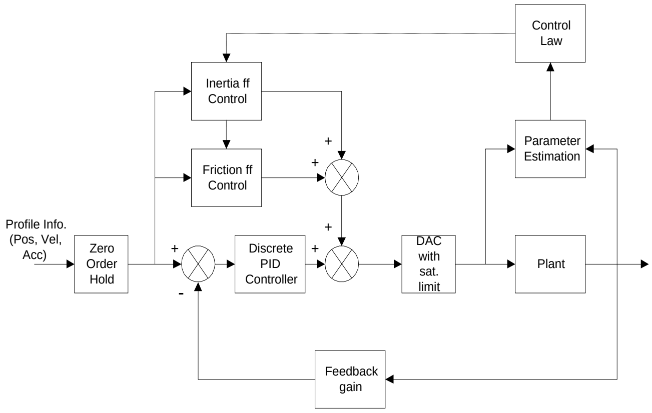

Figure 4 Block diagram of the adaptive controller

V. Simulation

The proposed control block diagram shown in figure 4 is simulated under MATLAB® and SIMULINK®.

A third order polynomial profile is used for command signal input to the system. Figure 5 shows the convergence and robustness of the RIVE algorithm.

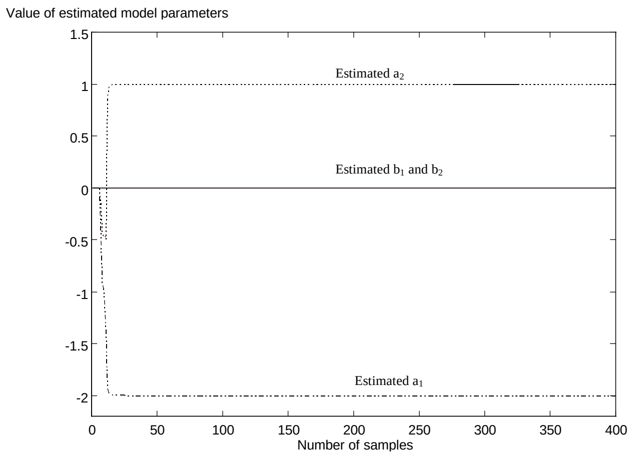

Figure 5: Convergence of the estimated model parameters by RIVE algorithm

Figure 5 shows that the model parameters estimated by RIVE converge to a steady level within the first 25 samples. Although the initial values of the estimated parameter vector will not cause any degrade nor affect to the convergence rate, it is a good practice to set those unknown parameters to zero at the beginning of estimation. The tracking performance of the adaptive controller is shown in figure 6.

Figure 6 shows that the proposed controller can perform good tracking ability over the motion profile. The simulation results have shown that the proposed control algorithm has a high adaptation capability.

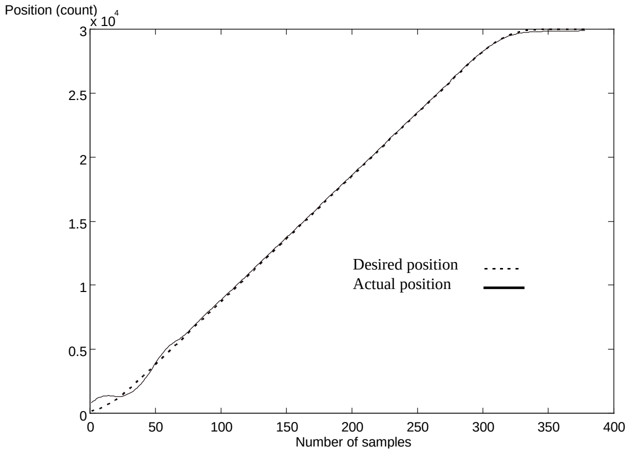

Figure 6: Tracking performance of the proposed controller

VI. IMPLEMENTATION

To enable flexibility in testing the self-tuning algorithm while the actual mechanical system is being designed and built, a test rig shown in figure 7 is constructed in our motion laboratory. The control signal issued from the adaptive controller is sent to the PWM servo driver. A driving voltage is used to command the PWM driver in a ratio with respect to the level of the control signal. A position encoder is mounted on the manipulator for real-time position feedback to the DSP.

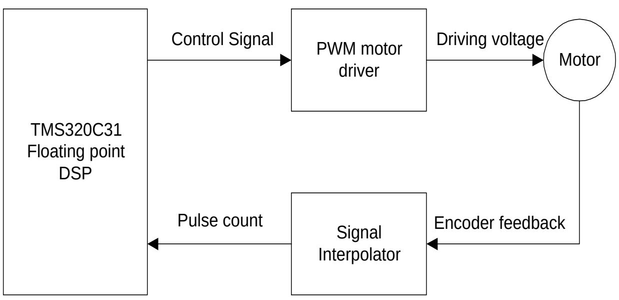

Figure 7 Block diagram of voice coil manipulator test jig

VII. EXPERIMENTAL RESULTS

Verification of the proposed RIVE algorithm is carried out first. A third order polynomial profile is used to drive the motor for point to point motions, and simple PID controller is used for trajectory tracking.

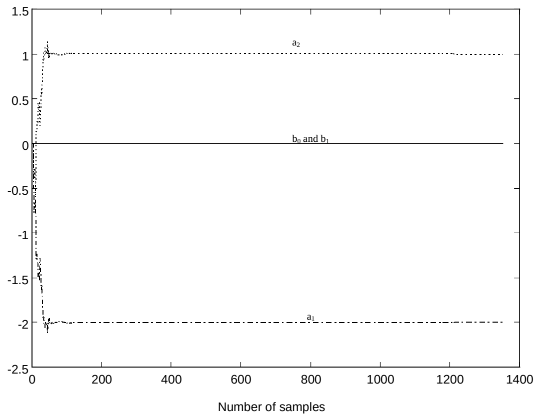

Figure 8: Estimated model parameters by RIVE

Figure 8 shows that the performance of the proposed estimation algorithm for on-line estimation of model parameters. Results confirms that it is convergent and consistent in both single rate and dual rate mode. Comparing the simulation result of figure 5 and figure 8, the experimental result and the predicted simulation result are very similar.

The proposed controller is employed in driving the motor for point-to-point motions. Figure 9 and 10 show the actual tracking performance of the manipulator running in a specific range of distance using the proposed control algorithm. This experimental result shows that the proposed adaptive controller can perform well in tracking manipulation according to the prescribed specification. This characteristic is essential for accurate, high speed and high precision motions.

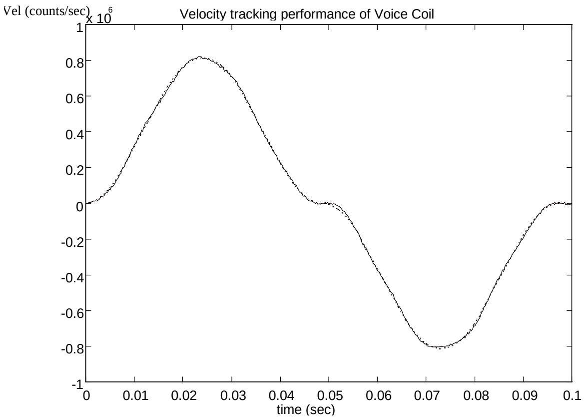

Figure 9: Velocity tracking performance of the manipulator

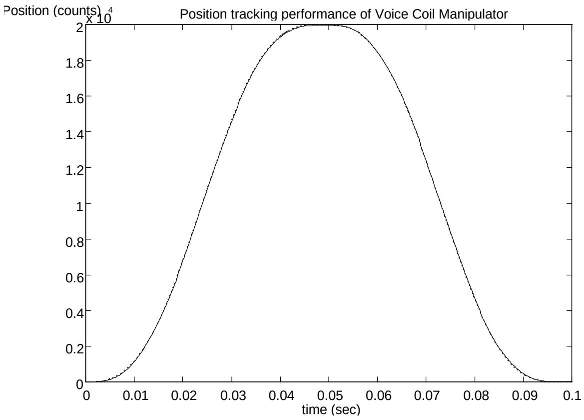

Figure 10: Position tracking performance of the manipulator

VIII. CONCLUSIONS

This paper has developed an adaptive control algorithm for on-line compensation of frictional and inertial effect on a high speed and high precision tracking manipulator. Although RLSE is commonly used for parameter estimation, it has been found that the algorithm is not suitable for our application due to its difficulty for ensuring parameter convergence. In our application, RIVE can provide a more robust and stable approach on parameter estimation, provided that the disturbances are uncorrelated. If the noise is correlated, a first order low-pass filter is required to filter out this kind of noise.

Through simulation and actual implementation, this paper has demonstrated that the proposed algorithm provides accurate estimation of friction and inertia. This leads to an effective generation of compensation forces which yields substantial improvement on the position and velocity tracking of the manipulator.

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