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Modelling and experimental validation of an ultra-high precision positioning system based on the FPGA architecture

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Abstract

The nonlinear model of a small-scale ultra-high precision positioning device is developed in this work in the MATLAB/SIMULINK environment. The conventional Stribeck model is used to describe the DC motor frictional nonlinearities, while the more sophisticated Dahl model is used for the behaviour of the mechanical components of the system. In the experimental set-up, a linear incremental encoder is used as a feedback sensor, while a laser interferometric system is employed to validate the obtained precision. The digital PID controller is implemented on the FPGA architecture by using the LabVIEW programming environment. A good matching of simulated and measured dynamic responses is obtained although some friction-induced discrepancies are still present.

Ultra-high precision positioning, frictional nonlinear disturbances, experimental validation, FPGA architecture

1. Introduction

Ultra-high precision mechatronics systems are broadly used in ICT, machine tools, optics, robotics etc. The interest in ultrahigh precision positioning is induced also by the development of nanotechnologies and their application in materials science, biotechnologies, advanced electronics, medicine, safety systems etc. [1-3]. In ultra-high precision mechatronics devices, the dominant disturbance is often friction with its stochastic nonlinear characteristics that influences significantly positioning precision and accuracy. In order to minimize this deteriorating influence, suitable control approaches have to be employed [3, 4]. Proper modelling of systems with friction can in turn enable an 'off-line' optimization of controllers so as to match systems' needs. A MATLAB/SIMULINK simulation model of one axis of a four DOFs ultra-high precision positioning device, to be used for point-to-point positioning in handling and assembly of microparts, i.e. where positioning accuracy is more relevant than its velocity, is developed in this work. The conventional Stribeck friction model, as well as more complex Dahl and LuGre dynamic models [5, 6], are considered. System's performances are validated experimentally via a control system based on a Field Programmable Gate Array (FPGA) and the LabVIEW environment [7, 8]. A conventional PID control approach is employed. Michelson-type laser Doppler interferometric measurements are then made to validate the overall precisions and accuracies.

2. Simulation model

A simulation model for a considered axis is developed by employing the MATLAB/SIMULINK environment (Fig. 1). It is based on a ball screw driven mechatronics system described by Sato [9]. The friction of the DC actuator is described via a Stribeck function, while that of the mechanical components is simulated by the Dahl friction model [6]:

$$\dot{F} = \sigma \left| 1 - \frac{F}{F_c} \operatorname{sign} v(t) \right|^n \operatorname{sign} \left(1 - \frac{F}{F_c} \operatorname{sign} v(t) \right) v(t) \quad (1)$$

where *F* is the overall friction force, $F_c = 30.4$ N is Coulomb friction, *v* is velocity, n = 1 is a parameter related to the force-displacement curve shape, while $\sigma = 75$ N/m is the stiffness i.e. the slope of this curve for F = 0 [5]. F_c is obtained by measuring the motor current for constant velocities. The other parameters are obtained numerically via the minimisation of the deviations of the modelled behaviour with respect to the measured response.



Figure 1. Simplified model of the ultra-high precision positioning system



Figure 2. Experimental set-up

3. Experimental set-up

All the experiments are conducted on a 50 mm translational axis of the multi-axes set-up of Fig 2. A ϕ = 17 mm, L = 24 mm

Faulhaber DC actuator with a nominal voltage $U_n = 6$ V and noload speed $n_0 = 8600$ rpm, is used. The motor with no rotary encoder is integrated with a 19:1 $L_g = 17.7$ mm gearhead. Rotation is converted to linear displacements via a recirculating SKF ball screw with a nominal diameter $d_0 = 6$ mm and a p = 2 mm lead, supported by SKF d = 4 mm, D = 9 mm, b = 2.5 mm ball bearings. A compliant Misumi coupling is used. Schneeberger MINIRAIL profiled guideways allow the translation of the movable part. A Heidenhain linear incremental encoder with a 100 nm resolution is used as a feedback sensor. The control of the system is achieved via a National Instruments FPGA module [7].

4. Obtained results and discussion

To compare the experimental and simulation results, unidirectional (avoiding the 20 μ m gearhead's backlash) pointto-point and low velocity (i.e. quasi-static) experiments, are conducted. Positioning steps of 100 μ m, 500 μ m, 1 000 μ m and 10 000 μ m are performed. The parameters K_P , K_I and K_D of the used digital PID controller implemented on the FPGA module are given in Table 1 whereas its form is given by:

$$u(n) = K_P e(n) + K_I \sum_{k=0}^{n} e(k) + K_D [y(n) - y(n-1)]$$
 (2)

where u(n) is the output from the controller, n is the discrete time step of a sampling time T = 1 ms, e(n) is the discrete proportional and derivative error term, e(k) is the integral error term, k is the summation variable, while y(n) and y(n-1) are the measured positions in two subsequent discrete time steps [7].

Due to the well-known stochastic nature of friction and the inherent geometrical inaccuracies of the used positioning system, the PID parameters, manually tuned for each experiment, are different for each positioning step. Repetitive point-to-point experiments starting from the same position on the stage are performed for 100 μ m and 1 mm positioning steps, while the achieved position is concurrently measured via the interferometric system. The established unidirectional point-to-point positioning accuracy and repeatability calculated, in the absence of specialised microparts standards, according to the ISO 230-2:2014 machine tools' standard, and establishing the limits of overall achievable positioning precision, are 3.19 μ m for the 100 μ m steps and 1.83 μ m for the 1 mm steps.

Table 1 PID parameters used in the simulations and the experiments

Displacement/µm	KP	Kı	KD
100	450	2	40
500	450	2	40
1000	450	5	10
10000	450	5	25

From the simulated and dynamic genuine step responses measured on the FPGA-controlled set-up, compared in Fig 3, it can be observed that a good matching of the model and the experiments is obtained. However, certain deviances are still present. These are due to the stochastic nature of friction, the position and time dependence of friction, frictional memory, rising static friction and presliding displacements [3, 4], as well as the lack of the Stribeck effect in Dahl's model. It is also to be noticed that the Dahl model is aimed at symmetrical hysteresis loops present in bearings subjected to small-amplitude sinusoidal excitations. However, in non-repetitive small step positioning along long stages, as considered here, sinusoidal excitations are not able to grasp many of the present position-dependent and plastic nonlinear effects. Part of the observed deviations could also be induced by the analogue electronics driving the actuator and by the dynamics of the electronics components. For example, the constant ramp, evident especially for the 1 mm step in



Figure 3. Dynamic responses for 100 μ m and 1 mm steps

5. Conclusions and outlook

A model of an ultra-high precision positioning mechatronics system is developed in this work. Stribeck and Dahl models are employed to describe nonlinear frictional effects. Unidirectional point-to point experiments with different positioning steps are conducted on an FPGA controlled system and the dynamic responses are recorded. Interferometric measurements allow establishing that overall positioning accuracies and repeatabilities are at the 2-3 μ m level. A good matching of simulated and measured dynamic responses is obtained, but some nonconformities can still be observed. These are due to stochastic, non-repetitive and plastic nonlinearities related to friction, as well as to electronics' dynamics and limited tunability and dynamic limitations of the PID controller.

To improve the simulation, i.e. off-line system tuning, the Lu-Gre friction model will be implemented next. Due to the listed nonlinear effects, the aimed truly nanometric accuracies and precisions of the considered positioning system, intended to be used for handling and assembly of microparts, will nonetheless be possible only by adopting an adaptive digital PID based on neural networks, which is currently being developed. Even more refined adaptive, learning or evolutionary control typologies, coupled with system identification procedures and metrics suitable to discriminate better the influence of frictional effects, could eventually be also employed. The achieved results will then be extended to the other axes of the multi-axes positioning system with different actuators (DC & stepper motors, voicecoils) and feedback sensors (encoders and LVDTs).

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