euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016

www.euspen.eu

Compensation of frictional disturbances in ultra-high precision mechatronics devices

Ervin Kamenar [1] and Saša Zelenika [1]

[1] *University of Rijeka, Faculty of Engineering & Centre for Micro and Nano Sciences and Technologies, Vukovarska 58, 51000 Rijeka, CROATIA*

ekamenar@riteh.hr

Abstract

Nonlinear frictional effects often limit the performances of ultra-high precision mechatronics devices. Frictional disturbances of a micromanipulation device are modelled in this work via an integrated Generalised Maxwell Slip model. Positioning performances achieved experimentally are compared to the modelled responses. Different control typologies, implemented via a Field Programmable Gate Array, are thus used with the aim of compensating frictional effects. The response of the system to sinusoidal excitations of varying amplitudes is studied next, allowing to establish that, by using an adaptive self-tuning regulator (STR), excellent positioning accuracies are achieved. The STR controller is hence used to repetitively position the mechatronics device in unidirectional point-to-point positioning steps. Nanometric-range precisions and accuracies are finally experimentally achieved.

Frictional disturbances, friction compensation, STR adaptive PID, nanometric precision and accuracy

1. Introduction

Ultra-high precision mechatronics systems are a critical feature of microsystems' technologies and precision engineering in general [1]. The dominant disturbance in these devices are often the time-, position- and temperature-dependent frictional forces. Frictional behaviour can, in turn, be considered in two typical motion regimes: gross sliding and pre-sliding [2-4]. Although the influence of friction can be reduced in the design phase, when ultra-high precision and accuracy are aimed for, frictional disturbances present in both motion regimes have to be compensated via suitable servo control approaches [1].

A translational axis of a micromanipulation device, whose positioning accuracy is hence more relevant than velocity, is analysed in this work. The respective frictional disturbances are modelled via the state-of-the-art integrated Generalised Maxwell Slip (GMS) model [2, 5] that is hence used to simulate the frictional effects of the studied system that is characterised by multiple frictional sources, where some of the elements can be in the sliding regime while others are still in pre-sliding. Positioning performances achieved experimentally are compared next to responses modelled in MATLAB/SIMULINK. With the aim of compensating frictional effects, different control typologies, implemented experimentally via a Field Programmable Gate Array (FPGA), are used. Conventional PID control, a feed-forward GMS model-based compensator and an adaptive self-tuning regulator (STR) are hence employed and the respective responses are compared in terms of maximum tracking deviations. It is established that the STR can efficiently compensate on-line all the system's dynamic changes. This control typology is thus finally used to repetitively position the used device in unidirectional point-to-point short-range (micrometric) and long-range (millimetre) positioning steps.

2. Experimental set-up and its modelling

As schematically shown in Fig. 1, the considered positioning system is composed of electrical elements and control system's electronics, mechanical elements and a laser interferometer. The used actuator is a Faulhaber M1724006SR DC motor with a 6 V nominal voltage and dimensions of ϕ 17.3 mm x 34.7 mm, coupled to a two-stage gearhead with a 19:1 reduction ratio. A Heidenhain MT60K linear incremental encoder with an EXE102 interpolation unit is employed as a feedback sensor, enabling a 25 nm measurement resolution. An SKF SH ball screw with a 2 mm pitch, supported on two SKF 618/4 ball bearings, is used to convert rotational to translational movements. The translating elements are supported by two Schneeberger MN7 linear guideways with an overall width of 8 mm and height of 17 mm. The control algorithms are programmed as Virtual Instruments (VI) in the LabVIEW environment and exported to National Instruments' (NI) FPGA 7833R real-time module. Finally, a Lasertex LSP30-3D Michelson-type laser Doppler interferometric system is used to independently assess the achieved positioning accuracy and repeatability.

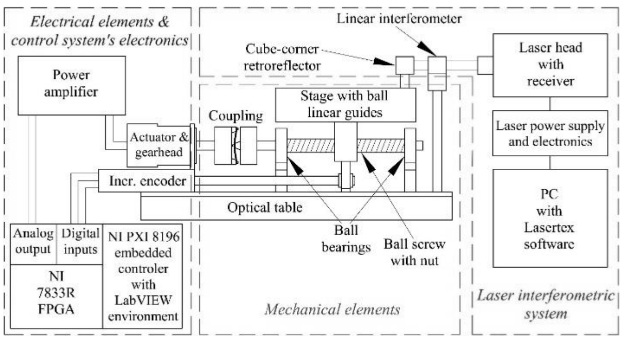

Figure 1. Simplified scheme of the considered positioning system.

To enable the modelling of frictional disturbances in the system, the parameters of the GMS model are experimentally identified separately for the DC actuator-gearhead assembly and for the stage. In fact, a continuous GMS function describes friction in both motion regimes, encompassing the elasto-plastic nonlinear behaviour with non-local memory and hysteresis in pre-sliding, stick-slip and the Stribeck curve with frictional lag. The model is based on a parallel connection of massless elementary slip blocks with a common input velocity and having as output the friction force. It is hence established that, due to reduction ratios, friction of the mechanical components, when reduced to the shaft of the actuator, will be comparable to the variability of friction in the actuator itself, i.e. the biggest frictional contribution is that of the actuator. Moreover, even when the actuator-gearhead assembly enters sliding, the downstream mechanical elements will still be in pre-sliding [5].

3. Ultra-high precision positioning

In a first instance, a discrete PID controller, thoroughly described in [6], with a 100 µs sample time, is used. The parameters of the controller are optimized via the developed MATLAB/SIMULINK model so to ensure the stable behaviour of the system; positive phase and gain margins of, respectively, at least 30° and 10 dB are hence achieved in all considered cases. As depicted in Fig. 2, an additional disturbance-based feed-forward control structure, based on the GMS friction parameters, is added next to the PID structure. Although being model-based, this controller proves to be computationally complex and is prone to overloading problems related to the limited number of logic blocks available in FPGA. An STR PID control structure suggested in [7] is finally employed to adapt on-line and in real-time the PID gains so as to compensate the changes of all the frictional effects and other eventual external disturbances that cannot be predicted in advance (Fig. 3). The adaptation of the parameters of the regulator is reduced in this case to an algorithm based on a single adaptation coefficient and the outputs of the considered subsystems [7], making its implementation quite straightforward. The controller is hence tuned via the MATLAB/SIMULINK model so that the values of its gains never approach those leading to a possible occurrence of instabilities.

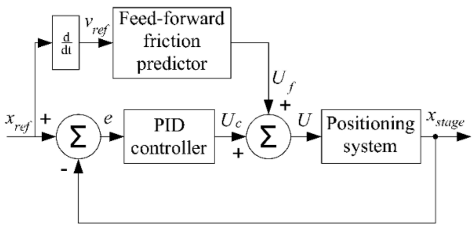

Figure 2. PID controller and additional feed-forward control block.

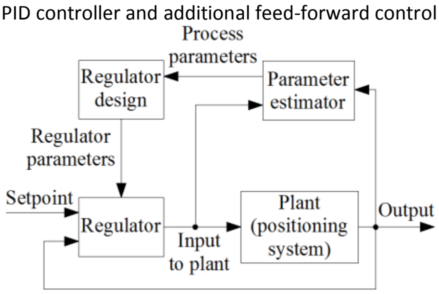

Figure 3. Scheme of adaptive STR controller.

Employing the different considered control typologies, a sinusoidal excitation with varying amplitudes from 1 µm to 1 mm and with varying frequencies is hence applied to the used mechatronics system. Trajectory deviations of results attained via experiments and by using the MATLAB model are related to the reference signal. In table 1 is thus reported a typical set of tracking deviations obtained by using the outlined control approaches for a 10 µm reference signal. It can hence be observed that STR adaptive control allows achieving the lowest tracking deviations, efficiently compensating all the stochastic variabilities of friction, as well as avoiding the need of repetitively tuning the gains of the PID controller and the complexity of the feed-forward control scheme. The STR regulator is therefore finally used in point-to-point positioning of the micromanipulation device for short-range (micrometric) and long-range (millimetre) positioning steps. The obtained results for a 10 µm positioning step, as measured via Heidenhain feedback sensor, are shown in Fig. 4. It is hence evident that the adaptive nature of the used controller allows compensating all the mechanical nonlinearities and their variabilities, permitting to achieve positioning precisions limited only by the resolution of the used feedback sensor, i.e. in a truly nanometric domain. The correspondingly achieved performances, measured independently via the interferometric system, encompassing hence effects and errors that cannot be detected and compensated by the control system, allow establishing that the achieved precision and accuracy (calculated according to the ISO 230-2:2014 standard) are better than 250 nm.

Table 1. Tracking deviations for a 10 µm sinusoidal reference signal.

Tracking deviations/nm	
PID	950
PID + feed-forward	500
STR	180

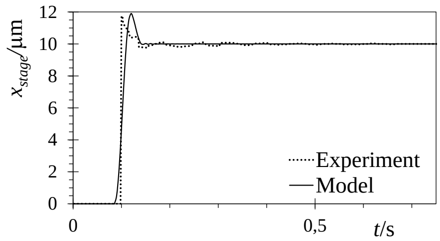

Figure 4. 10 µm point-to-point positioning with STR adaptive control.

4. Conclusions and outlook

One axis of a multi-DOF ultra-high precision positioning system is analysed in this work. Frictional effects are modelled via the integrated GMS model, which allows implementing different compensation approaches. Tracking deviations resulting from sinusoidal excitations permit establishing that the considered STR adaptive control scheme efficiently compensates on-line the nonlinear stochastic frictional effects. This controller is therefore used in the final repetitive unidirectional point-to-point short-range (where the motion is in pre-sliding regime) and long-range (where the system undergoes both sliding and pre-sliding effects) positioning. The experimentally achieved precision and accuracy are comparable to the nanometric resolution of the used feedback sensor while these values, validated externally via the interferometric system, are better than 250 nm.

In future work, the authors plan to investigate the possibility to use also other types of actuators (e.g. stepper motors, voice-coils) and of feedback transducers (e.g. linear variable differential transformers) i.e. to assess the full operability of the considered multi-axes micropositioning mechatronics systems in its foreseen application of handling and assembly of microparts. The option to incorporate the laser interferometric system in the feedback loop, in order to enhance the achievable performances, will also be considered.

Acknowledgements

Work enabled by using the equipment funded via the ERDF project RC.2.2.06-0001 “RISK” and supported by the University of Rijeka grant 13.09.1.2.09 “Characterisation and Modelling of Materials and Devices for Innovative Applications”.

References

[1] Schmidt R M, Schitter G, Rankers A and van Eijk J 2014 *The Design of High Performance Mechatronics* 2nd ed. (Delft, NL: U Press)
[2] Al-Bender F, Lampaert V and Swevers J 2005 *IEEE T. Automat. Contr*. **50**(11) 1883-7
[3] Yoon J Y and Trumper D L 2014 *Mechatronics* **24**(6) 734-41
[4] Zelenika S and De Bona F 2009 *J. Mech. Eng. Sci.* **223**(C8) 1955-63
[5] Zelenika S and Kamenar E 2016 *P2.14 in these proceedings*
[6] Kamenar E and Zelenika S 2013 *Proc. 37th MIPRO* (Opatija) 138-43
[7] Lin F, Brandt R D and Saikalis G S 2000 *Proc. American Control Conf.* **5** (Chicago, IL, USA) 3676-81