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Koopman-based model predictive control of a nanometric positioning system

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Abstract
Nonlinear frictional disturbances limit the performances of high-precision mechatronics systems. Recently it was shown that nanometric positioning can be achieved only if these disturbances are identified, modelled and compensated for via suitable control approaches. A PID controller, complemented with feed-forward based on the Generalized Maxwell-slip model, allows hence to achieve nanometric positioning but its real-time implementation is difficult, whereas a self-tuning regulator enables nanometric positioning with a marked overshoot. Koopman-based model predictive control (MPC) is applied in this work instead. This approach allows "lifting" the nonlinear dynamics of the considered device into a higher dimensional space where its behaviour can be predicted by a linear system; the computational complexity of the thus obtained controller is hence comparable to that of equivalent linear controllers. The resulting positioning performances are evaluated numerically in the MATLAB/Simulink environment and compared to those when the mechatronics device is driven by using different controllers. It is thus shown that the Koopman-based MPC virtually eliminates steady state errors, decreases the settling time and results in very small overshoots.

Nonlinear disturbances, nanometric positioning, Koopman-based model predictive control, modelling and validation

1. Introduction

Nanometric positioning devices are key components in microsystems' technologies and precision engineering in general. The mechanical elements used in these devices are characterized, however, by sliding and rolling frictional disturbances which limit positioning performances and are characterised by a marked stochastic behaviour. Although the influence of friction can be reduced in the design phase, its detrimental effects, in the form of steady-state errors, limit cycles, stick-slip and large settling times, still generally persist. If nanometric positioning precision and accuracy is aimed for, frictional disturbances have thus to be identified, modelled and compensated for via appropriate control methodologies [1].

A translational axis of a factual nanometric positioning system is analysed in this work. The device is driven by a brushed DC motor coupled to a 19:1 gearhead, its translating elements are supported onto linear guideways, while the feedback is attained by employing an incremental encoder that, with interpolation, enables a 25 nm resolution [1]. The system is characterized by multiple frictional sources and pre-sliding and sliding motion regimes, which are modelled via the integrated state-of-the-art Generalised Maxwell Slip (GMS) model that allows describing reliably all the most important frictional properties [2]. Separate friction blocks, whose characteristic parameters were experimentally identified in a previous work [1], are thus used to model the friction of the actuator-gearhead assembly and that of the linear guideways. In [1], different control approaches were employed to compensate the frictional disturbances: a discrete PID controller, PID coupled with an additional feed-forward (FF) GMS model-based compensator, and an adaptive self-tuning regulator (STR). The hence obtained results were validated both via simulations and experimentally. It was therefore shown that STR allows compensating efficiently the stochastic frictional disturbances of the considered system, thus allowing to attain precision and accuracy, calculated according to ISO 230-2, better than 250 nm. STR control allows also avoiding problems related to the difficult real-time implementation and the slow dynamics of the PID regulator complemented with feed-forward. In point-to-point experiments, STR gives, however, rise to an overshoot of up to 20 %, which could cause problems especially in the vicinity of the mechanical limits of the considered device.

With the aim of comparing the results attained by employing STR, as representative of state-of-the-art adaptive control, with innovative optimisation-based model predictive control (MPC) algorithms, Koopman-based MPC is used in this work. This approach allows validating the possibility to simplify the modelling of the considered nonlinear dynamic system while still successfully compensating the frictional effects, but also, implicitly, trying to reduce the residual overshoot obtained when using STR. The resulting performances of the studied mechatronics system in tracking and point-to-point positioning are thus evaluated numerically in the MATLAB/Simulink environment and compared to those of other considered control typologies. The results show hence that Koopman-based MPC is efficient in eliminating steady state errors as well as in reducing substantially overshoot and settling times.

2. Koopman model predictive controller

A set of linear predictors is applied in this work to estimate the behaviour (i.e. the future states) of the considered nonlinear dynamic ultra-high precision positioning system. In fact, recently the Koopman operator, whose numerical approximations allow "lifting" the nonlinear dynamics of the considered device (i.e. of its state-space model) into a higher dimensional space – where its behaviour can be accurately predicted by a linear system, was extended to controlled dynamic systems [3]. This scheme depends on the current state and the current and future inputs to the system, i.e. it is data-driven (it doesn't require a model) and practically reduces to a nonlinear transformation of the data (the lifting) and a linear least squares problem in the lifted space. The thus obtained linear predictors have shown superior prediction performances compared to other linear predictors (e.g. those based on local linearization). What is more, the obtained predictors were also successfully used in the design of MPCs for nonlinear dynamic systems, with the resultant computational complexity comparable to that of MPCs for linear dynamic systems of the same size [3].

The Koopman-based procedure is hence followed in the herein investigated cases to track the position of the used mechatronics device. The open-loop response of the nanopositioning device, modelled in the MATLAB/Simulink environment, obtained for a random input with all the frictional contributions taken into account via GMS blocks, is shown in Fig. 1. It can thus be inferred that the Koopman-based scheme indeed accurately follows the dynamics of the system.

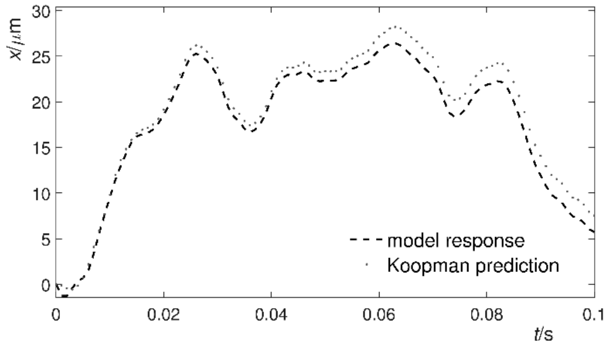

Figure 1. Validation of prediction performances of the Koopman-based scheme.

3. Numerical validation

The MATLAB/Simulink model is used next to track the closed-loop responses of the used mechatronics system while controlled with the considered control typologies (PID, PID + FF, STR and Koopman-based MPC). The sampling time is set to 1 ms. Tracking of sinusoidal excitations with varying amplitudes and frequencies is hence validated. As shown in Fig. 2, the largest tracking error is induced by the PID controller. When a FF term is added, the tracking error is reduced but the parameters of the PID have still to be adapted to each excitation condition, while the slow dynamics of the controller limits its real-time implementation. When STR and Koopman MPC are used, the tracking errors are significantly reduced in all considered cases. It is evident, however, that STR tracks better the reference signal at direction reversals, whereas in these points the MPC controller, with the cost function matrices set to $Q = 0.1$, $Q_{Np} = 0.2$ and $R = 4$ [3], results in “glitches”. However, in the here performed simulations, the lifting map is a simple delay embedding [3], so that presumably a more elaborate choice of this map could eliminate the glitches.

In the next step, point-to-point positioning simulations are performed for short-range (10 μm) and long-range (1 mm) positioning steps. Given the previous results, in Fig. 3 are depicted only the results attained by employing STR and Koopman-based MPC. In this case the parameters of the MPC have to be optimised again, resulting in cost function matrices $Q = 0.1$, $Q_{Np} = 3.5\cdot10^{-6}$ and $R = 3.555$; once optimised, these are valid for all the considered reference position magnitudes. The used prediction horizon is set to 50 ms. The results shown in Fig. 3 allow thus evidencing that with both control algorithms the steady state error is eliminated, while the rise times are similar. Nonetheless, when using the Koopman-based MPC the overshoot is reduced to a value < 2 % of the reference position (i.e. by ca. 10 times w.r.t. the STR values). Koopman-based MPC is characterised also by shorter settling times.

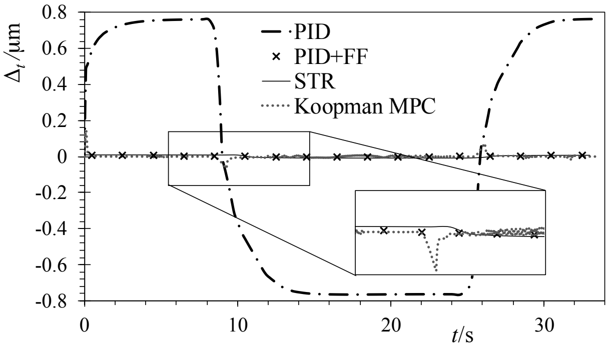

Figure 2. Tracking errors for a 10 μm sinusoidal excitation and different controllers.

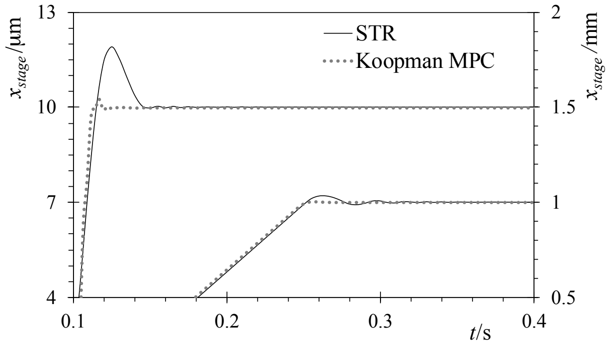

Figure 3. Numerical validation of point-to-point responses.

4. Conclusions and outlook

The data-driven Koopman-based MPC is used in this work to compensate the frictional disturbances of a nanometric positioning system, since it allows “lifting” the nonlinear system’s dynamics into a higher dimensional space where its behaviour can be accurately predicted by a linear system. The controller is numerically validated in MATLAB/Simulink. It is hence proven that it assures an excellent dynamic tracking of the behaviour of the system even when the latter is randomly excited. By comparing the performances of the Koopman-based MPC to those attained via other relevant control approaches, it is, in turn, concluded that, irrespective of the excitation amplitudes, MPC virtually eliminates steady state errors and is characterised by very small overshoots and reduced settling times, but gives rise to potential “glitches” at direction reversals.

In the follow-up of the work, the Koopman-based MPC will hence be used to control the actual mechatronics system, i.e. it will be implemented in the NI LabVIEW software and transferred onto the real-time NI FPGA control hardware. Given the stochastic nature of the frictional disturbances, special attention will be dedicated in this framework to the efficient real-time computation of the quadratic optimization problem and to the evaluation of the lifting mapping in each time-step of the closed-loop control [3]. The thus attained accuracy and precision of the nanometric positioning device, measured by using a laser interferometric system, will finally be quantified according to the ISO 230-2 machine tools’ standard.

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