PID-based learning control for frictional motion systems

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Summary. Classical PID control is exploited widely in industrial motion systems suffering from dry friction. This is motivated by the easy-to-use design tools available. However, friction-induced limit cycling (i.e., *hunting*) is observed when integral control is employed on frictional systems that suffer from the Stribeck effect, thereby compromising setpoint stability. In addition, the resulting time-domain behavior, such as, e.g., rise-time, overshoot, settling time, and positioning accuracy, highly depends on the particular frictional characteristic, which is typically unknown or uncertain. On the other hand, omitting integral control can lead to constant non-zero setpoint errors (i.e., *stick*). To achieve superior setpoint performance for frictional motion systems in a repetitive motion setting, we propose a PID-based feedback controller with a *time-varying* integrator gain design. To ensure optimal setpoint positioning accuracy, a data-based sampled-data extremum-seeking architecture is employed to obtain the optimal time-varying integrator gain design. The proposed approach does not rely on knowledge on the friction characteristic. The effectiveness of the proposed approach is evidenced experimentally by application to an industrial nano-positioning motion stage set-up of a high-end electron microscope.

Introduction

The vast majority of the high-precision industry employs classical PID control, since control practitioners are often well-trained in linear control design (loop-shaping). Moreover, it is well-known that integral action in PID control is capable of compensating for *unknown* static friction in motion systems. However, friction-induced limit cycling (i.e., *hunting*, see [1]) is observed when integral control is employed on systems where the friction characteristic includes the velocity-weakening (Stribeck) effect, so that stability of the setpoint is lost. Even if stability can be warranted, rise-time, overshoot, settling time (see [2]), and positioning accuracy depend on the particular friction characteristic, which is highly uncertain in practice. Hence, despite the popularity of the PID controller in industry, friction is a performance- and reliability-limiting factor in PID-controlled motion systems.

In this work, we propose a PID-based learning controller in order to achieve a high setpoint accuracy for repetitive tasks in motion systems subject to unknown static and velocity-dependent friction, including the Stribeck effect. The PID-based learning controller consists of two elements. First, a PID control architecture with a *time-varying integrator gain* design is proposed, facilitating a tailored design such that friction-induced limit cycles can be avoided, and high accuracy repetitive setpoint positioning can be achieved instead. In addition, similar robustness properties as for the classical PD control at the desired setpoint can be achieved. Second, a sampled-data extremum-seeking architecture (see [3]) is proposed, in order to iteratively find the optimal time-varying integrator gain, in the presence of unknown friction. The effectiveness of the proposed approach is evidenced experimentally by application to an industrial nano-positioning motion stage set-up of a high-end electron microscope

Control problem formulation for frictional motion systems

Consider a single-degree-of-freedom motion system, consisting of a mass m sliding on a horizontal plane, with measurable position x_1, velocity x_2, control input u_c, and subject to a friction force F_f. The friction force F_f takes values according to the set-valued mapping of the velocity $x_2 \rightrightarrows \Phi(x_2)$. The set-valued friction characteristic Φ consists of a Coulomb friction component with (unknown) static friction F_s, a viscous contribution γx_2 (where $\gamma \geq 0$ is the viscous friction coefficient), and a (unknown) nonlinear velocity-dependent friction component f, encompassing the Stribeck effect, i.e.,

$$F_f \in \Phi(x_2) := -F_s \text{Sign}(x_2) - \gamma x_2 + f(x_2), \tag{1}$$

The dynamics are governed by the following differential inclusion:

$$\dot{x}_1 = x_2,\ m\dot{x}_2 \in \Phi(x_2) + u_c. \tag{2}$$

We focus on achieving high-accuracy positioning for frictional motion systems that perform a T*-repetitive* motion. We consider, for the position x_1, a desired repetitive reference r, defined on the time interval $[0, T]$, where the system starts and ends at rest and define two particular time intervals; 1) the interval $t \in [0, T_B)$ during which the system is allowed to move from 0 to r, and 2) the interval $t \in [T_B, T]$, during which standstill at r is required. The time interval $[T_B, T]$ is typically used by the industrial machine, of which the motion system is part, to perform a certain machining operation, for which accurate positioning is required. We address the following setpoint control problem: *Design a PID-based control strategy for motion systems of the form* (2), (1)*, that perform a repetitive motion profile and are subject to unknown static and velocity-dependent friction, such that high-accuracy setpoint positioning during the standstill time window is achieved.*

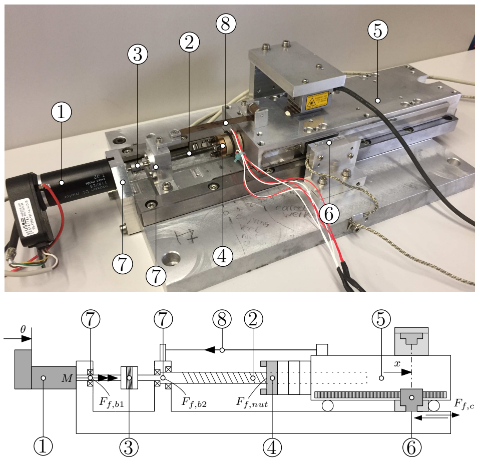

Figure 1: Nano-positioning motion stage set-up: ① Maxon RE25 DC servo motor, ② spindle, ③ coupling, ④ nut, ⑤ carriage, ⑥ linear Renishaw encoder, ⑦ bearings, ⑧ coiled spring.

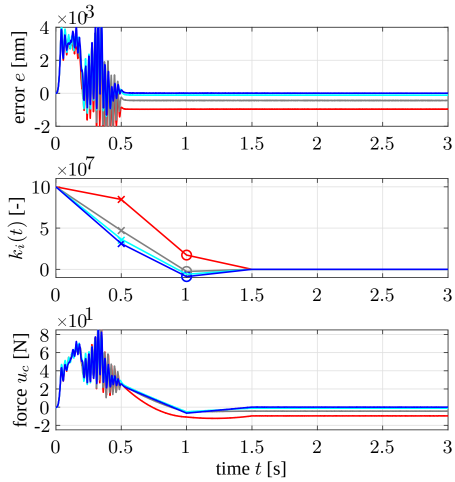

Figure 2: Experimental results that show the error and corresponding $k_i(t)$ and u_c after the initial parameter setting $u_0 = [0.85,\ 0.175]^\top \cdot 10^8$ (—), the 2nd (—), 4th (—), and 7th (—) extremum seeking controller update, leading to an achieved setpoint accuracy of about $4 - 6$ nm.

A time-varying integrator gain design for PID-based control of frictional motion systems

Limit-cycle behavior present in the case of PID control with *constant* integrator gain is caused by the build-up of integrator action (during transients and the stick phase) in interplay with the friction characteristic, see, e.g., [1]. This observation motivates the design of a novel *time-varying* integrator gain $k_i(t)$ for point-to-point motion, namely: 1) the presence of integrator action still allows the system to escape undesired stick phases, 2) overcompensation of friction due to, e.g., a severe Stribeck effect, can be avoided, by altering $k_i(t)$ during the slip phase, and 3) zero integral action can be enforced at the setpoint when standstill of the system is required, such that robustness against other force disturbances is provided by the static friction. The resulting controller is then given by $u_c = k_p e + k_d \dot{e} + k_i(t) x_3,\ \dot{x}_3 = \varsigma(t) e$, with $\varsigma(t) \in \{0, 1\}$ a to-be-designed switching function that prevents uncontrolled growth of x_3. We are able to 1) escape undesired stick phases by enabling $k_i \neq 0$ and $\varsigma(t) = 1$ during $t \in [0, T_B]$, and 2) create robustness to other force disturbances close to the setpoint, by enforcing $k_i = 0$ and $\varsigma = 0$ during $t \in [T_B, T]$. Thereto, we parametrize $k_i(t) = \sum_{j=1}^{6} [v^{(j)}\ v^{(j+1)}] \Psi^{(j)}(t)$ by linear spline basis functions $\Psi^{(j)}(t)$, with $v^\top = [1 \cdot 10^8\ u_0^\top\ 0^{1\times 4}]$, and u_0 a to-be-optimized parameter vector.

PID-based learning control for an industrial nano-positioning motion stage

The working principle and the effectiveness of the proposed PID-based controller are demonstrated on an industrial nano-positioning stage, representing a sample manipulation stage of an electron microscope, exhibiting significant and unknown frictional effects. The experimental setup and a schematic representation are presented in Fig. 1. A sampled-data extremum-seeking architecture (see, [3]) is used to iteratively find a time-varying integrator gain design $k_i(t)$, ultimately leading to a position error in the range of $4 - 6$ nm, depicted by (—) in Fig. 2. In contrast, the classical PID controller for this particular set-up yields an absolute error of about 100 nm on the same time interval, and does not provide robustness during the standstill time window. This clearly illustrates the performance benefits of the proposed PID-based learning controller in terms of the ability to cope with Stribeck friction and achieving superior setpoint positioning accuracy.

Conclusions

We have presented a novel time-varying integrator gain design for motion systems with unknown Coulomb and velocity-dependent friction, capable of achieving a high positioning accuracy, in contrast to classical PID control, which often leads to limit cycling. The optimal time-varying integrator gain is iteratively obtained by employing a sampled-data extremum-seeking architecture. The superior performance of the proposed control architecture over classical PID control is experimentally demonstrated on a nano-positioning stage of an electron microscope.

References

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