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System identification and control parameter optimization for a stylus profiler with exchangeable cantilevers

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ABSTRACT

Stylus instruments are widely used in production metrology due to their robustness. Interchangeable cantilevers allow a wide range of measuring tasks to be covered with one measuring device. When approaching the sample, the positioning of the stylus instrument tip relative to the measurement object has to be accomplished in a controlled way in order to prevent damages to the specimen and the stylus cantilever. This is achieved by a closed-loop control. We present a method for the objective description of the stylus cantilever dynamics with system-theoretical techniques and show a simple iterative approach to optimize closed-loop control parameters with boundary conditions.

1. Introduction

The characterization of technical surfaces on the microscale is a crucial task in the quality control of high-end components in a variety of industrial fields. The micro-geometry in terms of surface structures and roughness has an important influence on functionality and durability of the component [1]. Current measurement instruments for the geometric characterization are generally divided by their measurement principles into optical and tactile devices.

While optical profilers like the white-light interferometer or the confocal microscope [2] offer certain advantages over tactile instruments, for example high amount of (three-dimensional) measurement data at high speed, they reach their limit at measurement objects with large local height gradients [3], large amplitudes and optically uncooperative materials. In addition, due to small measurement fields, optical topography measurement devices may not always reach the required profile length, which inhibits the evaluation of 2D-roughness parameters Ra, Rz and Rk [4]. Further, optical devices react sensitively to environmental influences such as a contamination of the specimen or vibrations [5] resulting in artefacts.

Tactile instruments however, i.e. stylus instruments, offer a robust measurement principle, and hence are widespread not only in laboratory conditions, but also in production environments [6]. With Stylus instruments, a broad range of measurement tasks can be fulfilled easily by exchanging the cantilever, for example for upside down measurements, or measurements in drill holes. On the other hand, stylus instruments have certain limitations [7]. The lateral resolution is limited by the size of the stylus tip [8] and the measurement speed is restricted in order to maintain the contact between tip and the surface. The physical contact further results in wear of the tip and may even cause damage to the cantilever and the specimen in case of collisions or uncontrolled positioning of the stylus tip on a measurement object [3].

Thus, it must be ensured by a closed-loop controller that positioning follows a defined trajectory, in order to avoid uncontrolled contact with the specimen. For state-of-the-art stylus instruments a certain range of exchangeable cantilevers exist, for which individual closed-loop positioning parameters have to be identified in order to achieve optimal performance of the stylus instrument. These control parameters must also be adapted to customers' special requirements, for example when the cantilever is being used vertically, rotated by 90°. Since the parametrization task is performed manually by experts, it is time consuming and requires a high degree of experience. Furthermore, it is subjectively dependent on the operator and not objectively traceable. While stylus devices and controller optimization are well known in literature and have been studied for a long time, the parameterization of the controllers on the stylus instrument is a special task for which no literature is found.

The aim is therefore to develop an algorithm, which automatizes the parameterization of the cantilever positioning control. The resulting controller parametrization must be simple, robust

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and optimal regarding boundary conditions (i.e. overshooting behavior, settling time and limit oscillation) [9–11]. Existing techniques for automated controller optimization [12,13], are not feasible for this specific task with its specific boundary conditions, or are too complicated for industrial acceptance.

Thus, a simple approach is suggested: The first step for the automated optimization of control parameters is the identification of the system dynamics, which allows for the quantitative description and evaluation of a set of control parameters. Here, a simple mechanical model is being used. Secondly, based on the determined dynamics of the system, an iterative approach for the identification of optimized control parameters, similar to a gradient descend algorithm [14], is being formulated. The approach is verified on three different cantilevers and results are discussed.

2. Simple dynamic model of the system behavior of stylus instruments

In order to describe and quantify the dynamics of the cantilever, a simple model is created for a stylus profiler. The model allows for the description of the dynamics of a cantilever, depending on the parameterization, using the eigenvalues of the resulting closed system. The eigenvalues are the basis for the optimization problem (Section 4).

The motion of a cantilever of a stylus instrument can be approximated with the physical model of a pendulum with the angular displacement $\varphi(t)$. It can be described by a differential equation of second order, which is excited by an external moment $M(t)$ affecting the pendulum [15] such that:

$$\theta\ddot{\varphi}(t) + d\dot{\varphi}(t) + mgl\sin(\varphi(t)) = M(t) \tag{1}$$

The quantity θ denotes the moment of inertia of the cantilever, d is the damping caused by the bearing and the term mgl describes the moment resulting from the weight of the cantilever. $\dot{\varphi}(t)$ is the first derivative of $\varphi(t)$ with respect to time (cp. Fig. 1). The cantilever

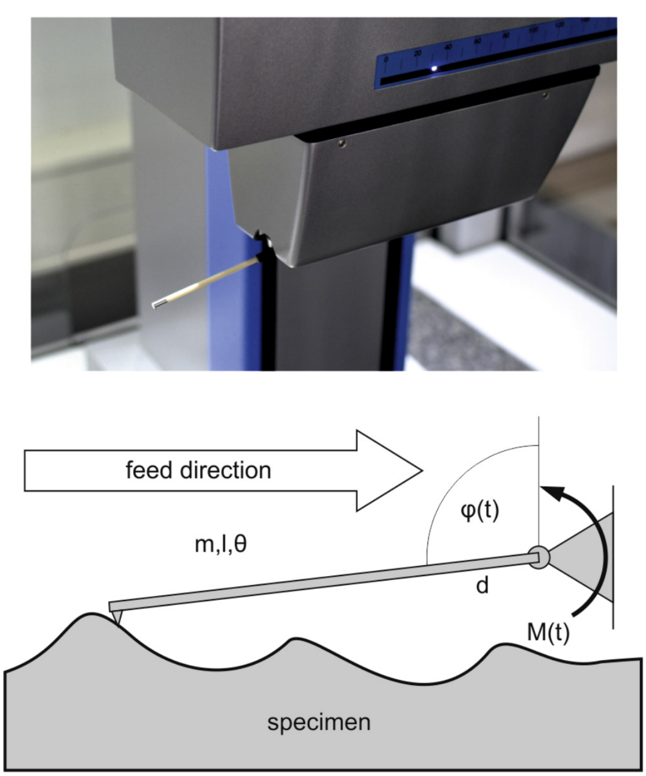

Fig. 1. Cantilever of a stylus instrument (above) and a simple physical model of it (below).

operates around a stable working point φ_0. The objective is to position the cantilever in a way, that it reaches its target position fast and without overshoot. Overshooting must be prevented, due to possible damage of the stylus tip or the specimen.

The angular position control, which computes the external momentum $M(t)$ consists in this case of a feed forward term $M_{FF}(\varphi_0)$ for the compensation of weight force and a PID (Proportional-Integral-Derivative) controller term $M_{Ctrl}(t)$ for the compensation of disturbances around the working point [16]. The coordinate system is rotated such that $\varphi_0 = 0$. The resulting momentum of the controller applied to the systems is then:

$$M(t) = M_{FF}(\varphi_0) + M_{Ctrl}(t)$$
$$= \overbrace{mgl\sin(\varphi_0)}^{M_{FF}(\varphi_0)} + \overbrace{k_P(\varphi(t)-\varphi_0) + k_I\int(\varphi(t)-\varphi_0)dt + k_D\dot{\varphi}(t)}^{M_{Ctrl}(t)} \tag{2}$$

The values k_p, k_I and k_D specify the proportional, integral and derivative PID-closed loop control parameters. The substitution of Eq. (2) in Eq. (1) with the assumption of small deflection around the working point $(\Delta\varphi(t) = \varphi(t) - \varphi_0 \approx 0 \rightarrow \varphi(t) \approx \varphi_0; \Delta\dot{\varphi} = \dot{\varphi})$ allows for neglecting the weight force in the following, since the feed forward term cancels out the weight force:

$$\theta\ddot{\varphi}(t) + d\dot{\varphi}(t) + \overbrace{mgl\sin(\varphi(t)) - mgl\sin(\varphi_0)}^{\approx 0}$$
$$= \overbrace{k_P(\varphi(t)-\varphi_0) + k_I\int(\varphi(t)-\varphi_0)dt + k_D\dot{\varphi}(t)}^{M_{Ctrl}(t)}$$

The integral behavior allows for the system to be controlled with a Proportional-Derivative-Controller (PD-Controller), without remaining control deviation. Thus k_I is omitted. The closed-loop system behavior is then described by a PT2-system:

$$\theta\Delta\ddot{\varphi}(t) + (d - k_D)\Delta\dot{\varphi}(t) - k_P\Delta\varphi(t) = 0 \tag{3}$$

There are different solutions for $\Delta\varphi(t)$ in Eq. (3) based on the choice of parameters and initial conditions. Under the premise of stability and the assumption of an impulse excitation, solutions of Eq. (3) are the underdamped (Eq. (4)), critically damped (Eq. (5)) and overdamped oscillation (Eq. (6)):

$$\varphi_{under}(t) = x_0 \cdot e^{-\delta \cdot t} \cdot cos(\omega_d \cdot t + \Phi_0) \tag{4}$$

$$\varphi_{crit}(t) = \frac{A \cdot (t - t_0)}{c^2} \cdot e^{(-(t-t_0)/c)} \tag{5}$$

$$\varphi_{over}(t) = C_1 \cdot e^{\lambda_1 t} + C_2 \cdot e^{\lambda_2 t} \tag{6}$$

The parameters x_0, Φ_0, A, C_1, C_2, t_0 describe initial conditions.

δ, ω_d, c, λ_1, λ_2 specify the system dynamics. Example curves for Eqs. (4)–(6) are given in Fig. 2. Looking at the impulse excitation as representative dynamics offers certain advantages: Other responses used for system characterization, like the step response or the frequency response can be obtained from the impulse response by convolution. Therefore, provided that the system behavior is linear, the impulse response is sufficient to describe the system.

The stability of Eq. (3) can be analyzed according to system theory by means of Laplace-Transformation, calculation of the transfer function and evaluation of the poles in the denominator. Alternatively, Eq. (3) can be converted into its state space representation, where stability and dynamics are given by the absolute value and angle of the complex eigenvalues $\lambda_{1,2}$ of the system matrix, with Eqs. (3)–(6):