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Adaptive inverse control of a galvanometer scanner considering the structural dynamic behavior

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ABSTRACT

In industrial applications, scanner systems are utilized for several operations, but do not always meet the desired dynamics. Various controller-based approaches, which concentrate on simple trajectories or changes in operation points, have been presented within the last years; however, these are not sufficient for many production processes. In this paper, adaptive inverse control is utilized to enhance the scanner's dynamics. The influence of structural dynamics is compensated by taking the behavior of the galvanometers' mirrors into account. The performance of the new approach is verified by experimental results, reducing the optical error by almost 95% compared to current scanner systems.

1. Introduction

Galvanometer laser scanners are utilized in many applications in order to position a laser beam within a 2-dimensional area [1]. This is done by deflecting the beam using two mirrors, which are positioned orthogonally to each other. The mirrors are mounted to and driven by galvanometers, giving the device its name. The areas of application range from production engineering, e.g. remote laser cutting [2] and additive manufacturing [3], to microscopic examinations [1]. Although a scanner is one of the fastest systems applied in production engineering, several modern processes require an even faster beam movement. Thus, to enhance the system dynamics, various controller and model designs have been presented over the past few years [4].

To encounter plant perturbations, caused by environmental as well as process influences, and variations in the manufacturing of the system many of these recently developed controllers are adaptive [5,6,7]. Because of the wide range of scanner applications, controllers are adapted to suit the particular use cases. Simple trajectories (e.g. triangle and sinusoidal signals), as applied in microscopy, are encountered in Ref. [5]. The authors designed a Smith predictor-based adaptive sliding mode controller and combined it with an internal model principle. The presented approach is able to handle model mismatches and has a significantly better performance compared to a traditional PI(D) controller. Due to fast movement and complex trajectories the structural dynamics have a strong impact on the overall behavior. These factors are considered in Ref. [6] within an appropriate model and approached by an adaptive deadbeat feedforward compensator. By varying the system's temperature, the ramifications of gain as well as resonant frequency perturbations are presented, showing the suitability of adaptive controllers. The developed controller is able to handle these perturbations in a robust way, but only for the galvanometer's sensor signal. The behavior of the mirror, which is on the opposite side of the galvanometer axis, remains unconsidered. In Ref. [7] the dynamics are also enhanced by an adaptive controller; however the mirror's behavior is ignored here as well, although it is essential for operation. To make up for this, the authors of Refs. [8] and [9] present an iterative learning approach to countervail this non-collocation of the position sensor and the laser deflecting mirror. The resulting controller achieves high speeds, but is only valid for one specific trajectory because of its iterative characteristics. Thus, whenever an alteration occurs, parameters have to be readjusted. A more universal method for trajectory tracking is presented in Ref. [10]. The approach is valid for any trajectory, but is not adaptive and consequently not capable to handle system perturbations or parameter changes.

In contrast to the presented algorithms, this paper introduces a novel approach of adaptive inverse control (AIC) for galvanometer laser scanners. The dynamics are enhanced and the position error is reduced. To consider the non-collocation of sensor and mirror, a photographic analysis of the laser movement is applied.

2. Adaptive inverse control (AIC) of laser scanners

2.1. System adaption of one axis

The output of a tapped delay filter g_k is calculated by the scalar product of two vectors:

$$g_k = \boldsymbol{w}^T \boldsymbol{x}_k = [w_1\ w_2\ \dots\ w_n]^T [x_{1k}\ x_{2k}\ \dots\ x_{nk}]. \quad (1)$$

The n-dimensional vectors $\boldsymbol{w}$ and $\boldsymbol{x}_k$ represent the filter coefficients (FIR-filter) and the input signal vector, respectively. Thereby, x_{1k} is the current input signal f_k, and x_{2k} is the input signal delayed by one sample f_{k-1}. If the filter is meant to map the transfer behavior of a given system

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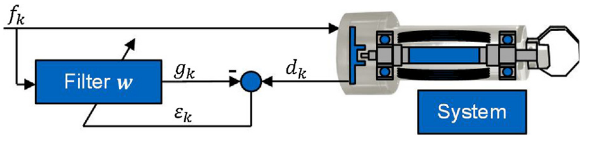

Fig. 1. Adaption of a digital filter.

(e.g. an axis of a scanner), the error $\varepsilon_k = d_k - g_k$ between the system's output d_k and the filter's output g_k has to be calculated (see Fig. 1). An error of $\varepsilon_k = 0$ corresponds to a perfect filter, which represents exactly the system's impulse response with an input magnitude of 1. To determine this perfect filter, the cross-correlation vector of the system's input and output $\boldsymbol{p}$ as well as the autocorrelation matrix of the system's input $\boldsymbol{R}$ are necessary. They can be calculated by

$$\boldsymbol{p} = E[d_k \boldsymbol{x}_k], \quad \boldsymbol{R} = E[\boldsymbol{x}_k \boldsymbol{x}_k] \tag{2}$$

and applied to express the mean square error (MSE)

$$\xi = E[\varepsilon_k \varepsilon_k] = E[d_k d_k] - 2\boldsymbol{p}^T \boldsymbol{w} + \boldsymbol{w}^T \boldsymbol{R} \boldsymbol{w} \tag{3}$$

according to Ref. [11]. The minimal MSE, which results in the best system approximation $\boldsymbol{w}^*$, can be attained by setting its gradient vector ∇ to $\boldsymbol{0}$:

$$\nabla = \begin{bmatrix} \frac{\delta E[e_k^2]}{\delta w_1} \\ \vdots \\ \frac{\delta E[e_k^2]}{\delta w_n} \end{bmatrix} = \begin{bmatrix} \frac{\delta \xi_k}{\delta w_1} \\ \vdots \\ \frac{\delta \xi_k}{\delta w_n} \end{bmatrix} = -2\boldsymbol{p} + 2\boldsymbol{R}\boldsymbol{w} = 0. \tag{4}$$

For the determination of the optimal filter $\boldsymbol{w}^* = \boldsymbol{R}^{-1}\boldsymbol{w}$ (Wiener solution [11]) the matrix $\boldsymbol{R}$ has to be invertible. This solution is static and requires great computational effort. Thus, it is not suitable for a high-frequency controlled system such as that of a scanner. A more efficient and also adaptable approach is to utilize the method of steepest descent, for which an initial filter $\boldsymbol{w}_0$ is necessary. Here, $w_0 = [10 \; \ldots \; 0]$ was chosen. The filter for the next time step $k + 1$ is adapted by

$$\boldsymbol{w}_{k+1} = \boldsymbol{w}_k + \mu(-\nabla_k), \tag{5}$$

where ∇_k is the gradient vector of the kth time step and μ is a manually chosen adaption parameter. The adaption parameter is responsible for stability as well as convergence and was set for the subsequent application to $\mu = 0.1$. The efficiency of Eq. (5) can be improved by an estimation of the gradient vector according to

$$\nabla_k \cong \hat{\nabla}_k = -2e_k \, x_k, \tag{6}$$

by using the error e_k instead of the mean [11]. This results in

$$\boldsymbol{w}_{k+1} = \boldsymbol{w}_k + 2\mu e_k \, \boldsymbol{x}_k \tag{7}$$

and represents a function of only current data. Although this kind of adaption yields a noisy filter, it converges towards the optimal solution $E[\hat{\nabla}_k] = \nabla$. An overview to the basic mathematics needed for this approach of this subsection is given in Ref. [11].

2.2. Adaptive inverse control of both scanner axes

By applying AIC, the system output (galvanometer sensor angle) is supposed to track a desired signal, which is provided by either a trajectory generator or the user. This is realized by a feedforward controller $\boldsymbol{c}$ (FIR-filter), in which the transfer function is the inverse of the system's linear dynamics. Thus, it has to be ensured that the scanner behaves in a linear way [11].

Fig. 2 shows the whole control structure for a scanner system. For this article, the utilized scanner is a *Racoon* 2-dimensional mid-sized galvanometer laser scanner from *ARGES GmbH*. All calculations and the implementation of AIC as an outer control loop are performed on a dSpace real-time system (DS1006 and DS5203). The indices in the figure represent the affiliation to the single axes x and y. First, the filters $\boldsymbol{w}$, of length L_w, are calculated according to the description in subsection 2.1. This yields in a model of the galvanometer. The length of a filter i will be denoted by the parameter L_i, henceforth. The parameter L_w has to be chosen according to Fig. 3b, so that the pulse response can be reproduced. This results in a real-time identification of the stabilized scanner behavior. In this case, the stabilization was performed by the originally installed PID controller. The filter $\boldsymbol{w}$ is then copied to a different (offline) processor, meaning calculations do not need to be done in real time. There, $\boldsymbol{w}$ is inverted by the same process according to subsection 2.1, i.e. filter $\boldsymbol{c}$ is adapted so that the transfer function of ($\boldsymbol{wc}$) equals 1. For the adaption of filter $\boldsymbol{c}$ a broadband signal is recommended, such as the triple flow snake fractal (Fig. 3a) introduced by Ref. [10]. This stimulus signal is a 2-dimensional plane filling periodic curve with 1029 sample points. To prevent overheating and cut out high frequencies, a reference model $\boldsymbol{M}$ (e.g. low pass filter) is utilized for adaption. In general, an arbitrary user-defined transfer function can be chosen. Additionally, the reference model contains a delay of Δ samples to gain a causal filter $\boldsymbol{c}$, giving the system time to react. The delay should be equal or slightly higher than the number of samples that the impulse response needs to reach its maximum. A lower value generates extremely high command inputs, because of a vast increase in acceleration. Too high values may cause an anticipation and thus an adaption to patterns close to the distance of the delay.

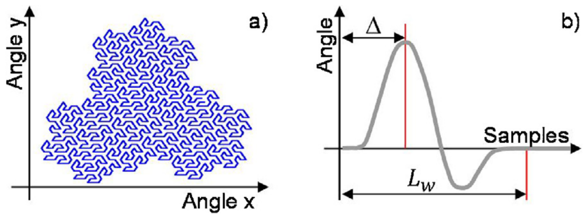

Fig. 3. a) Flow snake fractal, b) pulse response of an arbitrary system.

3. Photo adaptive inverse control (PHAIC)

3.1. Functional principle of PHAIC

The approach presented in chapter 2 increases the dynamics in accordance with the reference model and compensates for perturbations, taking only the behavior of the position sensor into account. To control the laser position and consider the non-collocation of sensor and mirror, the mirror behavior needs to be involved within a feedback of the controller.

To achieve this, a test rig inspired by Ref. [10] was utilized. As shown in Fig. 4, the scanner system is positioned on one side of a partially transparent screen. On the opposite side of the screen, a

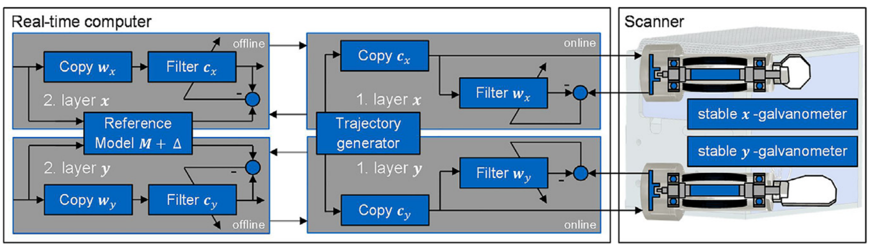

Fig. 2. Control schematic diagram for adaptive inverse control of a stabilized scanner system.

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