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CONTROL OF TIME-VARYING LATERAL TAPE MOTION IN A LINEAR-TAPE-OPEN DRIVE VIA ADAPTIVE REGULATION

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Introduction

This extended abstract summarizes a methodology along with the experimental results to adaptively reduce time-varying lateral tape motion (LTM) in a Linear Tape-Open (LTO) drive. For the adaptive regulation, the LTO actuator dynamics is modeled with a Linear Time Invariant (LTI) model and control of time-varying LTM disturbances is done via an adaptable linear feedback controller. Adaptive regulation is done via the direct estimation of a perturbation on the feedback controller. By simultaneously minimizing the variance of the Position Error Signal (PES) and the control output signal, the direct estimation of the controller perturbation is formulated as a weighted estimation problem that is implemented recursively for real-time implementation. The experimental results show a significant reduction of the variance of the PES over different tape cartridges and a constant PES variance during a complete reel-in/out operation of the tape drive.

Reducing LTM

For the competitive nature of tape storage, the number of data tracks per inch (TPI) of approximately 5000 TPI in LTO drives are projected to grow tenfold by 2022 [1]. With Lateral Tape Motion (LTM) as one of the main disturbances during data track following, a meticulous design of a tape transport mechanism [2] combined with a high performance control of the servo actuator [3, 4] can support high track density recording. A small PES has to be maintained despite interchangeable cartridges of magnetic flexible tape from different manufactures running at variable speeds. Moreover, the LTM is a function of the tape speed and depends on tape cartridge or manufacturer and LTM may even change as a result from external vibrations due to rack mounting or intermittently operating cooling fans in a tape servo system.

Recognizing that LTM in a tape servo system is a non-stationary disturbances with a time varying spectrum, the performance of an existing tape servo system can be further improved by allowing the feedback control algorithm to *adapt* to the unknown LTM disturbance. Adaptation of feedback to disturbance dynamics can be done via Adaptive Regulation [5] and earlier work has demonstrated how such algorithms can be implemented in real-time [6] to allow adaptive regulation of time varying disturbance dynamics. The Robust Estimation and Automatic Controller Tuning (REACT) as used in [6] can be used to minimize the variance of the PES and the control signal simultaneously in real-time to implement a adaptive feedback controller on top of an existing (Proportional-Integral-Derivative, PID) controller.

Controller perturbation

A well-know result in controller design and optimization is the Youla-Kucera parametrization [7] that allows the parametrization of the class of all stabilizing feedback controllers C_Q for a given model $\hat{G}$ by a single stable dynamical perturbation Q on an existing controller C. For a scalar and stable actuator model $\hat{G}$ and existing (PID) controller C in a tape servo system, the Youla-Kucera parametrization simplifies to

$$C_Q = \frac{C+Q}{1-\hat{G}Q} \tag{1}$$

and as long as $Q \in \mathcal{RH}_\infty$ (stable) we maintain stability for the feedback of C_Q and $\hat{G}$. The expression for the new controller C_Q in (1) also indicates that C_Q is formed by a simple ”add-on” to the existing controller C as indicated in Fig. 1. We maintain the favorable properties of a initially designed stabilizing feedback controller C and add on an additional perturbation that uses a model $\hat{G}$ of the actuator dynamics and a to-be-optimized stable transfer function Q to further improve the performance of the servo system.

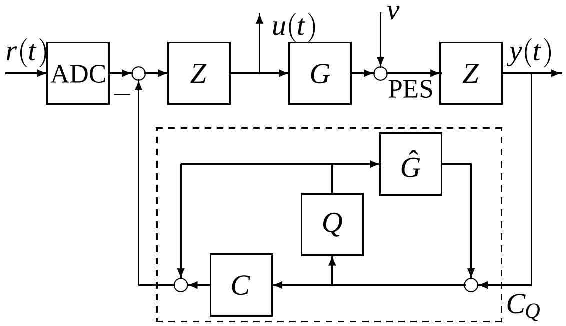

Figure 1. Schematics of closed-loop configuration with negative feedback for the adaptive regulation of an LTO drive.

In Fig. 1, G is used to indicate the servo actuator, whereas Z denotes a Zero Order Hold Digital to Analog Conversion (ZOH DAC). The model $\hat{G}$ is a model of the servo actuator G with the ZOH DACs. The notation C is used to indicate an existing and known (embedded) servo controller. The signal $v(t)$ indicates the unknown disturbances present on the servo system (such as LTM) that influence the PES $y(t)$ during track following.

Controller adaptation

For the simultaneous minimization of the variance of PES $y(t)$ and the control signal $u(t)$ indicated in Fig. 1, the affine relation of the controller perturbation Q in the signals $y(t)$ and $u(t)$ is used. With $Q = 0$ it is easy to verify that

$$(1+\hat{G}C)^{-1}v(t) = (1+\hat{G}C)^{-1}y(t) - (1+\hat{G}C)^{-1}\hat{G}u(t)$$

where the right hand side is completely known, creating the filtered closed-loop signal

$$w(t) = (1+\hat{G}C)^{-1}y(t) - (1+\hat{G}C)^{-1}\hat{G}u(t) \qquad (2)$$

that basically reconstruct the (filtered) noise signal $v(t)$ via the closed-loop signals $u(t)$ and $y(t)$. With $Q \neq 0$, the (weighted) closed-loop signals can now be written as

$$\begin{aligned} \begin{bmatrix} \gamma u(t) \\ y(t) \end{bmatrix} &= \left(\begin{bmatrix} -\gamma C \\ 1 \end{bmatrix} - \begin{bmatrix} \gamma \\ \hat{G} \end{bmatrix} Q \right) (1+\hat{G}C)^{-1} v(t) \\ &= \begin{bmatrix} -\gamma W C \\ 1 \end{bmatrix} w(t) - \begin{bmatrix} \gamma W \\ \hat{G} \end{bmatrix} Q w(t) \end{aligned}$$

where γ is a (scalar) weighting on the control signal $u(t)$ and where $w(t)$ is the filtered closed-loop signal given in (2). This last equation indicates that the error signal

$$\varepsilon(t,\theta) = \begin{bmatrix} -\gamma C \\ 1 \end{bmatrix} w(t) - \begin{bmatrix} \gamma 1 \\ \hat{G} \end{bmatrix} Q(\theta) w(t) \qquad (3)$$

is linear in the parameter θ if and only if $Q(\theta) \in \mathcal{RH}_\infty$ is parameterized linearly in θ. An obvious choice for $Q(\theta) \in \mathcal{RH}_\infty \; \forall\theta$ that is parametrized linearly in θ is a Finite Impulse Response (FIR) filter

$$Q(q,\theta) = b_0 + \sum_{k=0}^{\bar{k}-1} b_{k+1} q^{-k-1}, \; \theta = [b_0 \; b_1 \; \cdots \; b_{\bar{k}}] \qquad (4)$$

of order $\bar{k}$, allowing us to rewrite $\varepsilon(t,\theta)$ in (3) in a linear regression model of the format

$$\varepsilon(t,\theta) = \tilde{y}(t) - \phi(t)^T \theta \qquad (5)$$

The linear regression model allows a standard Least Squares optimization to minimize the variance of the error signal $\varepsilon(t,\theta)$ in (5) over θ for the adaptation of the controller C_Q given in (1). To anticipate changes in the spectrum $\Phi_v(\omega)$ if the noise $v(t)$, the variance of the error signal $\varepsilon(t,\theta)$ in (5) is minimized over only a finite number of time samples and formulated via a (filtered/smoothed) Recursive Least Squares (RLS) solution θ_t [8]. This allows for the real-time minimization of the variance of both the PES $y(t)$ and the γ-weighted control signal $u(t)$ included in $\varepsilon(t,\theta)$ via a time-varying feedback controller $C_Q(q,\theta_t)$.

Application to LTO3 drive

For comparison purposes, first an experiment with a fixed linear 6th order servo controller C operating at 20kHz sampling was used in an LTO3 drive. The PES and the reconstructed LTM during this experiment has been depicted in Fig. 2 where it can be seen that the variance of the PES increases slowly towards the end of the experiment.

For the implementtaion of the adaptive regulation, first a model $\hat{G}$ of the servo actuator is found by curve fitting a measured frequency response of the servo actuator in an LTO3 drive. The results of the curve fitting leads to an 8th

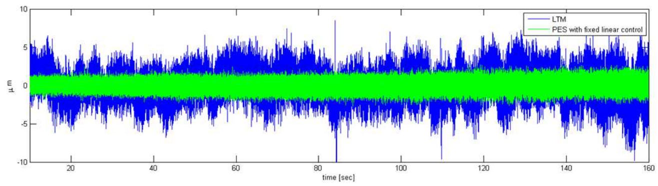

Figure 2. PES and LTM disturbances for an LTO drive with a fixed 6th order linear controller $C(q)$ at 20kHz using a single tape reel-out while maintaining track following.

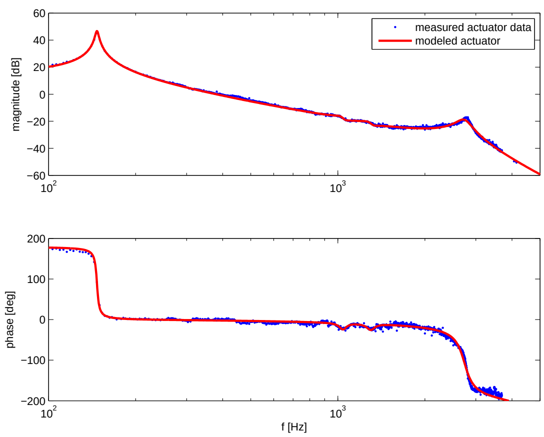

Figure 3. Bode response of the measured frequency response and the resulting 8th order model $\hat{G}(e^{j\omega_k}, \hat{\theta})$ (without ZOH DACs) of the servo actuator in an LTO3 drive.

order model for which the Bode response has been compared to the measured frequency domain data in Fig. 3.

With the model $\hat{G}$, the LTM can be reconstructed by a (non-causal) filtering of the PES through the inverse of the sensitivity function $S = (1 + C\hat{G})^{-1}$ and included in Fig. 2. Performing the same experiment with the same tape cartridge of a single tape reel-out while maintaining track following using the proposed adaptive regulation with a FIR filter $Q(q, \theta)$ with $k = 8$ in (4) results in the PES depicted in Fig. 4.

From the results in Fig. 4 it can be observed that the PES $y(t)$ during the adaptive regulation of the controller $C_Q(q)$ is significantly *smaller* than the PES during a fixed controller $C(q)$ experiment. Moreover, the PES variance remains small, even towards the end of the tape reel-out, while the control signal $u(t)$ slowly and adaptively increases to account for different disturbances towards the end of the tape real-out. The results indicate that a tape servo control algorithm can be regulated adaptively to handle changes in Lateral Tape Motion dynamics during servo operation of the tape drive.

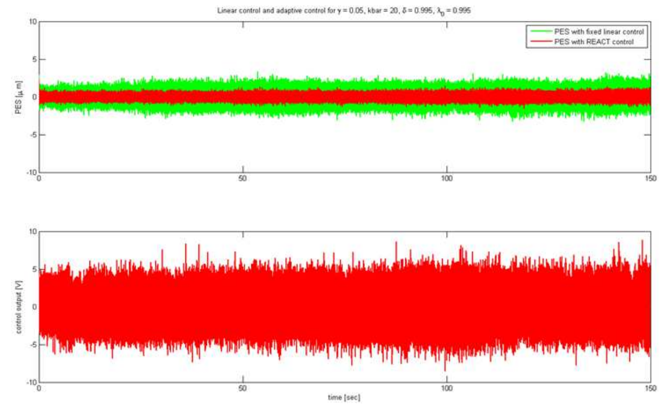

Figure 4. PES disturbances $y(t)$ (top figure) for a fixed 6th order linear controller $C(q)$ and an adaptive regulation of the controller $C_Q(q, \theta_t)$. Bottom figure shows the control signal $u(t)$ during the adaptive regulation of the controller $C_Q(q, \theta_t)$. Experiment was done at 20kHz using a single tape reel-out while maintaining track following.

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