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Reading of Cracked Optical Discs using Iterative Learning Control

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***Abstract*— Optical discs, including Compact Discs (CDs), Digital Versatile Discs (DVDs), and Blu-ray Discs (BDs), can get cracked during storage and usage. Such cracks commonly lead to discontinuities in the data track, potentially preventing reading of the data on the disc. The aim of the present paper is to improve tracking performance of the optical disc drive in the presence of cracks. A Hankel Iterative Learning Control (ILC) algorithm is presented that can perfectly steer the lens *during* the crack towards the beginning of the track immediately *after* the crack, i.e., the actuator is steered appropriately during the crack crossing to compensate for the discontinuity in the data track. Experimental results confirm improved reading capabilities of cracked discs. The presented approach potentially enables the recovery of data from cracked discs that were previously considered as unreadable.**

I. INTRODUCTION

Optical discs, including Compact Discs (CDs), Digital Versatile Discs (DVDs), and Blu-ray Discs (BDs), are media with data written on a layer by means of pits and lands in a spiral track, see Figure 1. These optical discs can get cracked in case they have been subjected to a static or dynamic mechanical load over a certain period of time. The resulting cracks are typically sharp, starting from the center of the disc and are possibly unfinished, see Figure 1.

The amount of lost data, caused by the damaged disc surface or information layer, is often only marginal, because of the data redundancy in the encoded track data. In this case, the existing error correction can recover the original data that is contained on the cracked disc. The main problem is a servo control problem: when the discontinuity is particularly large, the laser may lose track in radial direction (track-loss) and/or in focus direction (out-of-focus) [1]. Both consequences are fatal for reading optical discs. At present, control solutions in commercial drives include the so-called defect detector (DEFO) that switches off the normal feedback controller during the passing of a crack and holds the controller output at a constant value.

Although present approaches can cope with cracked discs to a certain extent, the tolerable crack dimensions are limited due to the fact that the zero-order-hold at the input does not result in an optimal connection between the end of the track before the crack and the beginning of the track after the crack. To improve tracking performance immediately after the crack, the lens can be steered towards the beginning of the track during the time the crack is passing. However, the design of an optimal command signal requires future information since it is not known *a priori* where the track is after the crack has passed. Thus, to compensate for the track discontinuity, the properties of the discontinuity should be known in an open-loop type of compensation algorithm.

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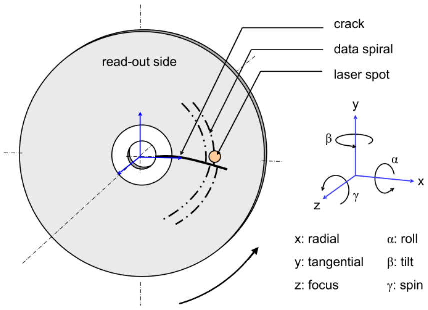

Fig. 1. Schematic top view of a typical cracked optical disc.

In the present paper, an Iterative Learning Control (ILC) algorithm [2], [3], [4], [5] is proposed that improves the data recovery in optical cracked discs by implementing a command signal that anticipates on the track location immediately after the crack. The main idea is that the crack results in a, possibly slowly varying, repeating error in case of rotating discs. By using measurement data from previous rotations, the command signal during the track can be improved to achieve perfect tracking immediately after the crack has passed. In essence, due to the anticipatory behaviour of the command signal, the resulting approach can be considered as not causal in the physical time domain [3].

The main contribution of the paper is the application of a specific ILC algorithm that can deal with the reading of cracked discs and experimental verification of the method in a commercially available optical disc drive. Specifically, application of the standard ILC algorithms is complicated by the absence of reliable measurements during the crack interval, since the light path of the laser beam is likely to be disturbed by the damaged disc surface or information layer. Hence, reliable measurement data is only available outside the crack interval. To deal with this situation, Hankel ILC [6], [7], [8] is considered, which extends standard ILC approaches by observing *after* and actuating *during* the crack interval. In addition, the DEFO, that is implemented in conjunction with the Hankel ILC controller, results in different system dynamics during the crack interval (open-loop) and outside the crack interval (closed-loop). This situation requires an appropriate extension of the Hankel ILC framework. Experimental results confirm that the Hankel ILC controller compensates discontinuities that are beyond the observation range of the lens while the tracking error does not contain systematic errors after the crack has passed.

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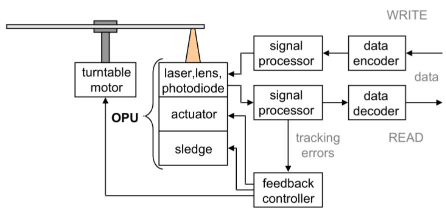

Fig. 2. Schematic representation of the optical storage principle.

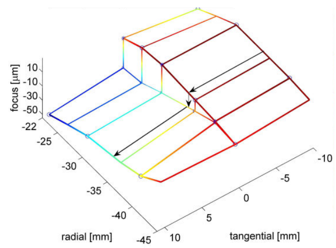

Fig. 3. Measured geometry of a typical cracked disc.

This paper is organized as follows. In Section II the drive and the cracked disc are introduced. The theory of Hankel ILC is presented in Section III. In Section IV, implementation aspects are discussed. In Section V, experimental results are presented. Finally, conclusions are provided in Section VI.

II. Experimental setup

A. Optical storage principle

The principle of optical storage is schematically depicted in Figure 2. The (cracked) optical disc, depicted in the upper left, is suspended to the turntable motor below. The turntable motor rotates the disc with respect to the laser beam in spin direction (γ).

The optical drive extracts data from the optical disc by using a laser-based Optical Pick-up Unit (OPU) to follow the spiral track. The laser beam is generated in the OPU, which typically consists of an actuator, laser, lens, and photodiode. The actuator together with the sledge provide accurate position information of the lens with respect to the disc. The combination of the laser, lens, and photodiode is able to optically read pits and lands in the data spiral on the disc. Additionally, this combination also provides tracking error information, see, e.g., [9], that is required for feedback control and Hankel ILC.

The geometry of a typical crack has been measured using a micrometer and an optical angle meter. The results are depicted in Figure 3, where the arrows indicate the read direction and the encountered discontinuity in the z-direction of a certain track.

B. Motion system

The motion system of the considered optical drive, which is a Philips BD1, is a dual-stage combination of an actuator and a sledge, see Figure 2. The optical drive is capable of reading and writing CDs, CD-Rs, DVDs, BDs, etc. In the present research, Hankel ILC is employed to recover data from a cracked CD-R. It is expected that the approach can also be employed to recover data from other disc types.

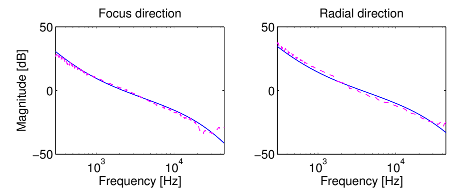

Fig. 4. Bode magnitude diagram of the open loop PC frequency response function in focus and radial direction: model P_{sys} (solid), identified frequency response function (dashed).

The actuator is designed for dynamic positioning of the lens in focus (z) and radial direction (x), while the sledge provides large radial jumps (x) and offset compensation in roll α, see Figure 1. The actuator is modelled mechanically as a suspended mass with three voice coil motors and has therefore three degrees-of-freedom, i.e., x, z, and β. The tilt β is nominally fixed to zero leaving two degrees-of-freedom. The sledge is modelled as a suspended mass with two electro motors to actuate its two degrees-of-freedom.

To anticipate on the Hankel ILC algorithm in Section III, it should be noted that ILC requires an approximate model of the plant to update the command signal. Based on the discussion in the previous paragraph, physical models of the actuators are used for both the focus and radial direction, i.e., the model

$$P_{sys} = \frac{k}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (1)$$

is considered in both focus and radial direction, where k is a motor constant, ζ is a dimensionless damping coefficient, and ω_n is the undamped natural frequency. In addition, s is a complex indeterminate representing the Laplace variable.

Comparing the model with the identified frequency response function, see Figure 4, where the open-loop gain $P_{sys}C$ is depicted, with C the feedback controller, reveals that the model accurately describes the true plant behaviour. In addition, measurements confirm that the plant is approximately decoupled. To facilitate the implementation, independent Single-Input Single-Output (SISO) ILC controllers are designed.

III. Hankel ILC

Iterative learning control (ILC) is a control technique that iteratively learns an optimal feedforward signal that minimizes tracking errors caused by deterministic disturbances in the same time interval. For the cracked CD, however, the measured tracking error during the duration of the crack is unreliable. Moreover, the primary interest is in the design of a feedforward signal *during* the time interval of the crack crossing, such that the focus and radial errors *after* the crack crossing are reduced. In other words, for cracked CDs, the task of the ILC controller is to learn a feedforward signal in one time interval such that the tracking error in the adjacent time interval is reduced. A special form of ILC, referred to as Hankel ILC, is capable of handling this task by exploiting separate time windows for the actuation and observation intervals in the control design, see [6] and Figure 5. The measurement results in Figure 5 already reveal the potential improvement of the tracking error due to Hankel ILC, which will be further explained in Section V.

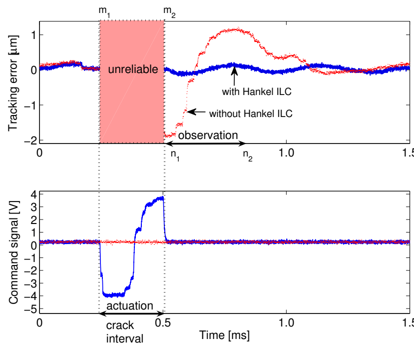

Fig. 5. Timing of actuation and observation: converged situation after application of Hankel ILC, see Section V (solid), initial error without Hankel ILC (dotted).

A. System formulation

Given the discrete-time SISO Linear Time Invariant (LTI) system P with a minimal state-space realization

$$P:\begin{cases} x(t+1) &= Ax(t)+Bf(t) \\ y(t) &= Cx(t)+Df(t) \end{cases}, \tag{2}$$

where $f(t)$ is the feedforward signal, $y(t)$ is the measured position, and $t \in \mathbb{Z}$ denotes discrete time. Then $P: f(t) \mapsto y(t)$ for $t = [0, N-1]$ can be written as a convolution matrix:

$$\begin{bmatrix} y(0) \\ \vdots \\ y(N-1) \end{bmatrix} = \underbrace{\begin{bmatrix} D & 0 & \dots & 0 \\ CB & D & \dots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ CA^{N-2}B & \dots & CB & D \end{bmatrix}}_{P} \begin{bmatrix} f(0) \\ \vdots \\ f(N-1) \end{bmatrix}. \tag{3}$$

With the actuation interval given by $t \in [m_1, m_2]$, the observation interval by $t \in [n_1, n_2]$, and $n_1 := m_2 + 1$ (in accordance with Figure 5), the convolutive mapping P_H from $f(t)$ during the actuation interval to $y(t)$ during the observation interval equals

$$\underbrace{\begin{bmatrix} y(n_1) \\ \vdots \\ y(n_2) \end{bmatrix}}_{y} = \underbrace{\begin{bmatrix} CA^{m-1}B & \dots & CB \\ \vdots & \ddots & \vdots \\ CA^{n+m-2}B & \dots & CA^{n-1}B \end{bmatrix}}_{P_H} \underbrace{\begin{bmatrix} f(m_1) \\ \vdots \\ f(m_2) \end{bmatrix}}_{f}, \tag{4}$$

$$m = m_2 - m_1 + 1, \quad n = n_2 - n_1 + 1, \quad n_1 = m_2 + 1, \tag{5}$$

with $P_H \in \mathbb{R}^{n \times m}$. Hence, $P_H = W_o P W_a$ with W_o and W_a the observation and actuation time windows, respectively:

$$W_o = \begin{bmatrix} 0_{n \times n_1} & I_n & 0_{n \times (N-n_2-1)} \end{bmatrix}, \tag{6}$$

$$W_a = \begin{bmatrix} 0_{m_1 \times m} \\ I_m \\ 0_{(N-m_2-1) \times m} \end{bmatrix}. \tag{7}$$

In the common case $\text{rank}(P_H) < \min(m, n)$, the matrix P_H is rank deficient. This rank deficient matrix P_H can be represented as the product of two full rank matrices using a full rank decomposition

$$P_H = P_o P_c, \tag{8}$$

where $P_o \in \mathbb{R}^{n \times p}$, $P_c \in \mathbb{R}^{p \times m}$, and $p := \text{rank}(P_H)$, representing the following two mappings

$$y = P_o x_{n_1} \tag{9}$$

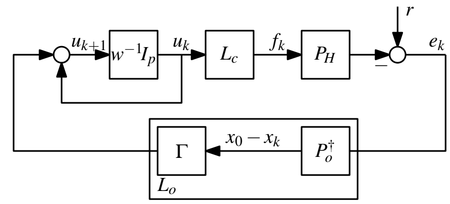

Fig. 6. Hankel ILC scheme.

$$x_{n_1} = P_c f \tag{10}$$

A possible choice regarding P_o and P_c in (9) and (10) is

$$P_o = \begin{bmatrix} C^T & (CA)^T & \dots & (CA^{n-1})^T \end{bmatrix}^T \tag{11}$$

$$P_c = \begin{bmatrix} A^{m-1}B & A^{m-2}B & \dots & B \end{bmatrix}. \tag{12}$$

In (9) and (10), $x_{n_1} \in \mathbb{R}^p$ is the state vector at $t = n_1$. Clearly, in case the state $x_{n_1} = 0$, then in virtue of (9) $y = 0$. Basically, the state x_{n_1} at time $t = n_1$ separates the command signal during the crack and the tracking error after the track, which has a close connection to the Hankel operator, see, e.g., [10]. Hence, the tracking error after the crack is fully determined by the state x_{n_1}.

B. Hankel ILC control framework

The Hankel ILC control framework is depicted in Figure 6. The input $f_k \in \mathbb{R}^m$ and output $y_k \in \mathbb{R}^n$ denote the feedforward signal during the actuation time interval and measured output during the observation time interval in trial k, respectively. Trial k in case of reading cracked discs refers to the k^{th} disc revolution after the learning algorithm was switched on. The signal $r \in \mathbb{R}^n$ is the trial invariant reference signal during the observation time interval, and $e_k = r - y_k$ the error signal. The state $x_k \in \mathbb{R}^p$ represents the time domain state x_{n_1} during trial k, and $x_0 = L_o r$ the state as function of external disturbance r. Finally, $u_k \in \mathbb{R}^p$ is the trial domain state vector.

As discussed in Section III-A, P_H corresponds to the time-windowed system $W_o P W_a$. Moreover, $L_c \in \mathbb{R}^{m \times p}$ and $L_o \in \mathbb{R}^{p \times n}$ constitute the Hankel ILC controller with $\text{rank}(L_c) = \text{rank}(L_o) = p$, and w^{-1} represents the one trial domain backward shift operator: $u_k = w^{-1} u_{k+1}$.

Based on Figure 6, the trial domain dynamics of the Hankel ILC controlled system are given by

$$u_{k+1} = u_k + L_o(r - y_k), \quad f_k = L_c u_k, \quad u_0 = 0 \tag{13}$$

$$u_{k+1} = (I_p - L_o P_H L_c) u_k + L_o r. \tag{14}$$

These dynamics are used to study the convergence (stability) and performance properties of the Hankel ILC controlled system. The properties will subsequently be used to analyze the Hankel ILC controller design.

1) Convergence: Convergence of the Hankel ILC controlled system is essential to improve reading performance for cracked discs. With (14) describing the evolution of the state of the system in trial domain, the system in Figure 6 is convergent if and only if $\rho(I_p - L_o P_H L_c) < 1$, with $\rho(\cdot) = \max |\lambda_i(\cdot)|$ and $|\lambda_i|$ the absolute value of the i^{th} eigenvalue.

If the system indeed is convergent, then it is guaranteed that the state u_k will converge to an asymptotic value $u_\infty = \lim_{k\to\infty} u_k$ after an infinite number of trials. It does, however, not provide any information about transient behaviour of f_k and y_k between $k = 0$ and $k \to \infty$. To avoid poor learning transients, monotonic convergence properties of the ILC controlled system are useful, see [11], [12].

2) Performance: Using (14) and the fact that $u_{k+1} = u_k$ for $k \to \infty$, e_∞ is given by

$$e_\infty = (I_n - P_H L_c (L_o P_H L_c)^{-1} L_o) r. \tag{15}$$

From (9), $x_0 - x_\infty = 0 \Rightarrow e_\infty = 0$. Using Figure 6

$$\begin{aligned}\Gamma(x_o - x_\infty) &= L_o e_\infty &(16)\\ &= L_o (I_n - P_H L_c (L_o P_H L_c)^{-1} L_o) r. &(17)\end{aligned}$$

Clearly, provided that the inverse in (17) exists, $x_o - x_\infty = 0$, hence perfect tracking is achievable.

C. Hankel ILC control design

The Hankel ILC controller used for the cracked CD application is based on an inverse model ILC controller. As a result, L_o and L_c are given by

$$L_o = \Gamma P_o^\dagger, \quad L_c = P_c^\dagger + (I_m - P_c^\dagger P_c) M_c. \tag{18}$$

where $P_c^\dagger = P_c^T (P_c P_c^T)^{-1}$ is the Moore-Penrose inverse of P_c, $P_o^\dagger = (P_o^T P_o)^{-1} P_o^T$ is the Moore-Penrose inverse of P_o, Γ is a user defined learning matrix, and M_c is a filter that can be used to exploit non-uniqueness in the feedforward signal f_k. The reader is referred to [6] for further details on the design of M_c.

Convergence of the Hankel ILC controlled system with controller (18) is based on $I_p - L_o P_H L_c = I_p - \Gamma$. Based on the choice for Γ, the system can be made convergent. In fact, for $\Gamma = \gamma I$ with $\gamma \in (0, 2)$, it holds that the ILC controlled system is monotonically convergent in f_k. In addition, Γ can be used as a design parameter to ensure robust convergence of the ILC controlled system in the presence of model uncertainty. Finally, with L_o and L_c satisfying the rank condition, $x_\infty - x_0 = 0$ can be achieved.

A specific choice regarding the design of L_o and L_c is based on the singular value decomposition of P_H, see [6], which in fact amounts to a full rank decomposition of P_H. The singular value decomposition of P_H is defined by

$$\begin{aligned} P_H &= \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} = U_1 \Sigma_1 V_1^T, &(19)\\ P_o &= U_1, \quad P_c = \Sigma_1 V_1^T. &(20)\end{aligned}$$

Moreover, let M_c be designed such that the energy of the weighted feedforward signal $\|f_\infty\|_W = f_\infty^T W f_\infty$ is minimized, with $W \in \mathbb{R}^{m\times m}$ a diagonal weighting matrix that separately penalizes every actuation sample in order to shape f_∞. Then L_o and L_c are given by

$$\begin{aligned} L_o &= \Gamma U_1^T &(21)\\ L_c &= (I_m - V_2 (V_2^T W V_2)^{-1} V_2^T W) V_1 \Sigma_1^{-1}. &(22)\end{aligned}$$

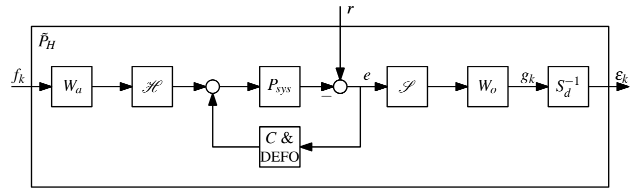

Fig. 7. Plant including open-loop error reconstruction.

In the next sections, L_o and L_c, as defined by the singular value decomposition in (21) and (22), are used to iteratively determine a command signal that enables the reading of a cracked optical disc.

IV. Implementation aspects

A. Trial-varying setpoint variations

From physical considerations, the crack dimensions vary over the surface of the cracked disc. In virtue of the smoothness of the crack, which is supported by Figure 3, the trial domain dynamics of the crack are significantly slower compared to the dynamics of the ILC controller, hence ILC can effectively attenuate disturbances caused by crack variations, see [13, Section 4.3.2].

B. Dealing with the DEFO

The DEFO switches off the updating of the feedback controller states in case an optical defect is detected to avoid excessive control inputs due to unreliable measurement data. For the application of Hankel ILC to cracked discs, this implies that the actuation of the lens during W_a involves an open-loop system, whereas the relevant tracking error during W_o is measured in a closed-loop situation. The reader is referred to Section III for the definition of W_o and W_a. Hence, in open-loop the dynamical behaviour is given by

$$e = r - P_{sys} f_k, \tag{23}$$

whereas in closed-loop the dynamical behaviour is given by

$$g_k = W_o \mathcal{S} (I + P_{sys} C)^{-1} (r - P_{sys} \mathcal{H} W_a f_k) \tag{24}$$

where $\mathcal{S}$ and $\mathcal{H}$ denote the ideal sampler and zero-order-hold interpolator, respectively. To reconstruct the error that would have resulted in open-loop, e_k is reconstructed by

$$\epsilon_k = S_d^{-1} g_k, \tag{25}$$

where ϵ_k the reconstructed e_k and S_d^{-1} the inverse of the finite time convolution matrix representation of the discrete time LTI sensitivity function. The resulting plant including reconstruction of the open-loop error is denoted by $\tilde{P}_H$ and is depicted in Figure 7.

The discrete time sensitivity function S_d is obtained by computing the zero-order-hold equivalent of $S_c = (I + P_{sys} C)^{-1}$ based on the physical model in Figure 4, see also [14]. In Figure 8, Bode diagrams of the continuous time and discrete time inverse sensitivity functions are depicted. It is concluded that discretization errors are negligible. In case discretization errors are significant, the digital implementation aspects should be explicitly addressed to ensure the resulting ILC controller performs well, see also [15].

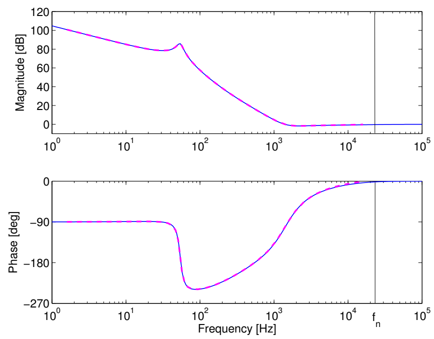

Fig. 8. Bode diagrams of S_c^{-1} (solid) and S_d^{-1} (dashed).

It should also be remarked that the inverse of the sensitivity may be unstable. Specifically, in Figure 8 the Bode diagrams of S_c^{-1} and S_d^{-1} are characterized by a high-gain low-frequent integrator, an underdamped resonance and a high-frequent asymptote of 0 [dB]. In this case, the integrator results in unstable behaviour. However, since the reconstruction is performed over a relatively short finite time interval n, the computation of the inverse is numerically reliable and the approach turns out to perform satisfactorily in practice.

C. State transformation to physical coordinates

The full rank decomposition of P_H based on an SVD does not necessarily result in a physically interpretable state $x_0 - x_k$. To gain more insight in the Hankel ILC control signals obtained after learning the cracked CDs, it is desirable to transform $x_0 - x_k$ to a state that can be physically interpreted. Specifically, this enables the identification of the crack geometry from learned command signals. Consider

$$\chi_0 = \begin{bmatrix} \chi_p \\ \chi_v \end{bmatrix}, \tag{26}$$

with χ_p the focus or radial position error as result of the crack, and χ_v the physical velocity error. Then the goal is to determine a state transformation matrix Q such that

$$\chi_0 - \chi_k = Q(x_0 - x_k). \tag{27}$$

Using the fact that

$$\epsilon_k = \underbrace{\begin{bmatrix} 1 & 0 \\ 1 & 1 \\ \vdots & \vdots \\ 1 & n-1 \end{bmatrix}}_{A} (\chi_0 - \chi_k), \tag{28}$$

Q is found by solving

$$\begin{aligned} \chi_0 - \chi_k &= Q(x_0 - x_k) && (29)\\ &= QP_o^\dagger \epsilon_k && (30)\\ &= QP_o^\dagger A(\chi_0 - \chi_k) \quad \Rightarrow \quad Q = (P_o^\dagger A)^{-1} && (31) \end{aligned}$$

As a consequence of the state transformation, the Hankel ILC filters L_o and L_c have to be altered to

$$\tilde{L}_o = \Gamma Q P_o^\dagger, \qquad \tilde{L}_c = L_c Q^{-1}. \tag{32}$$

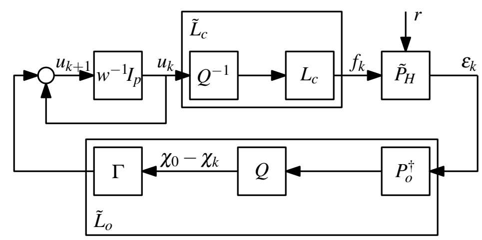

Fig. 9. Applied learning loop.

The learning matrix Γ is chosen diagonally, such that the convergence properties of the states corresponding to the position and velocity error can be tuned separately:

$$\Gamma = \begin{bmatrix} \gamma_p & 0 \\ 0 & \gamma_v \end{bmatrix} \tag{33}$$

From Section III-B.1 it is observed that $0 < \gamma_p, \gamma_v < 2$ for a convergent ILC controlled system.

The output of $\tilde{L}_o$ at trial k represents the scaled (with Γ) position and velocity error between χ_0 and χ_k. Additional information about the crack properties can be obtained by investigating the converged state u_∞. For that purpose, it is assumed that $\tilde{P}_H \approx P_H$ and $\epsilon_k \approx r - P_H f_k$. By design of L_o and L_c and based on the assumptions, the product $\tilde{L}_o \tilde{P}_H \tilde{L}_c \approx \Gamma$, and

$$\begin{aligned} u_\infty &= (I - \tilde{L}_o \tilde{P}_H \tilde{L}_c) u_\infty + \tilde{L}_o r && (34)\\ &= \Gamma^{-1} \chi_0. && (35) \end{aligned}$$

Hence, after the Hankel ILC controlled system has converged, the trial domain state u_∞ equals the scaled focus or radial error position and velocity. This result is illustrated in Section V. Note that by defining A as in (28), the velocity state χ_v is scaled to [V/sample].

D. Resulting Hankel ILC scheme

Summarizing the implementation aspects in the previous sections, the DEFO and state transformation lead to the modified Hankel ILC controller depicted in Figure 9, where $\tilde{P}_H$ is depicted in Figure 7. This Hankel ILC controller is implemented in the next section to improve the reading of cracked optical discs.

V. Measurements

In this section, the modified Hankel ILC controller in Figure 9 is implemented in the Philips BD1 player that is used for the recovery of data from a cracked disc. The measurements are performed with an effective actuation length of $\overline{m} = 24$, with $\overline{m} = 2m$ resulting in $m = 12$ individual sample values per state variable (χ_p or χ_v). The first measurement is performed in focus direction while reading the cracked CD-R, of which the geometry is given in Figure 3, at $x = 34$ [mm]. After convergence of the Hankel ILC algorithm, the measurement results in Figure 10 are obtained. In the considered cases, the Hankel ILC controller converged to a satisfactory command signal within $5 - 15$ iterations.

In Figure 10 (top) the tracking error after convergence of the Hankel ILC controller is depicted, where the light colored (grey) interval indicates the defect interval that is detected

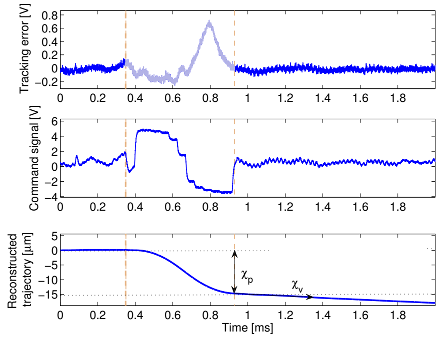

Fig. 10. Measurement results in focus direction.

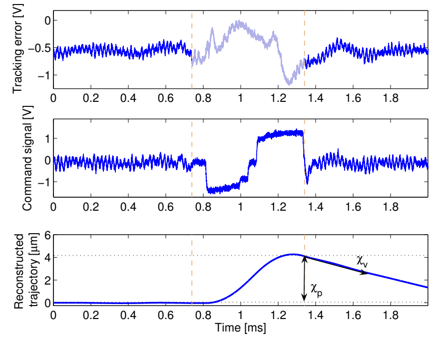

Fig. 11. Measurement results in radial direction.

by the DEFO. The tracking error signal in this light colored interval is unreliable and is neglected accordingly, i.e., it is neither used by the feedback controller nor by the Hankel ILC controller. The Hankel ILC controller results in a perfect compensation of the crack. For a comparison with the initial tracking error before the Hankel ILC controller is applied, the reader is referred to Figure 5.

In Figure 10 (middle), the required feedforward signal, which is equal to the actuator input, is depicted. Observe that in the defect interval, this signal almost saturates at 5.2 [V] indicating a suitable choice for $\overline{m}$. In Figure 10 (bottom), the reconstructed trajectory of the lens is shown, which is obtained by using the model P in (2). This trajectory shows a compensation in position (E_p) of 15 [μm] and in velocity (E_v) of -4[μm/ms] for which the latter corresponds to α=-1.7 [mrad]. This resembles the trajectory indicated by the arrow in Figure 3. Note that E_p is beyond the observation range of $\pm$ 2 [μm]. This implies that the Hankel ILC controller enables reading of cracked optical discs that were previously considered as unreadable.

A similar measurement result in radial direction is presented in Figure 11. The resulting trajectory shows that $E_p = 4.2$ [μm] and $E_v = -2.2$ [μm/ms] where the latter corresponds to γ=-1.0 [mrad]. As a result, the tracking error is compensated for outside the observation range of 0.8 [μm]. In the radial direction, it is important to check the continuity of the data track, i.e., whether the correct track is being followed. The data channel provides this information. In the experiments shown here, indeed the data could be reconstructed perfectly, and the right track was followed after the crack.

VI. Conclusions

In this paper, a novel ILC algorithm, referred to as Hankel ILC, has been further developed and implemented to enable the reading of cracked optical discs. In essence, the presented algorithm aims at perfectly steering the actuator during a crack towards the beginning of the track immediately *after* the crack has passed.

Experimental results resulting from a commercial optical disc drive indeed confirm improved tracking properties of the Hankel ILC controlled system. Specifically, measurements show almost full compensation of the tracking errors in both focus and radial directions. These compensated discontinuities lie significantly outside the observation range of the optics. Hence, the proposed Hankel ILC controller can indeed enable the recovery of data from damaged discs that were previously considered as lost.

Open issues include robustness analysis of the approach with respect to variation in disc cracks and for a large number of discs an actual comparison of the recovered data compared to prior approaches, i.e., in case only the DEFO is used. In addition, implementation aspects, both regarding the DEFO and state reconstruction, should be further theoretically justified, as well the theoretical aspects associated with the switching dynamics of the overall system.

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