FAULT PREDICTIVE CONTROL OF COMPACT DISK PLAYERS

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Abstract
Optical disc players such as CD-players have problems playing certain discs with surface faults like scratches and fingerprints. The problem is to be found in the servo controller which positions the optical pick-up, such that the laser beam is focused on the information track. A scheme handling this problem, called feature based control, has been presented in an other publications of the first author. This scheme is based on an assumption that the surface faults do not change from encounter to encounter. This assumption is unfortunately not entirely true. This paper proposes an improvement of the feature based control scheme, such that a prediction step is included. The proposed scheme is compared with the feature based control scheme, in the perspective of handling surface faults, by simulations. These simulations show the improvements given by the proposed algorithm.

Keywords: Fault Tolerant Control, CD ROM, Predictive Control, Fault Detection, Signal Analysis

1. INTRODUCTION

Today optical disc players can be found in most homes and offices, in form of CD-players, DVD-players, CD/DVD-ROM drives etc. These players have no problems playing normal healthy discs. However, if the disc has faults on its surface, such as scratches and fingerprints, it is likely that the player will encounter problems in playing the disc. In the worst case it results in music or data drop out from the player.

The information on the disc is stored in a spiral shaped track. An optical pick-up unit (OPU) emits a laser beam which is reflected at the disc surface (track). The reflected laser beam is following detected in the OPU. The information is stored using two different surface levels in the track. It is as a consequence important to position the OPU such that it is focused on and tracked at the disc. Two linear electro-magnetic actuators are used to position the OPU in focus and tracking directions. In addition to the data signal the OPU generates detector signals which can be used to estimate focus and tracking errors. These signals are fed into two controllers which position the OPU by using the electro-magnetic actuators, see (Bouwhuis *et al.* 1985) and (Stan 1998). The design of the controllers for playing normal discs have been the subject of extensive research activities.

The problem in handling surface fault is to be found in the servo controller. The main objective in the design of the controllers is to follow the reference given by the spiral shaped track, etc, and to suppress disturbances like mechanical shocks. This nominal control problem requires controllers with relative high-band width. On the other hand during a surface fault the position measurements are at least not entirely reliable. This means that the controller bandwidth should be low. These requirements of both high and low controller band width are indeed a set of conflicting controller specifications.

A possible method to handle these faults is to use a fault tolerant control strategy, where the surface faults are handled in a special way, when detected. A frequently used method for detection of faults is to observe changes in either the focus residual or the radial residual, see (Philips 1994). A simple fault tolerant control strategy has often been used to handle such surface faults. The core idea in this simple approach is not to rely on sensor information during the fault. The sensor signals are in principle fixed to zero as long as a fault is detected. This, however, means that the system is operated in an open loop, and might causes loss of tracking.

More advanced fault tolerant based control methods have been introduced for optical disk players like CD-players, with the purpose of handling surface faults on the disc, see (Vidal Sánchez 2003), (Odgaard *et al.* 2005) and (Odgaard 2004). These faults like scratches and fingerprints can lead to a loss of focusing and tracking of the optical pick-up, which reads the information stored on the disc. The method called feature based control, introduced by Odgaard et al., approximates fault components in the measurements based on past encounters, and subsequently subtract the fault estimate from the measurements when the fault is encountered again. This approach is based on the assumption that a surface fault does not change much from one encounter to the next one.

This assumption is only true to some extent. Surface faults normally develop by increasing over hundreds of tracks and decrease again over hundreds of tracks, where encounters of successive tracks are almost indistinguishable, a difference will be detectable after a number of encounters. This means that if the user requests a jump from one song to another, at this track a fault might be to large for the feature based control scheme to handle it.

In this paper the feature based control scheme is expanded with a prediction of the surface fault

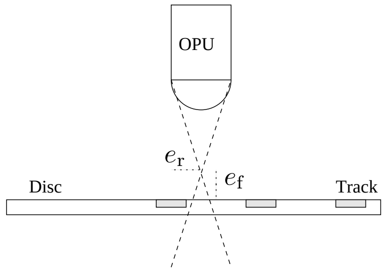

Figure 1. The focus distance, e_{f}, is the distance from the focus point of the laser beam to the reflection layer of the disc, the radial distance, e_{r}, is the distance from the center of the laser beam to the center of the track. The OPU is the Optical Pick-up Unit, which measures four detector signals. These can be used to estimate the distances as well as two residuals, used to detect surface defects as scratches.

component, such that the development of the faults are taken into account. The prediction is based on a knowledge of a known approximating basis of the surface faults.

The context of the paper is as follows: Section 2 gives a short description of the relevant parts of a CD-player, ending up with the relevant models. Section 3 introduces the previous proposed feature based control scheme for a CD-player playing CDs with surface faults. Section 4 describes the predictive method for handling surface faults on CDs. Section 5 compares the proposed predictive scheme with the previously proposed feature based control scheme, as well as a common industrial solution. Section 6 concludes the paper.

2. THE CD-PLAYER

The OPU in the CD-player is focused and radially tracked by movements of the OPU in two directions called focus and radial directions. These movements are enabled by a two axis device, where linear electro-magnetic actuators are used to perform the actual movements. The focus distance, e_{f}, and the radial distance, e_{r} can be minimized by moving the actuators in the two directions of the OPU. The two distances are illustrated in Fig. 1. The positions of the OPU in these two directions are measured by using smart optics in the OPU. The OPU generates four detector signals which can be used to generate the approximations of the distances. Two detector signals are related to each position. D_1 and D_2 are the focus detectors, and S_1 and S_2 are the two radial detectors. The differences in pairs are qualified approximations of the respective distances. Unfortunately these measurements are influenced by the surface faults.

A structural overview of the CD-player model and the signals involved are illustrated in Fig.

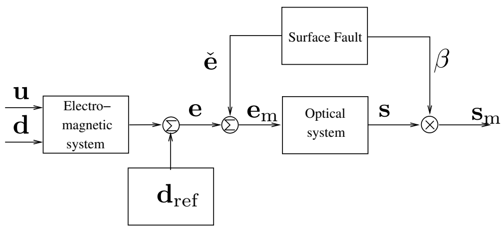

Figure 2. The principles of the model of the CD-player. The CD-player consists of four parts: The electro-magnetic system and the optical system, the unknown references (in a vector denoted $\mathbf{d}_\mathrm{ref}[n]$) and the surface fault.

2. In this figure the signals are defined as follows. $\mathbf{u}[n]$ is a vector of the control signals to the electro-magnetic system, $\mathbf{d}[n]$ is a vector of the unknown disturbances to the electro-magnetic system, $\mathbf{d}_\mathrm{ref}[n]$ is a vector of the unknown references (generated by local disc geometry) to the system, $\mathbf{e}[n]$ is a vector of the focus distances, $\check{\mathbf{e}}[n]$ is a vector of the distance components due to the surface fault, $\tilde{\mathbf{e}}[n]$ is a vector of the estimated/measured distances, $\beta[n]$ is a vector of scalings of the detector signals due to the surface fault, $\mathbf{s}[n]$ is a vector of detector signals without surface faults and $\mathbf{s}_\mathrm{m}[n]$ is a vector of the measured detector signals.

2.1 Model of the electro-magnetic system

The electro-magnetic system in the CD-player is modeled and described in a number of publications. The focus and radial models are much alike, and are often modeled by decoupled second order models, see (Stan 1998) and (Bouwhuis *et al.* 1985). In the discrete time version the model is given by

$$\eta[n+1] = \begin{bmatrix}\mathbf{A}_\mathrm{f} & \mathbf{0}\\ \mathbf{0} & \mathbf{A}_\mathrm{r}\end{bmatrix}\cdot\eta[n] + \begin{bmatrix}\mathbf{B}_\mathrm{f} & \mathbf{0}\\ \mathbf{0} & \mathbf{B}_\mathrm{r}\end{bmatrix}\cdot\mathbf{u}[n], \quad (1)$$

$$\begin{bmatrix}e_\mathrm{f}[n]\\ e_\mathrm{r}[n]\end{bmatrix} = \begin{bmatrix}\mathbf{C}_\mathrm{f} & \mathbf{0}\\ \mathbf{0} & \mathbf{C}_\mathrm{r}\end{bmatrix}\cdot\eta[n], \quad (2)$$

where $\eta[n] \in \mathcal{R}^4$ is the vector of states in the model, $\mathbf{A}_\mathrm{f} \in \mathcal{R}^{2\times 2}$, $\mathbf{B}_\mathrm{f} \in \mathcal{R}^{2\times 1}, \mathbf{C}_\mathrm{f} \in \mathcal{R}^{1\times 2}$ are the model matrices in the focus model, and $\mathbf{A}_\mathrm{r} \in \mathcal{R}^{2\times 2}$, $\mathbf{B}_\mathrm{r} \in \mathcal{R}^{2\times 1}, \mathbf{C}_\mathrm{r} \in \mathcal{R}^{1\times 2}$ are the model matrices in the radial model. This model is somewhat simplified, but sufficient for our purposes.

2.2 Model of the optical detectors

This optical model is expressed by the vector mapping, (see (Odgaard 2004)), described in (3),

$$\mathbf{f}: \begin{bmatrix}e_\mathrm{f}[n]\\ e_\mathrm{r}[n]\end{bmatrix} \rightarrow \begin{bmatrix}D_1[n]\\ D_2[n]\\ S_1[n]\\ S_2[n]\end{bmatrix}, \quad (3)$$

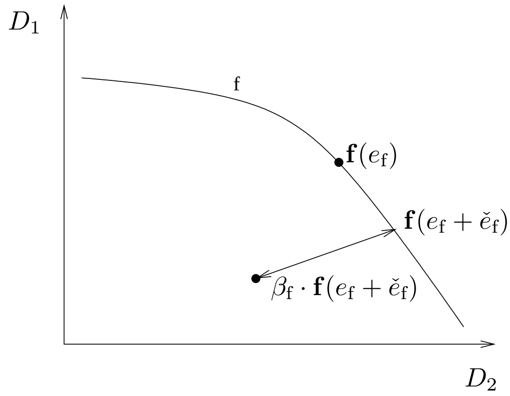

Figure 3. Illustration of how the surface faults influence the focus measurements D_1 and D_2. $\beta_\mathrm{f}\cdot\mathbf{f}(\mathbf{e}_\mathrm{f}+\check{\mathbf{e}}_\mathrm{f})$ is the measured point parameterized with β and $\check{\mathbf{e}}_\mathrm{f}$. $\mathbf{f}(\mathbf{e}_\mathrm{f})$ is the point where the measurements would have been if no surface fault has been present.

where $D_1[n]$ and $D_2[n]$ are the two focus detectors and $S_1[n]$ and $S_2[n]$ are the two radial detectors. The four coordinate functions of $\mathbf{f}$ can be simplified in the following manner,

$$f_i(e_\mathrm{f}[n], e_\mathrm{r}[n]) \approx h_i(e_\mathrm{f}[n])\cdot g_i(e_\mathrm{r}[n]), \quad (4)$$

where

$$i \in \{1,2,3,4\}, \quad (5)$$

moreover

$$g_1(e_\mathrm{r}[n]) = g_2(e_\mathrm{r}[n]). \quad (6)$$

In practice it is useful to simplify this model, $h_i(e_\mathrm{f}[n])$ and $g_i(e_\mathrm{r}[n])$ can be approximated with cubic splines.

2.3 Model of the surface faults

The surface faults decrease the energy received in all the detectors. This can be modeled by scaling the photo detector signals, such that the two focus detectors are scaled with one scale, $\beta_\mathrm{f}[n]$, and the two radial detectors are scaled with another one, $\beta_\mathrm{r}[n]$. However, if these scalings were the only influenced by the surface faults on the detector signals, the surface fault components could be removed from the detector signals by normalization of the detector signals. The surface faults introduce a pair of fault components in distance measurement. These fault components are represented by a vector $\check{\mathbf{e}}[n]$, see (Odgaard *et al.* 2004). These surface fault components are illustrated for the focus detector in Fig. 3. This leads to the following model of the detector signals during a surface fault,

$$\mathbf{s}_\mathrm{m}[n] = \begin{bmatrix}\beta_\mathrm{f}[n]\cdot\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \beta_\mathrm{r}[n]\cdot\mathbf{I}\end{bmatrix}\cdot\mathbf{f}\left(\mathbf{e}[n]+\check{\mathbf{e}}[n]\right). \quad (7)$$

3. FEATURE BASED CONTROL

In this section the core idea of the feature based control scheme of the CD-player will be described briefly.$\alpha_{\rm f}[n] = 1 - \beta_{\rm f}[n]$ and $\alpha_{\rm r}[n] = 1 - \beta_{\rm r}[n]$ are used to detect and locate the surface faults on the time axis. Approximations of the surface faults, given a basis supporting the faults, have been presented in (Odgaard *et al.* 2004). This approximation of the surface faults is used to remove the fault component from the measurement of the next surface fault encounter based on the previous encounters. The standard focus and radial controllers can be used, since the fault component is removed from the detector signals.

The feature based control strategy is illustrated in Fig. 4, from which it can be seen that the feature based control strategy consists of: Residual & Distance Estimator, Feature Extraction/Fault Detection, Fault Accommodation and a Controller. $\mathbf{s}_{\rm m}[n]$ is a vector of the measured detector signals, α is a vector of the residuals, $\tilde{\mathbf{e}}[n]$ is a vector of the distance measurements, $f_{\rm d}[n]$ is the fault detection signals, it takes the value 1 in case of a detected fault and 0 elsewhere, $\hat{\mathbf{e}}[n]$ is a vector of estimates of distances due to the control signals, $\bar{\mathbf{e}}[n] = \tilde{\mathbf{e}}[n] - \hat{\mathbf{e}}[n]$ is a vector of the part of distances which are unrelated to the control signals, $\grave{\mathbf{e}}[n]$ is a vector of the corrected distances, $\mathbf{u}[n]$ is a vector of the control signals. One should notice that $\bar{\mathbf{e}}[n]$ contains more than just the distance fault components, in addition $\bar{\mathbf{e}}[n]$ contains disturbances and noises. I.e. filtering is necessary in order to estimate the fault components.

This filtering is performed by subtracting approximation of the fault components from the measurements. The estimations of the fault components are performed by the use of Karhunen-Loève bases, see (Mallat 1999). The Karhunen-Loève bases are computed based on $\bar{\mathbf{e}}[n]$ containing measured surface faults. Denote the matrices with focus and radial $\bar{\mathbf{e}}[n]$ measurements as column vectors: $\mathbf{D}_{\rm f}$ and $\mathbf{D}_{\rm r}$ respectively, see (Odgaard 2004). The approximating bases can subsequently be computed as the Karhunen-Loève

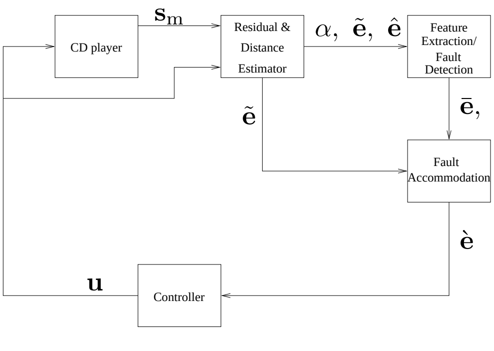

Figure 4. Illustration of the structure of the feature based control scheme, to handle surface faults as faults.

basis of these matrices. A number of the most approximating basis vectors are used for the approximation. These few most approximating basis vectors support the general structures in data matrices, and the remaining ones support the noises in the data vectors.

3.1 The adaptive feature based control algorithm

The adaptive feature based control algorithm is presented in (Odgaard *et al.* 2005). In this scheme the fault is removed by its application when detected. After each encounter the fault approximation basis is updated as well as new coefficients are computed.

3.2 Stability of the scheme

Assuming that the controller K stabilizes the system CD, a stability criterion for this feature based control scheme is derived in (Odgaard *et al.* 2005). One should notice that the only adaptive part of the system is approximation of the surface faults. The criterion is given by Lemma 1. Define $\mathcal{P}$ as

$$\mathcal{P}_m^{\rm L} = \mathbf{K}_{\check{e}_m} \cdot \mathbf{K}_{\check{e}_m}^T, \tag{8}$$

where $\mathbf{K}_{\check{e}_m}$ is matrix representation of the approximation filter computed at encounter m, and the lifted representation of the complementary sensitivity at encounter m is

$$T^{\rm L} = \begin{bmatrix} h_0 & 0 & \cdots & 0 \\ h_1 & h_0 & & \vdots \\ \vdots & & \ddots & \\ h_{255} & \cdots & & h_0 \end{bmatrix}, \tag{9}$$

where $\mathbf{h} = \begin{bmatrix} h_0 \; h_1 \; \cdots \; h_{255} \end{bmatrix}$ is time series of L samples of the impulse response of T.

Lemma 1. The adaptive feature based control system defined in Fig. 5, which is stable if and only if: $\max_m \left(\bar{\sigma}\left(T^{\rm L}\mathcal{P}_m^{\rm L}\right)\right) < 1$,
where $\mathcal{P}_m^{\rm L}$ is defined in (8) and $T^{\rm L}$ is defined in (9).

The stability shall be checked each time a new approximating basis has been computed. The stability problem occurs if the sensitivity of the closed loop is amplified too much at the given frequencies through the approximating basis. This might happen if a given fault has a near DC frequency content, and as the adaptive approximating basis covers these frequencies more and more, the stability margin of the system decreases. This might end in instability of the system.

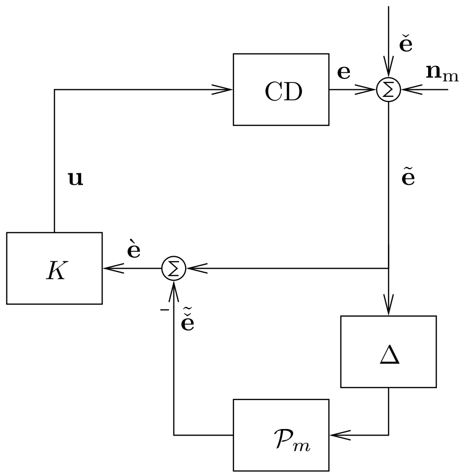

Figure 5. Illustration of the closed loop with the feature based correction $\mathcal{P}_m$ at encounter m, for the non-adaptive feature based control scheme, $\mathcal{P}_m = \mathcal{P}$, and time invariant.

The stability check procedure is as follows: When a new approximating basis is computed, determine if the new system is stable using Lemma 1. If the system is stable use the newly computed approximating basis, if not use the latest stable computed basis.

4. PREDICTION OF THE FAULT COMPONENT

In (Odgaard *et al.* 2005) a method for approximating a surface fault is proposed. This approximation can be used to predict the surface fault component at the next encounter. Define a function approximating the surface fault at encounter m for $\Phi_m(t)$, and at encounter $m+1$ for $\Phi_{m+1}(t)$. This means the prediction of encounter $m+1$ based on encounter m, should be close to the approximation of encounter $m+1$. A simple way to predict the surface fault at encounter $m+1$ is to scale the approximation of encounter m in time and amplitude.

$$\Phi_{m+1}[n] \approx c_m \cdot \Phi_m[a_m \cdot n], \qquad (10)$$

where c_m is amplitude scaling coefficient, and a_m is the time scaling coefficient. The time scaling coefficient, a_m, can be found by (11).

$$a_m = \max_{\alpha \in \mathcal{R}} | < \Phi(\alpha \cdot t), \Phi(t) > |. \qquad (11)$$

It might be difficult to compute a by (11), however, the length of the scratch of the different encounters is computed by the detection algorithm. Denote l_m as the length of the fault at encounter m. It is clear that

$$a_m = \frac{l_m}{l_{i+1}}, \qquad (12)$$

due to the small variations from encounter to encounter it can be assumed that

$$a_m \approx a_{m-1} = \frac{l_{m-1}}{l_m}. \qquad (13)$$

The amplitude scaling coefficient can be predicted in the same way.

$$c_m \approx c_{m-1} = \frac{\|\Phi_m(t)\|}{\|\Phi_{m-1}(t)\|}. \qquad (14)$$

4.1 The algorithm

In (Odgaard 2004) the feature based control scheme did use approximating bases supporting more than one fault, meaning than more than one basis vector has been needed to support the set of faults. However, the approximating basis is recomputed for the given surface fault. As a consequence only the most approximating basis vector is needed.

This fault predictive method is based on the adaptive feature based control scheme, with some improvements and modifications. The number of used basis vectors are restricted to the most approximating basis vector, and the prediction steps are introduced in the scheme.

(1) Detect the fault and locate its position in time, when the fault is detected at sample n, $f_\mathrm{d}[n] = 1$.
(2) If $f_\mathrm{d}[n] = 1$:
$$\bar{\mathbf{e}}[n] - \begin{bmatrix} \tilde{\check{\mathbf{e}}}_\mathrm{f}[\iota] \\ \tilde{\check{\mathbf{e}}}_\mathrm{r}[\iota] \end{bmatrix},$$
where ι is a counter used to position the correction in relation to the actual fault.
(3) Compute the focus approximating function by: $\Phi_{\check{e}_\mathrm{f}} = \{\text{eigenvector}\left(\mathbf{D}_\mathrm{f} \cdot \mathbf{D}_\mathrm{f}^T\right)\}\{N\}$, and the radial approximating function by: $\Phi_{\check{e}_\mathrm{r}} = \{\text{eigenvector}\left(\mathbf{D}_\mathrm{r} \cdot \mathbf{D}_\mathrm{r}^T\right)\}\{N\}$.
(4) Check stability using Lemma 1. If the system is stable use the newly computed approximating basis, if not use the latest computed stable basis.
(5) Compute a_m and c_m by (13) and (14) respectively.
(6) Compute the focus fault correction block by: $\tilde{\check{e}}_\mathrm{f} = c_m \cdot \Phi_\mathrm{f}[a_m \cdot n]$, and the radial fault correction block by:$\tilde{\check{e}}_\mathrm{r} = c_m \cdot \Phi_\mathrm{r}[a_m \cdot n]$.

5. TESTS

The fault predictive method is compared with the adaptive feature based method and a standard industrial solution, using a simulation model of CD-players playing CDs with surface faults, see (Odgaard *et al.* 2004). The faults are simulated with increasing amplitude and time duration. The algorithm responses are compared both for the focus and radial loops. The standard industrial

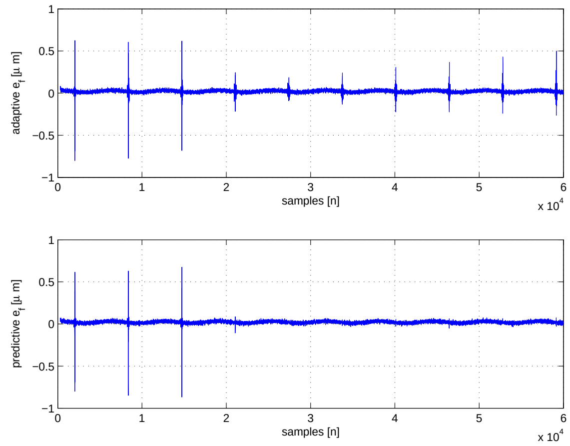

Figure 6. A plot of the simulated e_{f}. The upper plot shows the handling by the adaptive feature based control scheme, the lower plot shows the handling by the predictive scheme. In both plots the three first encounters are handled by the used industrial scheme.

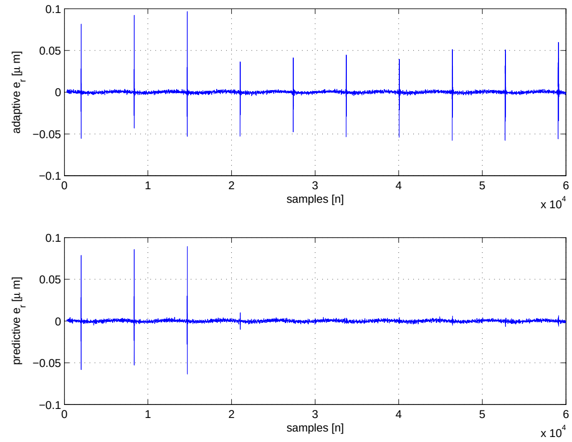

Figure 7. A plot of the simulated e_{r}. The upper plot shows the handling by the adaptive feature based control scheme, the lower plot shows the handling by the predictive scheme. In both plots the three first encounters are handled by the used industrial scheme.

solution used in this simulation, holds the focus and radial error at zero while the surface fault is detected.

The focus responses can be seen in Fig. 6, and the radial responses can be seen in Fig. 7.

In both plots the upper plots are the fault handled by the adaptive feature based control scheme and in the lower plot is the fault handled by the predictive scheme proposed in this paper. In all the plots the three first encounters of the surface fault are handled by the standard industrial fault handling solution.

From these plots it is clear to see that both the adaptive and predictive feature based control scheme handles the surface faults better than the industrial solution, and that the predictive scheme is again clearly better to handle the surface faults than the adaptive feature based control scheme.

6. CONCLUSION

This paper presents a method for CD-players playing CDs with surface faults, which uses predictions of the fault components in the measurements to remove these surface faults components from the error signals. These error signals are used to control the optical pick-up unit in the CD-player. The proposed method is compared with a version of the feature based control scheme which do not take prediction of the fault development into account. Both these methods are as well as compared with a standard industrial solution. Based on these simulations it is clear that the proposed predictive method is better to handle surface faults than the standard industrial solution and a non predictive feature based fault removal scheme.

7. ACKNOWLEDGMENT

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