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Feature-based handling of surface faults in compact disc players

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Abstract

In this paper a novel method called feature-based control is presented. The method is designed to improve compact disc players' handling of surface faults on the discs. The method is based on a fault-tolerant control scheme, which uses extracted features of the surface faults to remove those from the detector signals used for control during the occurrence of surface faults. The extracted features are coefficients of Karhunen–Loève approximations of the surface faults. The performance of the feature-based control scheme controlling compact disc players playing discs with surface faults has been validated experimentally. The proposed scheme reduces the control errors due to the surface faults, and in some cases where the standard fault handling scheme fails, our scheme keeps the CD-player playing.

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Keywords: CD-player; Fault-tolerant control; Karhunen-Loève approximations; Fault detection and isolation; Repetitive systems

1. Introduction

Optical disc players such as compact disc players (CDplayers) have in the past two decades been widely used in homes and businesses. However, performance issues are still to be improved on. A common problem with optical disc players is that they have difficulties playing certain discs with surface faults like scratches and fingerprints. An optical pick-up unit (OPU) is used to read the data/music stored in the information track on the disc. A main characteristic of the CD-player is the lack of physical contact between the OPU and the disc surface. Instead servo loops based on optical measurements are formed to keep the OPU positioned. The real problem with surface faults is that they degenerate the measures of focus and radial errors.

One 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 by a decrease in

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the amount of reflected light. Faults are detected as fast as possible and when a fault is detected, the control strategy is changed in a way that accommodates the detected fault. A simple fault-tolerant control strategy is often used to handle such surface faults. The core idea is not to rely on sensor information during the fault. The sensor signals are simply fixed to zero as long as a fault is detected. In the sequel, we shall present an alternative to this commonly used industrial method.

The research in control of CD-players has been intense in other directions than fault-tolerant control, especially in adaptive and robust controllers applied to the CD-player. The first application of a μ -controller used in a CD-player was reported in Steinbuch, Schoostra, and Bosgra (1992), which was based on DK-iterations. An example of an adaptive control design was Draijer, Steinbuch, and Bosgra (1992), where a self-tuning controller was suggested. Automatic adjustment of gains in dependence of the reflective characteristics is standard in commercial CD-players. A large number of different control strategies were applied to the CD-player. An adaptive repetitive method was suggested in Dötsch, Smakman, Van den Hof,

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Nomenclature

| (t) continuous time unit [n] discrete time unit sampled of (t) at 35 kHz $D_1[n]$ first focus detector signal $D_2[n]$ second focus detector signal $S_1[n]$ first radial detector signal $S_2[n]$ second radial detector signal u[n] vector of control signals d[n] vector of unknown disturbances $d_{ref}[n]$ vector of references $d_{ref}[n]$ vector of references | error |
|--|-------------------------|
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$ | error adial |
| $ \begin{array}{ll} [n] & \text{discrete time unit sampled of (t) at 35 kHz} \\ D_1[n] & \text{first focus detector signal} \\ D_2[n] & \text{second focus detector signal} \\ S_1[n] & \text{first radial detector signal} \\ S_2[n] & \text{second radial detector signal} \\ u[n] & \text{vector of control signals} \\ \mathbf{d}_{ref}[n] & \text{vector of unknown disturbances} \\ \mathbf{d}_{ref}[n] & \text{vector of references} \\ extractional e$ | error adial rting |
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| $\mathbf{d}[n] \text{vector of unknown disturbances} \qquad \mathbf{\dot{e}}[n] = \begin{bmatrix} \dot{e}_r[n] \end{bmatrix} \text{ vector of corrected focus and } \mathbf{r}_r$ $\mathbf{d}_{ref}[n] \text{vector of references} \qquad \mathbf{e}[n] = \begin{bmatrix} \dot{e}_r[n] \end{bmatrix}$ | adial |
| $\mathbf{d}_{ref}[n]$ vector of references $\begin{bmatrix} c_1[n] \end{bmatrix}$ | rting |
| olul vector of error clangle error clangle | rting |
| | rting |
| $\mathbf{s}_{m}[n]$ vector of measured detector signals ϑ fault encounter number | rting |
| $\mathbf{s}[n]$ vector detectors of signals without surface \mathbf{K}_{L} Karnunen-Loeve basis | rting |
| taults \mathbf{K}_n subset of the Karhunen–Loeve basis suppo | |
| $\eta[n]$ state vector the disturbances and noises | |
| $e_{\rm f}[n]$ waster of the focus and radial error $\mathbf{K}_{\tilde{e}}$ subset of the Karhunen–Loeve basis suppo | cting |
| $e[n] = \begin{bmatrix} e_r[n] \end{bmatrix}$ vector of the focus and fadial error components | |
| $\mathbf{n}_{m}[n]$ vector of measurement noises | |
| As $A_{\rm r}$ Bs B, Cs C _x state space model matrices \circ^L lifting operator | |
| $f(n, \mathbf{h}_{r}, \mathbf{h}_{r}, \mathbf{h}_{r}, \mathbf{h}_{r}, \mathbf{h}_{r}, \mathbf{h}_{r})$ focus and radial error measurements $e_{m,r}[n]$ focus and radial error measurements |) |
| mappings $g_{\rm f}, g_{\rm r}$ focus and radial optical gains | |
| $f_{d}[n]$ fault detection signal | |
| $\check{\mathbf{e}}[n] = \begin{bmatrix} e_{\mathrm{f}}[n] \\ e_{\mathrm{f}}[n] \end{bmatrix}$ vector of focus and radial fault error $\mathbf{k}_{\mathrm{f}}, \mathbf{k}_{\mathrm{r}}$ vectors of focus and radial approximation | iting |
| $\check{e}_{r}[n]$ coefficients | |
| component f_1 fault length in samples | |
| $\mathcal{P}()$ fault approximation operator | |
| $\tilde{\mathbf{e}}[n] = \begin{bmatrix} \mathbf{e}_1 \mathbf{e}_1 \\ \mathbf{e}_2 \mathbf{e}_1 \end{bmatrix}$ vector of estimated focus and radial K controller | |
| $\begin{bmatrix} e_r[n] \end{bmatrix}$ <i>CD</i> CD-player | |
| fault error component T complementary sensitivity of the closed loc | p of |
| $\left[\alpha_{\rm f}[n]\right]$ <i>CD</i> and <i>K</i> | |
| $\alpha[n] = \lfloor \alpha_r[n] \rfloor$ fault residuals relating to the fault S sensitivity of the closed loop of CD and K | - |
| Δ one revolution transport delay | |
| scanngs | |
| | |

and Steinbuch (1995), quantitative feedback theory was used in Hearns and Grimble (1999). In Li and Tsao (1999) rejection of non/repeatable disturbances was used, fuzzy control was used by Yen, Lin, Li, and Chen (1992). In Yao, Wang, and Cheng (2001), a hybrid fuzzy control was designed, linear quadratic Gaussian control was used in Weerasooriya and Phan (1995) and a disturbance observer was designed in Fujiyama, Tomizuka, and Katayama (1998). A vibration absorber to damp the mechanical disturbances was used in Wook Heo and Chung (2002). Steinbuch (2002) improves on the repetitive control scheme for reaction to the repetitive reference. Vidal Sánchez (2003) addresses the usage of fault-tolerant control in the handling of surface faults such as scratches, fingerprints, etc. The surface faults impose an upper limit on the controller bandwidth, which is in conflict with the minimization of the disturbance channels, since the controllers need a high bandwidth. Heertjes and Sperling (2003) and Heertjes and Steinbuch (2004) indirectly handle the surface faults by the use of non-linear filters to improve controller sensitivity without making the controllers more sensitive to the surface faults.

In this paper a control scheme based on fault-tolerant control and signal processing is presented. This scheme has been studied in the Ph.D. work by the first author, see Odgaard (2004). The scheme is called feature-based control, since features are extracted from the surface faults and subsequently used to remove the influence of surface faults on the error signals. The standard nominal controllers can subsequently be used to control the focusing and radial tracking. Minor parts of this featurebased control scheme have previously been published in a number of conference papers. These are: time localization and fault detection of surface faults, see Odgaard and Wickerhauser (2004b), fault classification of surface faults, see Odgaard and Wickerhauser (2004a), and a simulation model of CD-players playing CDs with surface faults (Odgaard, Stoustrup, Andersen, Wickerhauser, & Mikkelsen, 2004). This paper presents the entire feature-based control scheme, in which the loop is closed by the fault accommodation scheme in the algorithm, i.e. upon detection of a surface fault the surface fault features are extracted, and used to remove the fault influence at the next encounter. Stability and performance of the proposed feature-based fault accommodation scheme is discussed, and experiments which compares performance of the proposed scheme and a scheme commonly used in the optical drive industry are presented as well.

A short description of focus and radial servos in the CD-player is given together with a description of the relevant model. The general structure of the feature-based control scheme is presented, followed by the major contribution of this paper, which is the fault accommodation part of the feature-based control scheme. A necessary and sufficient stability condition for this scheme is given. Finally, the performance of the control scheme is validated by experimental work, where clear improvements in the handling of the surface faults are seen.

2. Description and model of the compact disc player

The laser beam emitted from the OPU in the CD-player is focused on the reflection layer of the disc, and radially tracked on the spiral-shaped data track by movements of the OPU in two directions, called focus and radial directions. These movements are enabled by an actuator with two actuated degrees of freedom, where linear electromagnetic actuators are used to perform the actual movements. The positions of the OPU in the two directions are measured by using smart optics in the OPU. The OPU regarded in this paper generates four detector signals which are correlated to the tracking errors. Many different detector types are used in the industry, in this section a short introduction to the two detectors used in this work is given. Experts in the field can skip this part. The two focus detector signals, D_1 and D_2 are formed by the use of the single Foucault principle applied to the main laser beam. The Foucault principle applied to the center of the laser beam is illustrated in Fig. 1. The upper part illustrates the



Fig. 1. Illustration of the single Foucault focus detector principle.

situation where the OPU is focused, $D_1 - D_2 = 0$, followed by the situation where the OPU is too close to the disc, $D_1 - D_2 > 0$, and the situation where the OPU is too far away from the disc, $D_1 - D_2 < 0$. Fig. 2 illustrates D_1 and D_2 's dependency on the focus error. Notice that when the beam is focused D_1 and D_2 are equal but different from zero because the laser beam has finite radius. For large errors, the laser spot will be larger than the detectors and the detector signals will decrease.

The radial detector signals are formed by the use of two additional satellite beams placed relative to the main beam with an offset a_k as illustrated in Fig. 3. The two satellite beams are detected by separate detectors, S_1 and S_2 . The energies in the two reflected beams depend on their respective placement over the track. I.e. if the main spot is centered over the track, $S_1 - S_2 = 0$, else if the main spot is to the right, $S_1 - S_2 < 0$, and if it is too much to the left, $S_1 - S_2 > 0$. For more information on these principles and other detector principles, see Stan (1998) and Bouwhuis et al. (1985).

A frequently used method for detection of faults is to observe changes in either the sum of focus signals or the sum of the radial signals, since these sums represent the amount of reflected energy from the disc, and a fault would reduce the amount of reflected energy, see Philips (1994), Andersen, Pedersen, Stoustrup, and Vidal (2001) and



Fig. 2. Illustration of the two focus detector signals $(D_1 \text{ and } D_2)$ dependency on the focus error. The dashed line illustrates the combined trajectory of D_1 and D_2 as the laser beam gets out of focus by either getting too close to or too far away from the reflection layer on the disc. The trajectory is for a fixed radial position.



Fig. 3. Illustration on how the three beams are placed relative to each other on the disc surface.



Fig. 4. The principles of the model of the CD-player. The CD-player consists of two parts. The electro-magnetic system and the optical system. This model contains in addition a model of the reference and the surface faults.

Vidal, Hansen et al. (2001). Unfortunately, the focus sum also depends on the radial error and the radial sum depends on the focus error. In Odgaard, Stoustrup, Andersen, and Mikkelsen (2006) a pair of decoupled fault residuals is defined, which can be used instead.

Unfortunately, the error measurements are influenced by surface faults. All this is illustrated by Fig. 4. 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, $\mathbf{d}_{ref}[n]$ is a vector of the unknown references to the system, $\mathbf{e}[n]$ is a vector of the focus errors, $\mathbf{s}_m[n]$ is a vector of the measured detector signals and $\mathbf{s}[n]$ is a vector of ideal detector signals without surface faults.

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 model are much alike, and are often modeled by decoupled second order models, see Stan (1998), Vidal, Stoustrup, Andersen, Pedersen, and Mikkelsen (2001), Bouwhuis et al. (1985) and Vidal, Hansen et al. (2001).

$$\dot{\eta}(t) = \begin{bmatrix} \mathbf{A}_{\mathrm{f}} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{\mathrm{r}} \end{bmatrix} \cdot \eta(t) + \begin{bmatrix} \mathbf{A}_{\mathrm{f}} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{\mathrm{r}} \end{bmatrix} \cdot \mathbf{u}(t), \tag{1}$$

$$\begin{bmatrix} e_{\rm f}(t) \\ e_{\rm r}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{C}_{\rm f} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_{\rm r} \end{bmatrix} \cdot \eta(t), \tag{2}$$

where $\eta(t)$ is the vector of states in the model, $e_{\rm f}[n]$ is the focus error, $e_{\rm r}[n]$ is the radial error, $\mathbf{A}_{\rm f} \in \mathscr{R}^{2\times 2}, \mathbf{B}_{\rm f} \in \mathscr{R}^{2\times 1}, \mathbf{C}_{\rm f} \in \mathscr{R}^{1\times 2}$ are the state space matrices in the focus model, and $\mathbf{A}_{\rm r} \in \mathscr{R}^{2\times 2}, \mathbf{B}_{\rm r} \in \mathscr{R}^{2\times 1}, \mathbf{C}_{\rm r} \in \mathscr{R}^{1\times 2}$ are the state space matrices in the radial model. In this model cross-couplings and a parasitic mechanical mode have been neglected since they only have minor influence on the response of the frequency range considered in this paper.

2.2. Model of the optical detectors

The optical model, mapping from physical focus and radial errors to the four detector signals, is expressed by the

vector mapping

$$\mathbf{f}: \begin{bmatrix} e_{\mathrm{f}}(t) \\ e_{\mathrm{r}}(t) \end{bmatrix} \rightarrow \begin{bmatrix} D_{1}(t) \\ D_{2}(t) \\ S_{1}(t) \\ S_{2}(t) \end{bmatrix}.$$
(3)

The mapping $\mathbf{f}(e_f(t), e_r(t))$ can be separated into a product of two mappings. One mapping representing the focusing of the OPU which only depends on the focus error, the second mapping represents the placement of the OPU in the radial direction. This mapping only depends on the radial error. This separation into a product of two functions results in the following model:

$$f_i(e_f(t), e_r(t)) \approx h_i(e_f(t)) \cdot g_i(e_r(t)), \tag{4}$$

where

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

moreover,

$$g_1(e_r(t)) = g_2(e_r(t)),$$
 (6)

since both mappings relate to the main beam. More specifically, they represent the main beam energy reflected from the surface, i.e. they represent the same mapping, and the difference between D_1 and D_2 is to be found in $h_1(e_f)$ representing the Foucault principle. In Odgaard, Stoustrup, Andersen, and Mikkelsen (2003b), detailed optical models are described. In practice, it is useful to simplify this model. This can be done by approximating $h_i(e_f[n])$ and $g_i(e_r[n])$ with cubic splines.

2.3. Model of the surface faults

Surface faults decrease the energy received in all the detectors. This can be described by scaling the photo detector signals, such that the two focus detectors are scaled with one scale, $1 - \alpha_f(t)$, and the two radial detectors are scaled with another one, $1 - \alpha_r(t)$. However, if these scalings were the only influence from 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 fault, however, also introduces a pair of faulty error components represented by a vector $\check{\mathbf{e}}(t)$, see Odgaard, Stoustrup, Andersen, and Mikkelsen (2003a) and Odgaard et al. (2004). These surface faults components are illustrated for the focus detector in Fig. 5.

This leads to the subsequent model of the detector signals during a surface fault. $1 - \alpha_f[n]$ and $1 - \alpha_r[n]$, respectively, scale the focus and radial output of the optical model, in which the fault error components ($\check{\mathbf{e}}[n]$) are added to the error signal, ($\mathbf{e}[n]$)

$$\mathbf{s}_{\mathrm{m}}(t) = \begin{bmatrix} (1 - \alpha_{\mathrm{f}}(t)) \cdot \mathbf{I} & \mathbf{0} \\ \mathbf{0} & (1 - \alpha_{\mathrm{r}}(t)) \cdot \mathbf{I} \end{bmatrix} \cdot \mathbf{f}(\mathbf{e}(t) + \check{\mathbf{e}}(t)).$$
(7)



Fig. 5. Illustration of how the surface fault influences the focus measurements D_1 and D_2 for a fixed radial position. $\alpha_f \cdot \mathbf{f}(e_f + \check{e}_f)$ is the measured point parameterized with α_f and \check{e}_f . $\mathbf{f}(e_f)$ is the point where the measurements would have been if no surface fault were present.



Fig. 6. 3D plot of $1 - \alpha_f[n]$ in sequential fault encounters. The duration and depth of the fault increases. The *x*-axis is samples of the *y*th encounter (the *y*-axis is the encounter number), and the *z*-axis is $1 - \alpha_f[n]$. Note that variations from one encounter to the next are almost negligible.

An important remark is that a surface fault does not vary much from one encounter to the next encounter. This is based on observations of a large number of different scratches with different orientations on the disc. An example is illustrated in Fig. 6, where $1 - \alpha_f[n]$ of a small scratch from 78 revolutions is illustrated. In all these observations of scratches, the scratches develop slowly during hundreds of encounters of the scratch, but the development from one encounter to the next can be neglected.

2.4. Experimental setup and practical considerations

The experimental setup consists of a CD-player, with a three beam single Foucault detector principle, a PC with an

I/O-card, and some hardware in order to connect the CDplayer with the I/O-card. Due to the limited computational power of the CPU in the PC, the sampling frequency is chosen at 35 kHz. This is lower than the normal CD-servo sampling frequency (44 kHz). The four detector signals and the two control signals are sampled. It is possible to control focus and radial error by the use of software running on the PC or by using the built-in controller of the CD-player.

In the following, the system is viewed as a discrete time system meaning that the models used are discretized with the sampling frequency of 35 kHz.

3. Feature-based control of compact disc players

In this section, the core of the feature-based control scheme of the CD-player will be described and designed. The idea is, in short, that the residuals are used to detect and locate the surface faults. The feature extraction presented in Odgaard and Wickerhauser (2004a) gives a classification of the fault. Approximating coefficients of the surface faults in a given basis representing the class of the fault has been presented in Odgaard, Stoustrup, Andersen, and Mikkelsen (2002) and 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. Since the fault component is removed from the detector signals, standard focus and radial controllers can be used.

The feature-based control strategy is illustrated in Fig. 7, from which it can be seen that the feature-based control strategy consists of: residual generator, feature extraction/ fault detection and fault accommodation. The residual generator uses an iterative computation of the inverse of the optical mapping to generate the residual pair $\alpha[\mathbf{n}]$, and a noise estimate of the focus and radial errors $\tilde{\mathbf{e}}[n]$. Internally in the residual generator, a Kalman estimator removes the measurement noise and surface fault components from $\tilde{\mathbf{e}}[n]$. This signal denoted, $\hat{\mathbf{e}}[n]$, is used as the initial guess for the position by the inverse optical mapping which is computed by a numerical iteration. In addition, $\hat{\mathbf{e}}[n]$ is used by the fault accommodation. $\alpha_{\rm f}[n]$ and $\alpha_{\rm r}[n]$ are fed to the fault detection, which detects the surface faults based on these residuals. It is optional to use the decoupled residuals to detect the surface faults; the normally used sum signals can be used instead for simplicity and reduced computational burden.

The fault detection detects and locates the fault in time. The time localization gives information of when to extract features and when to accommodate the fault. It can be done by the use of simple thresholds or by the methods presented in Odgaard and Wickerhauser (2004b), where time–frequency-based methods are used to design filters for detections of the faults. However, the experiments with surface faults strongly indicate that they are better located in time than in frequencies. In Odgaard and Wickerhauser (2004b), a time-based method is suggested in which the



Fig. 7. Illustration of the structure of the feature-based control scheme, which handles surface defects as faults.

surface faults are detected with multiple thresholds. $\mathbf{f}_{d}[n]$ is signal representing information on if a fault detected.

The feature extraction provides signals for fault accommodation using the class of the fault, see Odgaard and Wickerhauser (2004a), and approximating coefficients in the Karhunen–Loève basis of the given class of the fault. The vector of the approximated faults is denoted $\tilde{\mathbf{e}}[n]$. Different bases were tried and the Karhunen–Loève basis showed to be the best qualified. It has a very important property in this context, as it approximates the general trends in a set of signals by a few basis vectors, and the remaining ones support the noise in the signals (at least in the present case).

The fault accommodation is performed by removing the surface fault component from the measured error signals by subtracting the fault approximation. The vector containing these corrected error signals is denoted $\dot{\mathbf{e}}[n]$.

From this description of the feature-based control scheme it can be seen that the feature-based control strategy is strongly related to a fault-tolerant control scheme. The fault detection/locator performs the fault detection by locating the fault in time. In this application only surface faults are considered, so fault isolation is not required. The estimation of the fault is performed by fault classification and approximation of the fault, where a disturbance decoupled fault estimation is performed. This means that the fault detection together with the feature extraction form the fault diagnosis. These parts provide the fault accommodation with the information needed for handling the surface faults.

In Odgaard et al. (2004), the surface faults were simulated by the use of Karhunen–Loève approximations. It is seen that just a few Karhunen–Loève basis vectors can be used to approximate the surface faults very well, see



Fig. 8. Illustration of the Karhunen–Loève approximation of $\check{e}_{\rm f} + m_{\rm n,f}$ (fault and measurement noise of the focus signals) which contains a typical scratch. The approximation is denoted with $\check{e}_{\rm f}$. The first approximation is based on the most approximating coefficient. The second approximation is based on the four most approximating coefficients.

Fig. 8, where approximations with one and four basis vectors are compared to surface faults extracted from measurements. The idea is now to subtract that approximation from the measured detector signals the next time the fault is encountered before the measurements are fed to the nominal controllers. The algorithm will be described in the subsequent section.

4. Fault accommodation by removal of the surface fault

It has previously been stated that a fault does not vary much from one encounter to the next encounter. This means that an approximation of the fault at encounter ϑ can be subtracted from the fault at encounter $\vartheta + 1$. This will almost remove the fault from the measured signals as well as it could if the approximation was used at encounter ϑ . The signals used in the following are defined as follows: $\tilde{\mathbf{e}}[n]$ is a vector of the estimates of the faulty sensor components due to the surface fault. $\mathbf{e}_m[n]$ is a vector of the measured error. The relations among these signals are illustrated in Fig. 9.

4.1. Karhunen–Loève approximations

The Karhunen-Loève basis has a desirable property in this context. It supports the general signal trends in a matrix in which each column vector is an occurrence of one of the signals. The remaining basis vectors support the noise in the signals. This imply that if a Karhunen-Loève basis is computed of a set of $\check{\mathbf{e}}[n]$ during different surface faults, a few most approximating basis vectors will support the general trends in these signals, which can be assumed to be the fault component. I.e. if a $\check{e}[n]$ sequence is subsequently projected onto these approximating basis vectors, the fault component can be approximated, see Mallat (1999) and Wickerhauser (1994). Another sign of this basis' good approximating properties can be seen by the following fact. Given a matrix, \mathbf{X} , of u row vectors in \mathscr{R}^m , where u > m, the Karhunen–Loève basis minimizes the average linear approximation error of the vectors in the set (Mallat, 1999).

The Karhunen–Loève basis is computed based on X, first of all it is assumed that the column vectors in X have zero mean, if not a preliminary step is introduced in order to fulfill that assumption. The Karhunen–Loève basis, \mathcal{K} , which can be defined as

$$\mathscr{K} = \{v_1, \dots, v_m\} \tag{8}$$

is an orthonormal basis of eigenvectors of the matrix $\mathbf{X}\mathbf{X}^{\mathrm{T}}$, ordered in such a way that v_n is associated with the eigenvector λ_n , and $\lambda_i \ge \lambda_j$ for i > j. A matrix of the basis



Fig. 9. Illustration of the signals used in the feature-based control scheme.

vectors can be defined as follows:

$$\mathbf{K}_{\mathrm{L}} = [v_m, v_{m-1}, \dots, v_i]. \tag{9}$$

So in other words the Karhunen–Loève basis are the eigenvectors of the autocorrelation of \mathbf{X} . The eigenvalues of the autocorrelation have the values of the variances of the related Karhunen–Loève basis vectors. The approximating properties of the Karhunen–Loève basis vectors are sorted in increasing numerical order of their corresponding eigenvalues, that means that if the basis consists of p vectors, the basis vector p is the most approximating basis vector. In addition, the general structures in all the vectors in \mathbf{X} are often represented by only a few basis vectors. The remaining basis vectors represent the signal parts which are not general for \mathbf{X} , i.e. noise in the signal, etc.

The approximating qualities have been verified in practice on a large set of different scratches. The experiments have shown that by setting q = 4, the general trends of all the tested signals containing scratches have been supported by those four basis vectors, see Odgaard (2004) for more details. Consequently, the remaining basis vectors, \mathbf{K}_n , are assumed to span the noise and disturbances in the error signals. In Fig. 8, the approximation of the scratch by the four most approximating Karhunen–Loève basis vectors is illustrated. The partition of the Karhunen–Loève basis is described below

$$\mathbf{K}_{\mathrm{L}} = [\mathbf{K}_{\mathrm{n}} \ \mathbf{K}_{\check{e}}],\tag{10}$$

where

$$\mathbf{K}_{\mathrm{L}} \in \mathscr{R}^{(m \times m)},\tag{11}$$

$$\mathbf{K}_{\mathbf{n}} \in \mathscr{R}^{(m \times (m-q))},\tag{12}$$

$$\mathbf{K}_{\check{e}} \in \mathscr{R}^{(m \times q)},\tag{13}$$

$$q \ll m. \tag{14}$$

Based on (10), the fault component in the measured error signals can be separated from the measurement noise, which $\mathbf{K}_{\tilde{\mathbf{e}}}$ is constructed not to support. This is supported by observations on the data set: $\check{\mathbf{e}}$ from encounter n is correlated with $\check{\mathbf{e}}$ from encounter n+1, while the measurement noise at encounter n+1 is not correlated to measurement noise from encounter n. In addition, an observation has been made by inspection of the measured data, that the disturbances give small projections on $\mathbf{K}_{\check{\mathbf{e}}}$. The reconstruction of measured signals without this surface fault will reduce the fault components of focus and radial errors dramatically.

In the sequel a recurrent system is defined as a system where specific signal sequences of constant window lengths are recurring with non-specific intervals. The length of these signal sequences are denoted l_w and the windows begins at samples T_1, T_2, \ldots .

The lifting operator L transforms a linear recurrent system to a time invariant representation defined as in (15). A more detailed description of the lifting operator is given

in Khargonekar, Poolla, and Tannenbaum (1985). The concept in the lifting is to take the repeated signal parts out of the measurements and place them as row vectors in a matrix.

$$L: (y_0, y_1, \dots)^{\mathrm{T}} \mapsto \begin{bmatrix} (y_{T_0}, y_{T_0+1}, \dots, y_{T_0+l_w-1}) \\ (y_{T_1}, y_{T_1+1}, \dots, y_{T_1+l_w-1}) \\ \vdots \end{bmatrix}^{\mathrm{T}},$$
(15)

where y is the signal which shall be lifted. In this case, the window length is equal to m, the length of the Karhunen–Loève basis vectors.

An estimate of $\check{\mathbf{e}}[n]$ during a fault at encounter ϑ can be computed by

$$\tilde{\check{\mathbf{e}}} = \begin{bmatrix} \mathbf{K}_{\check{e}_{\mathrm{f}}} \mathbf{K}_{\check{e}_{\mathrm{f}}}^{\mathrm{T}} \cdot (e_{\mathrm{m,f}}^{L}[\vartheta] - \hat{e}_{\mathrm{f}}^{L}[\vartheta]) \\ \mathbf{K}_{\check{e}_{\mathrm{r}}} \mathbf{K}_{\check{e}_{\mathrm{r}}}^{\mathrm{T}} \cdot (e_{\mathrm{m,r}}^{L}[\vartheta] - \hat{e}_{\mathrm{r}}^{L}[\vartheta]) \end{bmatrix}.$$
(16)

Here, $\cdot^{L}[\vartheta]$ denotes the lifted signals, where the ϑ th fault encounter begins at sample no. n_{ϑ} .

In order to use the approximation in (16), it is needed to estimate $\hat{\mathbf{e}}[n]$ by the use of a filter, e.g. the Kalman estimator described in Odgaard et al. (2006). However, if $\hat{\mathbf{e}}[n]$ does not have large projections of $\mathbf{K}_{\check{\mathbf{e}}}$, (16) can be approximated by

$$\tilde{\check{\mathbf{e}}} = \begin{bmatrix} \mathbf{K}_{\check{e}_{\mathrm{f}}} \mathbf{K}_{\check{e}_{\mathrm{f}}}^{\mathrm{T}} \cdot e_{\mathrm{m,f}}^{L}[\vartheta] \\ \mathbf{K}_{\check{e}_{\mathrm{r}}} \mathbf{K}_{\check{e}_{\mathrm{r}}}^{\mathrm{T}} \cdot e_{\mathrm{m,r}}^{L}[\vartheta] \end{bmatrix}.$$
(17)

The Kalman estimator is only used to estimate $\hat{\mathbf{e}}[n]$. The Kalman estimator is not mandatory in the closed-loop feature-based control scheme, but it is needed in order to pre-compute the Karhunen–Loève basis of the surface faults. Intuitively, the Kalman estimator can be seen here as a tool for converting closed-loop measurements into open-loop equivalents.

If focus and radial errors are in the nominal operation range, the faults can be approximated by the use of the normalized focus and radial difference signals:

$$e_{\mathrm{m,f}}[n] \approx g_{\mathrm{f}} \cdot \frac{D_1[n] - D_2[n]}{D_1[n] + D_2[n]},$$
 (18)

$$e_{\rm m,r}[n] \approx g_{\rm r} \cdot \frac{S_1[n] - S_2[n]}{S_1[n] + S_2[n]},$$
 (19)

where $g_{\rm f}$ is the optical gain in the focus loop and $g_{\rm r}$ is the optical gain in the radial loop.

Due to limitations in the PC computational power, only the approach without the on-line Kalman estimator is tested on the test setup. An extension of the proposed method could contain an adaptive scheme where the basis is trained based on faults on a given CD.

The stability and performance issues of the fault removal scheme is dealt with in Section 5.

The approximation of the surface fault has now been computed. The next problem is to determine when to begin the correction of focus and radial errors. This involves a synchronization of the correction with the error signals, where a correct synchronization results in a removal of the fault from the measurements. An incorrect synchronization might result in an increase of the controller reaction to the surface fault, and could actually make the problem with the surface faults more severe than if no correction was performed.

4.2. Synchronization of the fault removal

In order to synchronize the correction of the measured signals two methods were used: detection of the beginning and the end of the surface fault, and prediction of the next fault based on previous encounters of the faults and knowledge of the revolution period. The first method uses detection at a given fault to correct this fault. This method has a good synchronization, but unfortunately has the drawback that since it uses a threshold, it will locate the beginning of the fault some samples after beginning of the fault and locate the end some samples before the actual ending of the fault. Using the previous location of the fault in time to predict the next fault makes it possible to begin and end the correction at a more correct time than if detection based on the given fault is used. This prediction is based on some time localization scheme, e.g. the one developed in Odgaard and Wickerhauser (2004b). However, it is not possible in practical settings to predict the placement of a fault. The reason for this is the implementation of the controller of the disc motor, which should guarantee a constant linear speed of the OPU relative to the track. However, this controller is implemented in a way that does not result in a constant linear speed but only in a linear speed in intervals. It might be possible to compensate this by using sub-codes from the CD. Unfortunately, these were not available for the controller in the test setup.

In practice, a combination of the two fault localization methods is used. The prediction, based on the time localization methods presented in Odgaard and Wickerhauser (2004b), is used to give an interval in which the fault is located and in this interval a lower threshold, than if the prediction was not used, can be used, see Fig. 10. This approach is possible since the problem in using low threshold during the entire playback is not the measurement noise but disturbances. These are time located and the risk of encountering them during the short low threshold interval is thereby limited.



Fig. 10. Illustration on the fault location and the interval in which the fault is located.

4.3. The algorithm of the feature-based control strategy

The fault correction algorithm can now be stated:

(1) Detect the fault and locate its position in time, when the fault is detected at sample n, $f_d[n] = 1$.

(2) If
$$f_d[n] = 1$$
:

$$a = \begin{cases} 0 & \text{if } f_{d}[n-1] = 0, \\ a+1 & \text{if } f_{d}[n-1] = 1, \end{cases}$$
$$\dot{\mathbf{e}}[n] = \mathbf{e}_{m}[n] - \begin{bmatrix} \tilde{\mathbf{e}}_{f}[n] \\ \vdots \end{bmatrix}_{t=1}^{t},$$

 $|\check{\mathbf{e}}_{\mathrm{r}}[\iota]|'$

where

$$l = ((256 - l_f) \operatorname{div}(2)) + a_f$$

where a is a counter counting the number of samples the given fault is present, and i is a counter used to locate the given sample relative to the fault correction block.

- (3) When the fault has been passed, classify the fault, time locate the fault, and compute the fault length $l_{\rm f}$.
- (4) Compute the focus correction block coefficients by $\mathbf{k}_{f} = \mathbf{K}_{\check{e}_{f}} \cdot e_{m,f}[v]$

and the radial correction coefficients by

 $\mathbf{k}_{r} = \mathbf{K}_{\check{e}_{r}} \cdot e_{m,r}[v]$, where v is the interval of 256 samples in which the fault is present.

(5) Compute the focus fault removal correction block by $\tilde{\tilde{e}}_{\rm f} = K_{\tilde{e}_{\rm f}} \cdot k_{\rm f},$

and the radial fault removal correction by $\tilde{\check{e}}_{r} = \mathbf{K}_{\check{e}_{r}} \cdot \mathbf{k}_{r}$.

The fault is thereby only located once per encounter, since the length of the fault maximally changes with one sample from encounter to encounter.

In the following, $\mathscr{P}(\cdot)$ denotes an operator that maps measured signals into their fault components by applying the correction algorithm. Due to the design of $\mathbf{K}_{\check{\mathbf{e}}}$ it does in principle not make any difference whether $\mathbf{e}_{\mathrm{m}}[n] - \hat{\mathbf{e}}[n]$ is used to estimate the surface fault, since $\mathbf{K}_{\check{\mathbf{e}}}$ is designed to support $\check{\mathbf{e}}[n]$ and assumed not to support $\mathbf{e}_{\mathrm{m}}[n]$. This means that

$$\mathscr{P}(\mathbf{e}_{\mathrm{m}})[n] \approx \mathscr{P}(\check{\mathbf{e}})[n] \Rightarrow \tag{20}$$

$$\mathscr{P}(\hat{\mathbf{e}})[n] \approx 0, \tag{21}$$

which in turn implies that it is not necessary to estimate $\hat{\mathbf{e}}[n]$. The normalized focus and radial differences, (18, 19), can be used instead and thereby save computing power. Only the last version of the algorithm is implemented due to limitations in the computing power in the experimental setup (Fig. 11).

5. Stability and performance of the feature-based control scheme

The feature-based control strategy is illustrated in Fig. 12. This figure illustrates how the influence from the



Fig. 11. Illustration of the feature-based control scheme illustrated as a state machine. The dashed lines do not illustrate state changes but illustrate data transfers. If a fault is detected at sample n, f_d has 1 as its value; if a fault is not present, it takes the value 0. f_u denotes an indication of whether the fault has been updated. The Fault Removal represents step 2 in the feature-based control scheme and Fault Update represents step 3–5 in this scheme.



Fig. 12. Illustration of the closed loop with the feature-based correction.

surface fault is removed by the use of $\mathcal{P}(\cdot)$. This means that the controller, K, reacts on the sum of $\mathbf{e}[n]$ and the measurement noise, $n_{\rm m}$.

In the following, some stability and performance issues of the algorithm will be discussed starting with dealing with the stability.

5.1. Stability

It is assumed that K and CD are internally stable, and that the nominal controller K stabilizes the plant CD, if $\check{e}[n]$ is zero or near zero. If $\check{e}[n]$ increases, it might force the CDplayer outside its linear region and could cause an unstable closed loop. On the other hand, if $\check{e}[n] \approx e[n] + n_m[n]$ the effect from the surface fault has been removed from the closed loop. This means that the control signal would be the same as in the fault-free case, meaning that the system is stable since it is nominally stable. \mathscr{P} reconstructs the recurrent part of the measurement signals meaning that

$$\mathbf{e}_{\mathrm{m}} - \mathscr{P}(\mathbf{e}_{\mathrm{m}}) \approx \mathbf{e} + \mathbf{n}_{\mathrm{m}}.$$
(22)

This can be achieved if

$$\check{\mathbf{e}} \approx \mathscr{P}(\mathbf{e}_{\mathrm{m}}) \Rightarrow \tag{23}$$

$$\mathscr{P}(\mathbf{n}_{\mathrm{m}}) \approx 0 \land \mathscr{P}(\mathbf{e}) \approx 0 \land \check{\mathbf{e}} = \mathscr{P}(\check{\mathbf{e}}).$$
(24)

This in turn is fulfilled if the approximating bases in $\mathcal{P}(\cdot)$ approximate $\check{\mathbf{e}}[n]$ well but not $\mathbf{e}[n]$ or $\mathbf{n}_{\mathrm{m}}[n]$. $\mathscr{P}(\cdot)$ is designed to be the best approximating basis of $\check{\mathbf{e}}[n]$. The Karhunen-Loève basis is not designed to support e[n], but no guarantees are given that it does not. Instead $\mathcal{P}(\cdot)$ might amplify the system dynamics to a degree that causes the entire system to be unstable. From this it is clear that $\mathcal{P}(\cdot)$'s amplification of the system dynamics must be small, such that the energy in a given system response is decreased through $\mathscr{P}(\cdot)$ from revolution to revolution. By inspecting in Fig. 12 the way the feature-based control scheme influences the control loop, it can be observed that the influence can be analyzed by using the complementary sensitivity of the servo system. The influence from the feature-based fault handling on the nominal servo system can be analyzed by the diagram of Fig. 13, where T denotes the complementary sensitivity of the nominal servo system, and Δ is the one revolution delay, see Fig. 13.

In order to combine these systems, the complementary sensitivity of the nominal servo system and \mathcal{P} are lifted, meaning that both subsystems are represented by a discrete time series of a given length.

The lifted \mathcal{P} can be computed by

$$\mathscr{P}^{\mathrm{L}} = \mathbf{K}_{\check{e}} \cdot \mathbf{K}_{\check{e}}^{\mathrm{T}},\tag{25}$$

and the lifted representation of the complementary sensitivity is

$$T^{\rm L} = \begin{bmatrix} h_0 & 0 & \cdots & 0 \\ h_1 & h_0 & & \vdots \\ \vdots & & \ddots & \\ h_{255} & \cdots & & h_0 \end{bmatrix},$$
(26)

where $\mathbf{h} = [h_0 \ h_1 \ \cdots \ h_{255}]$ is time series of 256 samples are the impulse response of *T*. The 256 samples are sufficient, since the response of a scratch can be covered in those 256 samples. This fact can be determined by analysis of the impulse response, and it is confirmed by experiments.

By lifting the system illustrated in Fig. 13, one gets a set of discrete difference equations of the form

$$\xi[N+1] = \mathbf{A}\xi[N] + \mathbf{K}\mathbf{u}[N], \tag{27}$$



Fig. 13. Closed loop of the feature-based control system.

where $\mathbf{A} = T^{L} \mathscr{P}^{L}$. These definitions make it possible to formulate Lemma 1, which states when the linear system is stable.

Lemma 1. *The feature-based control system defined by Fig.* 12 *is stable if and only if*

$$\max(|\operatorname{eig}(T^{\mathsf{L}}\mathscr{P}^{\mathsf{L}})|) < 1,$$

where \mathscr{P}^{L} is defined in (25) and T^{L} is defined in (26).

Proof of Lemma (*Necessary and sufficient conditions*). The stability of the closed-loop system shown in Fig. 12 is equivalent to stability of the system in (27), which is a standard LTI discrete time system, from which the result follows, due to the standard Schur condition.

It is now possible to test if the feature-based control scheme is linearly stable regarding both focus and radial loops. It is done by using models of the focus and radial loops. The nominal controllers and the computed $\mathbf{K}_{\check{e}_{\mathrm{f}}}$ and $\mathbf{K}_{\check{e}_{\mathrm{f}}}$. The computed value of max($|\operatorname{eig}(T^L \mathscr{P}^L)|$) in the focus case is 0.6894 and in the radial case 0.499. The conclusion is that the linear stability criteria are fulfilled for both servo loops. I.e. as long as the focus and radial servos are in the linear region of the optical sensors these controllers are stable.

5.2. Performance of the feature-based control scheme

High performance in the context of the proposed algorithm means the fault approximation only relies on the fault directly and not on fault through the closed-loop response of the OPU and the nominal controller. In order to inspect the performance of the algorithm, it is needed to take the closed loop into account, i.e. to determine the influence from the closed loop on the approximation of the surface fault. In this regard, influence will change from encounter to encounter due to the dynamics of the closed loop, and since the system is linear and stable, it will converge. By inspecting Fig. 12, it can be seen that the approximation of the surface fault directly and through the closed-loop sensitivity

$$\tilde{\check{\mathbf{e}}}_{1}^{L} = \mathscr{P}^{\mathrm{L}}(\mathbf{I} + \mathbf{S}^{\mathrm{L}})\check{\mathbf{e}}_{0}^{L},$$
(28)

where S^{L} is the lifted sensitivity of the servo. Another important issue to verify is whether the performance converges over a number of fault encounters. Hence, the same approximation is computed for encounter $\vartheta = 2$ as well. In principle, this approximation also depends on the previous fault encounter. However, for simplification it is assumed that the fault component of the successive encounters of the faults are equal to each other. This means that the response of the fault component and its approximation depend on the past approximation of the fault component in the error signals. This leads to this approximation of the fault at the second encounter

$$\tilde{\check{\mathbf{e}}}_{2}^{L} = \mathscr{P}^{\mathrm{L}}(\mathbf{I} + \mathbf{S}^{\mathrm{L}} - \mathbf{T}^{\mathrm{L}}\mathscr{P}^{\mathrm{L}}\mathbf{S}^{\mathrm{L}})\check{\mathbf{e}}_{1}^{L},$$
(29)

and the same scheme is repeated again for computing the estimate at encounter $\vartheta = 3$

$$\tilde{\tilde{\mathbf{e}}}_{3}^{L} = \mathscr{P}^{L}(\mathbf{I} + \mathbf{S}^{L} - \mathbf{T}^{L}\mathscr{P}^{L}\mathbf{S}^{L})\tilde{\mathbf{e}}_{2}^{L} + \mathbf{P}^{L}\mathscr{T}^{L}\mathbf{P}^{L}\mathscr{T}^{L}\mathbf{S}^{L}\tilde{\mathbf{e}}_{2}^{L}.$$
(30)

The estimates of these three encounters have been computed. This means that the influence from the closed loop can be determined by computing the energy of $\tilde{\mathbf{e}}_{1,2,3}$ over the energy of $\mathscr{P}^{\mathsf{L}}\mathbf{\check{e}}[n_3]$, $\vartheta \in \{1, 2, 3\}$. I.e.

$$\frac{\|\check{\mathbf{e}} - \check{\mathbf{e}}\|}{\|\check{\mathbf{e}}\|}.$$
(31)

These energy ratios are computed for the signals in the data set, and the mean of all these ratios are subsequently computed for focus and radial servos. The ratio for focus is 0.1134 and for radial it is 0.033 for all the encounters meaning that, given this system and controller and the approximating basis and surface faults, the algorithm converges in the first iteration. In addition, it can be seen that the influence on the approximations from the controller and CD-player is small, meaning that the performance of the algorithm is almost only depending on the quality of the approximations of the surface faults, which has previously been concluded to be quite high.

6. Experimental results

The next step is to verify the algorithm on the experimental test setup, see Section 2.4.

6.1. Practical implementation of the algorithm

The implementation uses only the four most approximating basis vectors, of three different classes of scratches, where only one was tested at each time for each of the two error signals. The four basis vectors are chosen in order to limit the number of computations in the algorithm, and since experiments have shown that these four basis vectors approximate the faults very well. More classes are properly needed in order to cover all possible surface faults. In order to avoid book-keeping algorithms, it is assumed that the CD only has one scratch. The applied controllers are the frequently used PID-based controllers, see Stan (1998), where some additional filters are used in addition to a PIDcontroller. One way to do the book keeping is to use the placement of the scratches to identify each encountered fault, and subsequently relate the encountered fault with the approximation of the specific scratch. The algorithm should be robust towards multiple faults in the approximation window.

The algorithm has been tested on a CD with a scratch which was not included in the training set of the algorithm.

The scratch has been classified to be contained in the class of small scratches. Due to limitations in the computing power in the test setup, the algorithm was not used on both focus and radial loops at the same time. For the same reason, only the method without the Kalman estimator was tested. It has not been possible to implement the entire method due to computational limitations. However, the other optional parts of the method have previously been validated by practical work, see Odgaard (2004). A scheme combining all these scheme parts is assumed to give better results.

In these experiments the fault is located by predicting a region in which the fault is present. A threshold algorithm is used inside this region to locate the fault. This threshold can as a consequence be chosen lower. The fault correction is subsequently applied when the fault is located and detected. It is assumed that the length of the fault is the same as at the last encounter. The length of the fault is denoted f_1 . The length of the correction block is 256, since $f_1 < 256$ for the entire data set of surface faults. As long as the fault is located, the fault can be corrected as given in the algorithm listed in Section 4.3.

6.2. The experiments

The first experiment was to verify that synchronization based on prediction only is not possible. The result can be seen in Fig. 14. From this figure it is seen that it is not possible to handle surface faults by using prediction alone for their time localization, as mentioned in Section 4.2. Instead the prediction is used to give a broader region in which the fault is assumed to reside, and in this region a



Fig. 14. A plot of the measured normalized focus difference, while the feature-based correction algorithm is applied with the use of prediction of the fault location. The fault accommodation of fourth and fifth encounters of fault results in a clear improvement. The fault correction in the following encounters is out of synchronization. The correction results in the best case has no improvements. As a consequence, this synchronization scheme is not used further.

lower threshold is used to detect the occurrence of the fault. As will be seen implicitly in the subsequent plots, this method works nicely, and no synchronization problems were encountered during those experiments. In the experiments, the feature-based control scheme is compared with a scheme commonly used in optical disc industry, which is implemented in the computer in the experimental setup. In this industrial method, the error signals are set to zero during the fault. Subsequently, two experiments are shown, one with the focus loop and one with the radial loop.

In Fig. 15, an example of handling the focus loop is illustrated. The first encounter of the scratch is handled by the standard method, and in addition used to train the proposed scheme. The peak sizes of the scratch at the encounters handled by the correction algorithm are minimized. Additional peaks can be seen in the part where the fault correction operates. However, these peaks are due to disturbances or measurement noise, and not due to the error correction algorithm (since measurements are only corrected during the one scratch per revolution). A short deviation from the focus point is not of large importance, since a significant number of lost bytes can be reconstructed by an error correction algorithm. The improvement can be seen more clearly from the zoom on the first and fifth encounter of the fault, see Fig. 16. The figure shows $(D_1 - D_2)/(D_1 + D_2)$ and not the physical focus error, and the approximation of the fault component has not been subtracted from the signal in the figure. The signal part underlined with the text "Surface Faults" is the fault, and this is the same for both handling methods. The difference is to be found in the CD-player's response on the fault component in the error measurement. From the figure, it is clear that the feature-based algorithm reacts



Fig. 15. A plot of the measured normalized focus difference while the correction algorithm is applied with the use of fault detection. It is clear to see that the correction results in a limitation of the influence from the fault on the measured normalized focus difference.



Fig. 16. A zoom on the first and fifth encounter of the fault shown in Fig. 15.



Fig. 17. A plot of the measured normalized radial difference while the fault correction algorithm is applied with the use of thresholding in a predicted interval. It is clear to see that the fault correction algorithms result in limitation of the influence from the fault on the approximated $e_r[n]$, when the correction algorithm is applied at the fourth encounter of the fault and onward.

more correctly than the scheme commonly used in optical drive industry handling does.

Subsequently, the algorithm was tested on the radial servo loop, which is known as being more sensitive to faults than the focus servo. An example of the algorithm handling a scratch can be seen in Fig. 17. The first three encounters are handled by the scheme commonly used in optical drive industry, and it actually looses the radial tracking in the example in Fig. 17, which can be seen by the heavy OPU oscillations. The asymmetry in the oscillations is due to a bias in the measurements. However, when the featurebased correction algorithm is applied, the radial tracking is



Fig. 18. A zoom on the second and fourth encounter of the fault shown in Fig. 17. It can be seen that if no correction is applied, the fault forces the OPU into heavy oscillations, which are avoided when the correction algorithm is used.

not lost. A zoom on the second (without correction) and fourth (with correction) encounter of the fault is shown in Fig. 18.

These experimental results show that a limited version of the feature-based fault correction algorithm, which is proposed in this chapter, gives a clear improvement of the performance handling of the surface faults, at least in the case of the tested scratches. The full algorithm based on both loops might even give better results, as simulations indicate. In the test with the focus loop, the error response due to the fault was clearly decreased by the feature-based control scheme compared to the tested commonly used industrial fault handling scheme. In the test of the radial loop, the industrial handling scheme failed to keep the CD-player tracked, whereas the proposed feature-based control algorithm succeeded in doing this.

6.3. System requirements

The feature-based control scheme has a clear potential for improving the handling of surface faults. It is therefore relevant to discuss the requirements to the CD-player for usage of the proposed scheme. The scheme has been developed using a specific CD-player and test equipment, but it is possible to adapt the scheme to other CD-players. In this work a drive with three-beam single Foucault detector principle has been used. In the following, the important requirements and use of resources will be mentioned and discussed. The resources are counted for one loop (focus or radial). In the experimental work, three different classes of faults (scratches) have been considered.

The algorithm does not require any changes in the sample rate of the control system in the CD-player. Actually in this experiment, a lower sample rate than normal has been used. The strong requirements to the player from the scheme are the demands of memory and computations. The use of these resources has not been optimized in this work. The length of the approximating basis vectors has in this paper been chosen to 256 samples (corresponding to approximately 9.5 mm), which might be much more than needed. By comparing the sample frequency, reading speed, and maximal error correction length, it seems that a length of 64 samples is enough. It might even be possible to use shorter vectors than 64 samples. The number of basis vectors could also be decreased to three or two basis vectors, though this will result in a decreased performance improvement. A third factor which should be taken into consideration is the number of possible faults for which the approximating coefficients are stored. In addition, in this work each measurement has been sampled in 16 bit; this can be reduced.

The following elements are required to be stored in the memory: the approximating basis vectors and approximating coefficients. The basis vectors fill: 4 vectors of 64 samples in 16 bits: $4 \times 64 \times 16 = 4096$ bits. For each fault which the scheme shall handle, it requires in addition: 4 coefficients of 16 bits: $4 \times 16 = 64$ bits. This means the required memory can be computed to: $4096 + (number of handled faults) \times 64$ bits. However, if vector length and measurement resolution are decreased, the storage requirement can be reduced.

The number of required additional computations by the feature-based scheme can be computed by: $2 \times$ the number of basis vectors \times the vector length: $2 \times 4 \times 64 = 512$ multiplications per fault encounter, and $2 \times$ the number of basis vectors \times the vector length $-1 + 4 \times$ vector length: $2 \times 4 \times 63 + 4 \times 64 = 760$ additions per fault encounter.

In addition to these requirements of the scheme parts presented in this paper, other parts of the scheme use the following resources. The classification and detection scheme allocates 272 bits, and requires 256 multiplications and 252 additions per fault encounter. If the Kalman estimator is used on-line, it will allocate 372 bits and require 19 multiplications and 16 additions at each sample time.

One should also be aware that this algorithm works by adapting to the slow development of the surface faults, and the handling performance cannot be assumed if the CD-player jumps from one track to another. If the player cannot resume play after a jump to a track with a scratch, the approach would involve iterative jumps backwards one track at a time, until playing is again possible. Playing continuously from the start of the scratch, the algorithm should then be expected to be able to pass the desired track with the difficult scratch.

7. Conclusion

In this paper a feature-based control scheme for CDplayers has been derived and verified. This scheme is essentially a fault-tolerant control scheme. The fault accommodation part of the feature-based control algorithm is based on removal of the influence from the surface faults. The surface faults are approximated by computing the projection of the normalized measured focus and radial differences feedback on the Karhunen-Loève bases vector approximating the surface faults. The estimated fault-free error signals are computed by subtracting the estimated surface fault from the measured error signals. Stability and performance issues of the feature-based control algorithm are discussed, and it is proven that the scheme is stable, based on a linear model of the CD-player. The scheme is verified by experimental results, in which a simplified version of the feature-based control scheme is implemented. These experimental results show that the algorithm handles the tested surface faults better than a scheme commonly used in the optical drive industry. In one case, the scheme commonly used in the optical drive industry failed playing a disc, whereas the proposed algorithm succeeded. The proposed algorithm has higher requirements to computational power and memory capacity, which are not met by all existing platforms. Some issues are still to be addressed before it can be used industrially. These include: book keeping of multiple faults, improved synchronization, and expansion of the fault data basis.

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