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1992

ISSN 0280–5316
ISRN LUTFD2/TFRT--7490--SE

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May 1992

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Document name
INTERNAL REPORT

Date of issue
May 1992

Document Number
ISRN LUTFD2/TFRT--7490--SE

Author(s)
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Supervisor

Sponsoring organisation

Title and subtitle
Optimal Modification of Reference Signals for Critical Processes using Alarm Signals

Abstract

Submitted to IFAC 12th World Congress, 1993

Key words
Stochastic control, Optimal control, Level-crossings, Supervision, Discrete events

Classification system and/or index terms (if any)

Supplementary bibliographical information

ISSN and key title
0280–5316

ISBN

Language
English

Number of pages
16

Recipient's notes

Security classification

Optimal Modification of Reference Signals for Critical Processes using Alarm Signals

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Classification R–11–5

Keywords Stochastic control, Optimal control, Level-Crossings, Supervision, Discrete events

Abstract An optimal scheme for the modification of reference signals based on information obtained from alarm signals is proposed. The modification may be interpreted as a feed-forward controller from the alarm. The scheme is simulated on some process-examples.

Mode of Presentation Preffered 20 minute oral

Prize The paper is to be considered for IFAC Congress Young Author Prize.

1. Introduction

Many processes in industry are critical. They are often critical in the sense that they have a limiting level. This can be either physical or artificial. Examples of the former are such levels that cannot be exceeded without catastrophic consequences, e.g. explosion. One example on the latter is alarm levels, which if they are exceeded will initiate emergency shutdown or a change in operational conditions. Another is quality levels, which if they are exceeded will cause unsatisfied customers. Common to the critical processes are that they enter their critical region abruptly as a signal exceeds a limiting level.

Control of critical processes has been described in [Hansson, 1991a; Hansson and Nielsen, 1991; Hansson, 1991b; Hansson, 1991c; Hansson, 1992a; Hansson, 1992b; Hansson, 1993]. There the aim has been to design feedback controllers for the case of a constant reference value.

Most critical processes are equipped with supervision. Often an alarm is given when a signal crosses a certain alarm level. Then an operator, depending on the situation, either initiates emergency shutdown or a temporary change of the operational conditions. This temporary change could be to choose a new reference value in order to avoid that the controlled signal continues to increase and thus preventing an exceedance of a higher more dangerous level. This change of reference value is mostly done in an ad hoc fashion. It would be of interest to make the modification in a more controlled and automatic way.

In this paper automatic and optimal modifications of reference values are proposed. The scheme can be interpreted as an optimal feed-forward controller. The measurement signal is an alarm, or more precisely the event that a signal crosses an alarm level. Thus the scheme is based on discrete events. It is supposed that the process is stable or stabilized by a feedback controller. This will make it possible to use the proposed controller without having to modify existing feedback controllers. This is of great importance, since permission to modify working feedback controllers for critical processes in industry is usually very difficult to get.

In Section 2 the problem formulation is given. The process is modeled as a stochastic differential equation. The modified reference signal is obtained by minimizing a certain loss function. In Section 3 it is shown how the solution to the problem may be obtained by computing one-dimensional integrals and performing some linear filtering. In Section 4 the resulting scheme is investigated on some process-examples. Finally, in Section 5 the results are summarized.

2. Problem Formulation

In this section the problem formulation is given. In the first subsection the process is modeled as a stochastic differential equation. In the second subsection a loss function is proposed. Minimizing this will give the modified reference signal. The solution may be interpreted as a feed-forward controller. In the last subsection the results are summarized.

Process Model

Different types of mathematical models have been used for the design of controllers. Usually differential or difference equations are considered. These describe among other things the dependence between the control signal and the controlled signal. Furthermore they usually describe how disturbances influence the controlled signal. Models are often obtained via process identification, and as a by-product of the identification-schemes statistical information about the disturbances are usually obtained,[Ljung, 1987]. Therefore stochastic differential equations will be considered as models of the critical processes for which the reference signal scheme is to be designed.

Let the asymptotically stable process be modeled as

$$\begin{cases} dx(t) = Ax(t)dt + B_1\left[r(t) + u(t)\right]dt + B_2 dv(t), & x(0) \in \mathcal{N}(m_0, R_0) \\ y(t) = C_1 x(t) \\ z(t) = C_2 x(t) \end{cases}$$

where $y(t) \in R$ is a signal related to an alarm, $z(t) \in R$ is the controlled signal, $r(t) \in R$ is the nominal reference value, $u(t) \in R$ is the modification of the reference value to be chosen based on the alarm, and v is a Wiener process with incremental covariance $R(t)dt$. For the signal y to be differentiable in mean square, it will be assumed that $C_1 B_2 = 0$. The reason for having $C_1 \neq C_2$ is that the signal y may sometimes be a filtered version of z due to sensor dynamics.

Loss Function

How should the modification u of the reference value r in the above model be chosen? As stated previously the idea is to make this modification based on an alarm, i.e. the upcrossing of a certain level, say y_0, by the signal y at time t_0. A possible choice would be to choose u as the solution that minimizes the loss function

$$J = \mathrm{E}\left\{ \frac{1}{2}\int_{t_0}^{t_1} \left[(z(t) - r(t))^2 + \rho u^2(t)\right] dt \middle| y(t_0) = y_0,\ \dot{y}(t_0) > 0 \right\} \quad (1)$$

It is assumed that the optimal u is a function of the alarm and that $u(t) = 0, \quad t \leq t_0$. Further it is assumed that $\rho > 0$. With a suitable choice of this weighting it will be possible to tune the speed of the modification. It will be seen that the solution to this problem is an open-loop controller, and thus the modification of the reference value may be interpreted as a feed-forward controller from the alarm signal.

It may be argued that other types of loss functions would be more appealing. The feedback-case with constant reference value described in [Hansson, 1991a; Hansson, 1991b; Hansson, 1993] would inspire loss functions of the type

$$\mathrm{E}\left\{\sup_{t\in[t_0,t_1]}[z(t)-r(t)]\big|y(t_0)=y_0,\ \dot{y}(t_0)>0\right\}$$

However, the approximate solutions given there, making use of the upcrossing intensity, are difficult to use here, since the expression for the upcrossing intensity is much more complicated for the case of time-varying reference value, see e.g. [Cramér and Leadbetter, 1967, Chapter 13.2].

The conditioning made in (1) is not the only possible one. It is also possible to use so called vertical-window conditioning in stead of the here used horizontal-window conditioning. This was first described in [Kac and Slepian, 1959]. See [Cramér and Leadbetter, 1967, Chapter 11.1] for a good explanation of the difference. However, since the reference value is time-varying, it will not be possible to benefit from the advantages due to considering other definitions of conditioning.

Summary

A model in terms of a stochastic differential equation has been proposed for the critical process. It is assumed that the model is asymptotically stable and that the signal that causes the alarm is differentiable in mean square. Further the modification of the reference value is to be obtained by solving an open-loop optimal stochastic control problem, where the measurement is given in terms of an upcrossing of an alarm level.

3. Controller Design

In this section the control problem posed in the previous section will be solved. It will be sen that the solution can be obtained by using standard numerical routines. In the first subsection the problem is rewritten into a deterministic optimal open-loop control problem. In the second subsection this problem is solved using the Euler-Lagrange formalism, and in the third subsection the input signals to the Euler-Lagrange equation are computed. Finally, in the fourth subsection the results are summarized.

Deterministic Optimal Control Problem

To rewrite the loss-function introduce

$$\begin{cases} \dfrac{d\bar{m}_x}{dt} = A\bar{m}_x + B_1(r+u), \quad \bar{m}_x(0) = m_0 \\ \bar{m}_y = C_1\bar{m}_x \\ \bar{m}_z = C_2\bar{m}_x \end{cases} \tag{2}$$

Thus it holds that

$$\begin{cases} d\tilde{x} = A\tilde{x}dt + B_2dv, \quad \tilde{x}(0) \in \mathcal{N}(0, R_0) \\ \tilde{y} = C_1\tilde{x} \\ \tilde{z} = C_2\tilde{x} \end{cases}$$

where

$$\begin{cases} \tilde{x} = x - \bar{m}_x \\ \tilde{y} = y - \bar{m}_y \\ \tilde{z} = z - \bar{m}_z \end{cases}$$

Now the state vector and the output-signals are decomposed into one term corresponding to the influence of the Wiener-process and one term corresponding to the influence of the reference signal and its modification. Let

$$\begin{cases} m_x(t) = \mathrm{E}\{\bar{m}_x(t)|y(t_0) = y_0,\ \dot{y}(t_0) > 0\} \\ m_y(t) = \mathrm{E}\{\bar{m}_y(t)|y(t_0) = y_0,\ \dot{y}(t_0) > 0\} \\ m_z(t) = \mathrm{E}\{\bar{m}_z(t)|y(t_0) = y_0,\ \dot{y}(t_0) > 0\} \end{cases}$$

By expanding the signal it is seen that

$$\begin{aligned} &\mathrm{E}\left\{(z(t) - r(t))^2\middle|y(t_0) = y_0,\ \dot{y}(t_0) > 0\right\} \\ &\quad = \eta(t, t_0) + 2\xi(t, t_0)[m_z(t) - r(t)] + [m_z(t) - r(t)]^2, \quad t > t_0 \end{aligned}$$

where

$$\xi(t, t_0) = \mathrm{E}\left\{\tilde{z}(t)\middle|\tilde{y}(t_0) = y_0 - m_y(t_0),\ \dot{\tilde{y}}(t_0) > -\dot{m}_y(t_0)\right\}, \quad t > t_0$$
$$\eta(t, t_0) = \mathrm{E}\left\{\tilde{z}(t)^2\middle|\tilde{y}(t_0) = y_0 - m_y(t_0),\ \dot{\tilde{y}}(t_0) > -\dot{m}_y(t_0)\right\}, \quad t > t_0$$

Thus it holds that

$$J = \int_{t_0}^{t_1} L(m_x(t), u(t), t)\,dt$$

where

$$L\left(m_x(t), u(t), t\right) = \frac{1}{2}\{\eta\left(t, t_0\right) + 2\xi\left(t, t_0\right)\left[C_2 m_x(t) - r(t)\right] + \left[C_2 m_x(t) - r(t)\right]^2 + \rho u^2(t)\}$$

If ξ and η are known, then this is a deterministic optimal control problem.

Euler-Lagrange Solution

To minimize the loss function J introduce the Lagrange-multiplier λ. Then it is easily shown, [Leitmann, 1981] that the optimal modification of the reference value is given by

$$u(t) = -\rho^{-1} B_1^T \lambda(t)$$

where λ is part of the solution to the boundary problem

$$\begin{pmatrix} \dot{m}_x \\ \dot{\lambda} \end{pmatrix} = \bar{A} \begin{pmatrix} m_x \\ \lambda \end{pmatrix} + \bar{B} \begin{pmatrix} \xi \\ r \end{pmatrix} \tag{3}$$

with $m_x\left(t_0\right) = \bar{m}_x\left(t_0\right)$ given by Equation (2), and $\lambda\left(t_1\right) = 0$, and where

$$\bar{A} = \begin{pmatrix} A & -\rho^{-1} B_1 B_1^T \\ -C_2^T C_2 & -A^T \end{pmatrix}$$

$$\bar{B} = \begin{pmatrix} B_1 & 0 \\ -C_2^T & C_2^T \end{pmatrix}$$

$$\tilde{B} = \begin{pmatrix} B_1 \\ 0 \end{pmatrix}$$

To solve the boundary problem introduce

$$\Sigma(t) = \begin{pmatrix} \Sigma_{11}(t) & \Sigma_{12}(t) \\ \Sigma_{21}(t) & \Sigma_{22}(t) \end{pmatrix} = e^{\bar{A}t}$$

where the blocking is done to correspond to the partitioning of the state vector. Now let

$$\begin{pmatrix} \alpha_1(t) \\ \alpha_2(t) \end{pmatrix} = \int_{t_0^{(i)}}^{t} \Sigma(t-s) \bar{B} \begin{pmatrix} \xi(s) \\ r(s) \end{pmatrix} ds$$

i.e. the solution to (3) for zero initial values. Then it holds that

$$0 = \lambda\left(t_1\right) = \Sigma_{21}\left(t_1 - t_0\right) m_x\left(t_0\right) + \Sigma_{22}\left(t_1 - t_0\right) \lambda\left(t_0\right) + \alpha_2\left(t_1\right)$$

from which $\lambda\left(t_0\right)$ can be found. This makes it possible to treat the boundary problem (3) as an initial value problem. It then holds that the λ-part of the solution to (3) is given by

$$\lambda(t) = \Sigma_{21}\left(t - t_0\right) m_x\left(t_0\right) + \Sigma_{22}\left(t - t_0\right) \lambda\left(t_0\right) + \alpha_2\left(t\right), \quad t_0 < t \leq t_1$$

Conditioned Expectations

It now only remains to calculate the conditioned expectation ξ. To this end introduce the Lyapunov equation

$$\frac{dP}{dt} = AP + PA^T + B_2RB_2^T, \quad P(0) = R_0$$

where R may be time-dependent. Now by [Åström, 1970, Theorem 6.1, p. 66 and Theorem 3.2, p. 219] it holds that

$$\begin{aligned} & \mathrm{E}\left\{\tilde{z}(t)\middle|\tilde{y}(t_0) = b, \dot{\tilde{y}}(t_0) = c\right\} \\ & = C_2 e^{A(t-t_0)} P(t_0) \begin{pmatrix} C_1 \\ C_1 A \end{pmatrix}^T Q^{-1} \begin{pmatrix} b \\ c \end{pmatrix} \end{aligned}$$

where

$$Q = \begin{pmatrix} C_1 \\ C_1 A \end{pmatrix} P(t_0) \begin{pmatrix} C_1 \\ C_1 A \end{pmatrix}^T$$

is the covariance matrix for $\tilde{y}(t_0)$ and $\dot{\tilde{y}}(t_0)$. Further by the formula for total probability and an interchange of integration and expectation it follows that for $t > t_0$ it holds

$$\begin{aligned} & \xi(t, t_0) \\ & = \frac{\int_{-\dot{m}_y(t_0)}^{\infty} p\left(y_0 - m_y(t_0), y\right) \mathrm{E}\left\{\tilde{z}(t)\middle|\tilde{y}(t_0) = y_0 - m_y(t_0), \dot{\tilde{y}}(t_0) = y\right\} dy}{\int_{-\dot{m}_y(t_0)}^{\infty} p\left(y_0 - m_y(t_0), y\right) dy} \end{aligned}$$

where p is the Gaussian density function for $\tilde{y}(t_0)$ and $\dot{\tilde{y}}(t_0)$. This has zero mean and covariance Q. If it is assumed that $\tilde{y}$ is a stationary random process, which is the case if e.g. $P(t) = R_0$, $\forall t$, then $\tilde{y}(t_0)$ and $\dot{\tilde{y}}(t_0)$ are independent, and the expression for ξ can be somewhat simplified

$$\begin{aligned} & \xi(t, t_0) \\ & = \frac{\int_{-\dot{m}_y(t_0)}^{\infty} p(y) \mathrm{E}\left\{\tilde{z}(t)\middle|\tilde{y}(t_0) = y_0 - m_y(t_0), \dot{\tilde{y}}(t_0) = y\right\} dy}{\int_{-\dot{m}_y(t_0)}^{\infty} p(y)\, dy} \end{aligned} \tag{4}$$

where now p is the Gaussian density function for $\dot{\tilde{y}}(t_0)$. This has zero mean and covariance given by $\sigma_{\dot{y}}^2 = C_1 A P A^T C_1^T$. Note that the denominator in (4) is easily expressed in terms of the normalized Gaussian distribution function $\Phi(x) = \int_{-\infty}^{x} \phi(t) dt$, where $\phi(x) = \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)$, i.e.

$$\int_{-\dot{m}_y(t_0)}^{\infty} p(y)\, dy = \Phi\left(\frac{\dot{m}_y(t_0)}{\sigma_{\dot{y}}}\right)$$

which is easily computed with standard numerical routines. Thus only one non-standard integral for the numerator has to be computed to obtain ξ for the case of $\tilde{y}$ being stationary.

Summary

It has been seen how it is possible to solve the problem posed in Section 2 by rewriting it as a deterministic optimal control problem and solving that problem by means of the Euler-Lagrange formalism. The solution involves solving a linear initial value problem. The input signals to this problem can be obtained by solving a linear Lyapunov equation and computing one-dimensional integrals. Further the initial values can be obtained by computing a matrix exponential and solving a linear set of equations. Thus the modification of the reference value is obtained by using numerical routines that are easy to implement.

4. Example

In this section the scheme designed in Section 3 will be computed for some process-examples. In the first subsection a badly damped second order process will be considered. The influence of the design-parameters, i.e. the weighting ρ and the integration time $t_1 - t_0$, will be investigated by means of simulations. In the second subsection a third order non-minimum phase process will be investigated. Although the non-minimum phase characteristics are difficult to handle, it will be seen that it is possible to obtain a usable modification also for this difficult process. Finally, in the last subsection the results of the previous subsections are summarized.

Second order Process

Let the process be given by

$$\begin{cases} dx(t) = \begin{pmatrix} -1 & 1 \\ -1 & 0 \end{pmatrix} x(t)dt + \begin{pmatrix} 0 \\ 1 \end{pmatrix} [r(t) + u(t)]\, dt + \begin{pmatrix} 0 \\ 1 \end{pmatrix} dv(t) \\ y(t) = \begin{pmatrix} 1 & 0 \end{pmatrix} x(t) \\ z(t) = \begin{pmatrix} 1 & 0 \end{pmatrix} x(t) \end{cases}$$

where $y = z$ is the controlled signal which is related to the alarm, r is the nominal reference value, u is the modification of the reference value to be chosen based on the alarm, v is a Wiener process with incremental covariance dt, and $x(0) \in \mathcal{N}(0, R_0)$. The covariance R_0 is chosen such that $\tilde{y}$ is stationary. Notice that the relative damping is only 0.5. Thus this example will illustrate

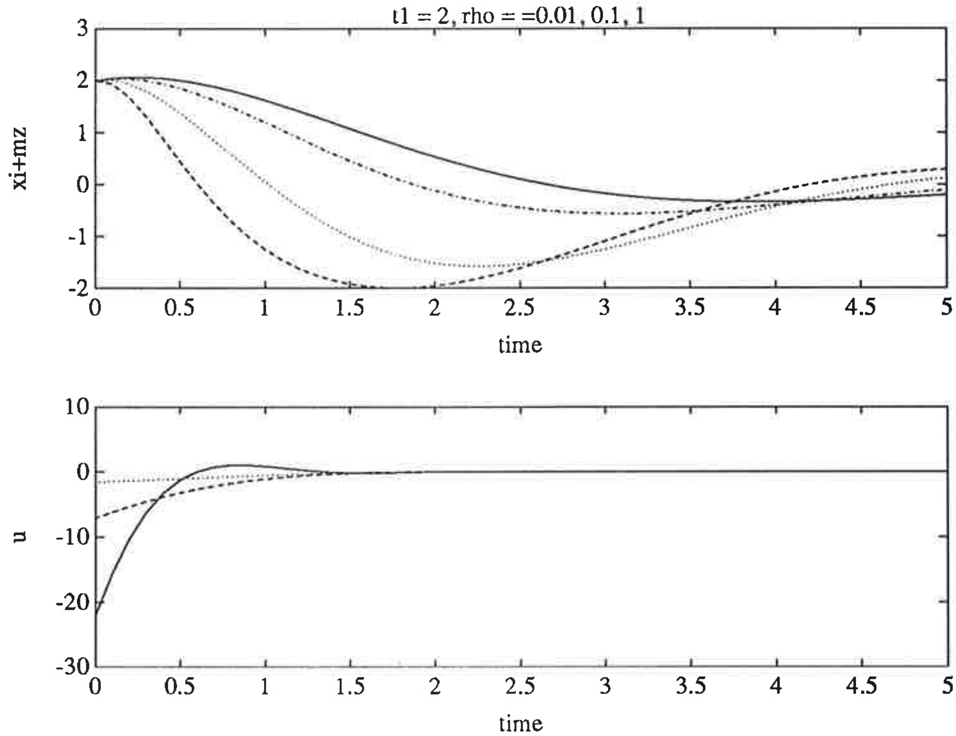

Figure 1. Plot of ξ and $\xi + m_z$—top, and of u—bottom, as functions of $t - t_0$. The solid line in the top plot is ξ. The dashed lines corresponds to $\rho = 0.01$, the dotted lines to $\rho = 0.1$, and the dash-dotted lines to $\rho = 1$.

the behavior of the scheme when applied to a badly controlled process; remember that the process model describes the system when being controlled with a feedback controller, i.e. the model is a closed loop model.

The optimal modification u has been computed for the alarm level $y_0 = 2$, the constant reference value $r = 0$ and different values of the weighting ρ and the integration time $t_1 - t_0$, where $t_0 = 0$. In Figure 1 the optimal modification u is plotted together with ξ and the resulting $m_z + \xi$ for $t_1 = 2$ and $\rho = 0.01,\ 0.1,\ 1$. Remember that it suffices to consider

$$\mathrm{E}\left\{ z(t) \middle| y(t_0) = y_0,\ \dot{y}(t_0) > 0 \right\} = m_z(t) + \xi(t, t_0)$$

since the conditioned variance η is not influenced by u. It is seen that the modification of the reference value has greater influence on $\xi + m_z$ the smaller ρ is. A reasonable value seams to be $\rho = 0.1$. In Figure 2 the optimal modification u is plotted together with ξ and the resulting $m_z + \xi$ for $\rho = 0.1$ and $t_1 = 1,\ 2,\ 3$. It is seen that the modification of the reference value has greater influence on $\xi + m_z$ the larger t_1 is. A reasonable value seams to be $t_1 = 1$.

It could be argued that the conditioning in the loss-function J on $y(t_0) > 0$

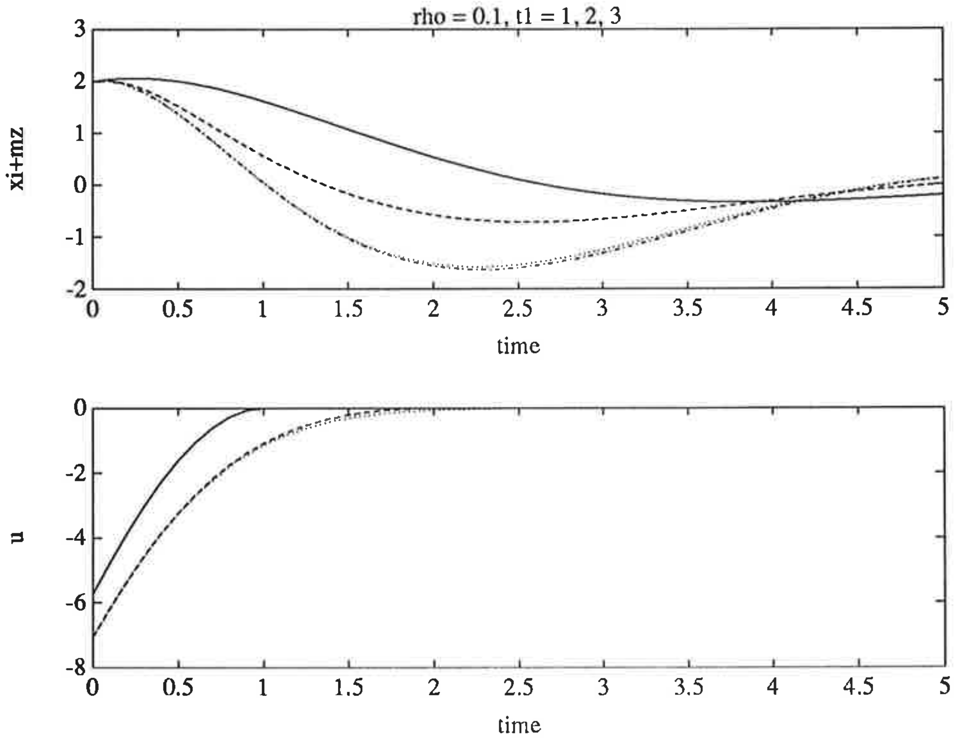

Figure 2. Plot of ξ and $\xi + m_z$—top, and of u—bottom, as functions of $t - t_0$. The solid line in the top plot is ξ. The dashed lines corresponds to $\rho = 0.01$, the dotted lines to $\rho = 0.1$, and the dash-dotted lines to $\rho = 1$.

not will give much more information than conditioning on only $y(t_0) = y_0$. However, if this extra information is not considered, then it can be shown that $\dot{\xi}(t_0, t_0) = 0$, and then ξ would not increase as in Figure 1 for small values of $t - t_0$. This increase is of paramount interest to take care of when controlling critical processes, since not considering it would give too small a modification of the reference value, which could cause a catastrophe.

Third order non-minimum phase Process

Let the process be given by

$$\begin{cases} dx(t) = \begin{pmatrix} -2 & 1 & 0 \\ -2 & 0 & 1 \\ -1 & 0 & 0 \end{pmatrix} x(t)dt + \begin{pmatrix} 0 \\ -1 \\ 1 \end{pmatrix} [r(t) + u(t)]\, dt + \begin{pmatrix} 0 \\ -1 \\ 1 \end{pmatrix} dv(t) \\ y(t) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} x(t) \\ z(t) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} x(t) \end{cases}$$

where $y = z$ is the controlled signal which is related to the alarm, r is the nominal reference value, u is the modification of the reference value to be chosen based on the alarm, v is a Wiener process with incremental covariance dt, and $x(0) \in \mathcal{N}(0, R_0)$. The covariance R_0 is chosen such that $\tilde{y}$ is stationary.

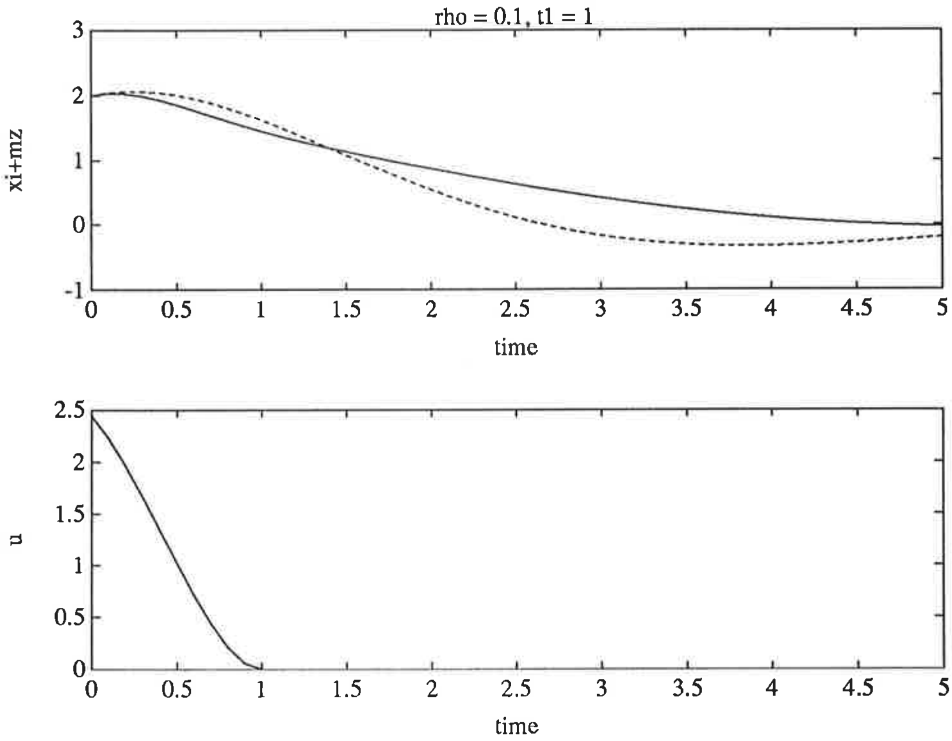

Figure 3. Plot of ξ and $\xi + m_z$—top, and of u—bottom, as functions of $t - t_0$. The solid line in the top plot is $\xi + mz$, the dashed line in the top plot is ξ, and the solid line in the bottom plot is u.

Notice the process zero at $s = 1$. Thus the closed loop is non-minimum phase, and it will be difficult to control.

The optimal modification u has been computed for the alarm level $y_0 = 2$, the constant reference value $r = 0$ and different values of the weighting ρ and the integration time $t_1 - t_0$, where $t_0 = 0$. In Figure 3 the optimal modification u is plotted together with ξ and the resulting $m_z + \xi$ for $t_1 = 1$ and $\rho = 0.1$, which are the best values of the investigated ones. Note that the modification u is positive. This is due to the process being non-minimum phase.

Summary

The proposed scheme has been investigated on some examples. It has been seen how the weighting and the integration time influences the modification. Further it has been seen that also modifications of reference values for very difficult processes, such as non-minimum phase processes, are easily obtained.

5. Conclusions

Many processes in industry are critical, and they are often equipped with supervision. Usually an operator use information from the supervision scheme, such as e.g. alarms, to modify the operational conditions. One such important modification is the change of reference value in order to avoid catastrophes.

In this paper automatic and optimal modifications of reference values have been investigated. The scheme can be interpreted as an optimal feed-forward controller. The measurement signal is an alarm, or more precisely the event that a signal crosses an alarm level. Thus the scheme is based on discrete events.

The process is modeled as a stochastic differential equation. The modified reference signal is obtained by minimizing a certain loss function. It has been seen how the solution to the problem may be obtained by computing one-dimensional integrals and performing some linear filtering. Thus the computations needed are moderate. Further, if the reference value is constant and the alarms are rare, then the initial values for (2) are zero, and the modification may be pre-computed once and for all at the design-stage. The proposed scheme has been investigated on some process-examples. It has been seen that modifications of reference values for difficult processes, such as non-minimum phase processes, are easily obtained.

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