Control Engineering Practice 26 (2014) 107–115

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Fault-tolerant control based on algebraic derivative estimation applied on a magnetically supported plate

Lothar Kiltz [a,*], Cédric Join [b,d], Mamadou Mboup [c,d], Joachim Rudolph [a]

[a] Chair of Systems Theory and Control Engineering, Saarland University, Campus A5 1, 66123 Saarbrücken, Germany
[b] CRAN (CNRS, UMR7039), Université de Lorraine, BP 239, 54506 Vandoeuvre-lès-Nancy, France
[c] CReSTIC - UFR SEN, Université de Reims Champagne-Ardenne, BP 1039 Moulin de la Housse, 51687 REIMS cedex 2, France
[d] Non-A–INRIA Lille Nord Europe, France

ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form
10 October 2013
Accepted 9 January 2014
Available online 8 February 2014

Keywords:
Fault-tolerant control
Fault diagnosis
Change-point detection
Numerical differentiation
Algebraic estimation

ABSTRACT

A fault-tolerant control method based on algebraic derivative estimation is introduced. It is applied on an electromagnetically supported plate as an example of a nonlinear and an open-loop unstable system. The design of the closed loop control is facilitated assuming that relevant faults are identified sufficiently precisely and fast. This is justified by a novel robust model-based fault identification scheme which relies on algebraic methods for numerical differentiation. Derivative estimation parameters and fault-detection thresholds are chosen systematically based on the properties of the measurements. The experimental results show the practical usefulness of the presented methods.

1. Introduction

Improving safety, reliability, and performance of industrial processes has become a major issue in control engineering practice. Fault-tolerant control plays an important role in this context. There are many different approaches to achieve such control, see for instance the survey (Patton, 1997) or the book (Blanke, Kinnaert, Lunze, & Staroswiecki, 2003), and the references therein.

In the present work, fault-tolerance is achieved in the following sense. Based upon fault detection, isolation, and identification (FDI), estimated faults are compensated in an independently designed control law. The FDI method is based on the concept of analytical redundancy, i.e., the measured behaviour of the process is compared to its nominal behaviour, the latter being defined by a mathematical model. Deviations between measured and nominal behaviour are evaluated to detect, isolate, and identify a fault.

Concerning FDI for linear systems, many different approaches have been proposed. Examples are those based on observers including Kalman filters (Frank, 1990), parity relations (Gertler & Singer, 1990), parameter estimation (Isermann, 1997; Patton, Frank, & Clark, 2000), and statistical tests (Basseville & Nikiforov, 1993). Useful surveys are given in the books (Blanke et al., 2003; Chen & Patton, 1999; Gertler, 1998; Noura, Theilliol, Ponsart, & Chamseddine, 2009).

For nonlinear systems, model-based FDI typically requires considerable realization effort (cf. the geometric approach in De Persis & Isidori, 2001), specifically when accounting for model uncertainties (Alavi & Saif, 2010; Zhang, Polycarpou, & Parisini, 2010). This effort may be reduced using the so-called algebraic estimation techniques as demonstrated in Fliess, Join, and Sira-Ramirez (2008), Mai and Hillermeier (2010), Ali, Join, and Hamelin (2011), and Kiltz, Mboup, and Rudolph (2012).

These results motivate the new fault-tolerant control approach used here on a magnetically supported plate. Here, a fault is interpreted as an abrupt change like a step in one of the control currents. FDI is particularly challenging in this setting where the process exhibits fast dynamics and dominant nonlinearities. Good performance of the proposed approach is shown in a real-time implementation.

This paper is structured as follows. In Section 2, the experimental setup and its mathematical model are introduced. Also, the considered faults are specified and the fault-tolerant control is explained assuming that the faults are identified. In Section 3, the fault identification scheme is presented. In Section 4, the parameter choice for the fault identification scheme driven by measurements is discussed. In Section 5, the presented results are summarized. Throughout the paper, the proposed methods are illustrated by experimental results.

2. Mathematical model and fault-tolerant control

The proposed fault-tolerant control relies on mathematical models of the physical process and the faults. In this section, these

* Corresponding author. Fax: +49 681 302 64722.
E-mail address: l.kiltz@lsr.uni-saarland.de (L. Kiltz).

0967-0661/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2014.01.009

models are introduced. Also, the control law is given since it is based on the nominal process model. Fault-tolerance is achieved by the FDI method discussed in Section 3.

2.1. Electromechanical system

The experimental setup is shown in Fig. 1. It consists of a rectangular aluminium plate with four iron profiles at its corners. Four electromagnets mounted to the frame above the iron profiles allow for the application of attracting forces $\boldsymbol{f}:\mathbb{R}\to\mathbb{R}^4$ to lift the plate. The setup also comprises four sensors measuring vertical displacements $\boldsymbol{y}:\mathbb{R}\to\mathbb{R}^4$ between the plate and the frame.

On the experimental setup, only small tilt angles are achievable. Hence, the magnetic forces are assumed to pull on the centers of the iron profiles. Under these assumptions, the plate can schematically be drawn as shown in Fig. 2, where m, J_x, and J_y denote the mass of the plate and its moments of inertia about the x_b- and y_b-axis, respectively. Additionally, l_{fx} and l_{fy} are the horizontal distances between the center of mass of the plate and the centers of the iron profiles in the x_b and y_b directions, respectively, while l_{dx} and l_{dy} determine the positions of the displacement sensors. Consequently, equations of motion describing the vertical translation of the plate and its rotation about two body-fixed coordinate axes can be written as

$$\boldsymbol{A}\ddot{\boldsymbol{y}}(t)=\boldsymbol{B}\boldsymbol{f}(t)+\boldsymbol{f}_g+\boldsymbol{\varpi}(t), \tag{1a}$$

where $\boldsymbol{f}_g=(-mg,0,0)^T$ is the gravitational force, and the matrices $\boldsymbol{A}\in\mathbb{R}^{3\times3}$, $\boldsymbol{B}\in\mathbb{R}^{3\times4}$ are given by

$$\boldsymbol{A}:=\begin{pmatrix}0 & -\frac{m}{2} & -\frac{m}{2}\\ -\frac{k_1}{2} & \frac{k_1}{2} & 0\\ -\frac{k_2}{2} & 0 & \frac{k_2}{2}\end{pmatrix},\quad \boldsymbol{B}:=\begin{pmatrix}1 & 1 & 1 & 1\\ 1 & -1 & 1 & -1\\ 1 & 1 & -1 & -1\end{pmatrix} \tag{1b}$$

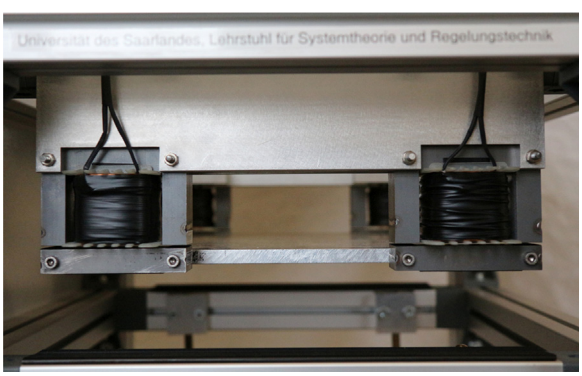

Fig. 1. Experimental setup.

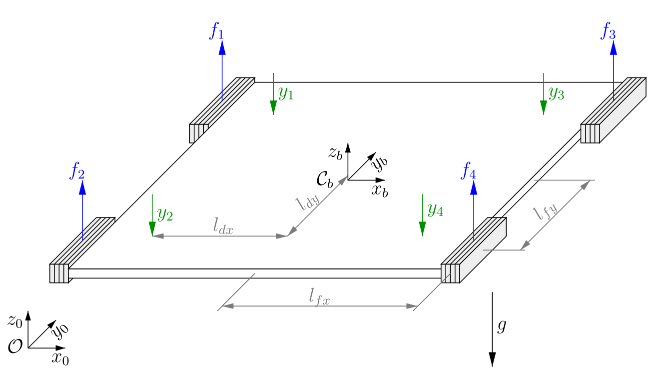

Fig. 2. Schematic of the plate's kinematics.

with $k_1:=J_x/(l_{dy}l_{fy})$, $k_2:=J_y/(l_{dx}l_{fx})$. The function $\boldsymbol{\varpi}:\mathbb{R}\to\mathbb{R}^3$ in (1a) summarizes the model uncertainties, such as slow model variations, or the influence of the non-modelled dynamics, such as mechanical eigenmodes.

The dynamics of the magnetic field generation are neglected due to the fact that the iron cores of the electromagnets and the iron profiles at the plate are laminated to prevent the generation of eddy currents. Thus, the magnetic forces are modelled as

$$f_k(t)=\frac{i_k^2(t)}{g_k(h_k(t))},\quad k=1,\dots,4, \tag{1c}$$

where $\boldsymbol{i}:\mathbb{R}\to\mathbb{R}^4$ are the currents through the magnetic coils. Here, $\boldsymbol{g}:\mathbb{R}\to\mathbb{R}^4$ approximates the measured relationships between the coil currents of the magnets, the forces they generate, and the distances $\boldsymbol{h}:\mathbb{R}\to\mathbb{R}^4$ between the magnets and the corresponding iron profiles at the center of the profiles:

$$\boldsymbol{h}(t)=\boldsymbol{C}_y^h\boldsymbol{y}(t). \tag{1d}$$

The coefficient $\boldsymbol{C}_y^h\in\mathbb{R}^{4\times3}$ is given by

$$\boldsymbol{C}_y^h:=\frac{1}{2}\begin{pmatrix}k_x+k_y & 1-k_y & 1-k_x & 0\\ k_x-k_y & 1+k_y & 1-k_x & 0\\ -k_x+k_y & 1-k_y & 1+k_x & 0\\ -k_x-k_y & 1+k_y & 1+k_x & 0\end{pmatrix} \tag{1e}$$

with $k_x:=l_{fx}/l_{dx}$, $k_y:=l_{fy}/l_{dy}$. The electromagnets are driven by underlying closed-loop current controllers. Thus, the dynamics of the current generation are neglected, and the magnet currents are considered as the control inputs of the electromechanical system. This is justified by Fig. 3, where a very fast step response of the closed loop current control may be observed. The fast fluctuations of the actual current around the desired current are captured by the model uncertainty $\boldsymbol{\varpi}$ in (1a).

Remark 1. Such a cascaded control structure, consisting of a fast current controller and a higher level controller, the latter being based on the neglection of the current dynamics, is typical for many industrial applications of electromagnetic actuators.

2.2. Measurements and faults

The mathematical model (1) defines relations between the actual coil currents $\boldsymbol{i}$, the actual magnetic forces $\boldsymbol{f}$, the actual displacements $\boldsymbol{y}$, and their second order derivatives $\ddot{\boldsymbol{y}}$ at each point of time t. In the practical application, only *measured* values $\boldsymbol{y}_m:\mathbb{R}\to\mathbb{R}^4$ of $\boldsymbol{y}$ and *desired* values $\boldsymbol{i}_d:\mathbb{R}\to\mathbb{R}^4$ of $\boldsymbol{i}$ are available, where the first ones are captured by the displacement sensors and the second ones are calculated by the position controller. Also, the acceleration $\ddot{\boldsymbol{y}}$ is unknown.

When compared to the actual displacements, their measured values are primarily corrupted by measurement noise $\boldsymbol{\eta}:\mathbb{R}\to\mathbb{R}^3$. The actual coil currents differ from their desired values essentially

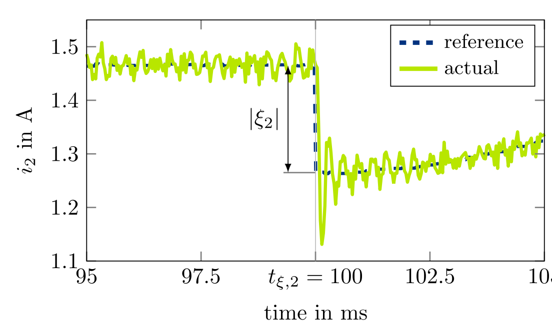

Fig. 3. Reference and actual coil current on actuator 2 when an abrupt fault is introduced.