Contents lists available at ScienceDirect

ISA Transactions

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

Research Article

Optimised sensor selection for control and fault tolerance of electromagnetic suspension systems: A robust loop shaping approach

Konstantinos Michail [a,*], Argyrios C. Zolotas [b], Roger M. Goodall [c]

[a] *Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, Limassol, Cyprus*
[b] *School of Engineering and Informatics, University of Sussex, United Kingdom*
[c] *Control Systems Group, School of Electronic, Electrical and Systems Engineering, Loughborough University, United Kingdom*

ARTICLE INFO

Article history:
Received 27 September 2012
Received in revised form
14 May 2013
Accepted 4 August 2013
This paper was recommended for publication by Dr. Didier Theilliol.

Keywords:
Optimised sensor selection
Robust control
Fault tolerant control
Magnetic levitation
Multiobjective optimisation
Electromagnetic suspension

ABSTRACT

This paper presents a systematic design framework for selecting the sensors in an optimised manner, simultaneously satisfying a set of given complex system control requirements, i.e. optimum and robust performance as well as fault tolerant control for high integrity systems. It is worth noting that optimum sensor selection in control system design is often a non-trivial task. Among all candidate sensor sets, the algorithm explores and separately optimises system performance with all the feasible sensor sets in order to identify fallback options under single or multiple sensor faults. The proposed approach combines modern robust control design, fault tolerant control, multiobjective optimisation and Monte Carlo techniques. Without loss of generality, it's efficacy is tested on an electromagnetic suspension system via appropriate realistic simulations.

1. Introduction

Optimum sensor selection in practical control system design can be a complex process especially if the selection is done with respect to a number of properties in order to achieve robust optimum performance and reliability properties.

A typical closed-loop control system is shown in Fig. 1. Typically, a system to be controlled has a number of candidate control inputs (actuators) and outputs (sensors) that could be used to control it by proper controller design using one of the existing modern control methods. Moreover the system suffers from input disturbances and uncertainties or model inaccuracies.

Additionally, faults highly affect the closed-loop performance of a control system. Particularly, actuator and sensor faults can cause performance degradation or even instability. This problem has been extensively considered by the scientific community in the last few years. Some typical work with applications to industrial systems includes [1–4].

The problem of sensor/actuator selection has been addressed before in the literature [5] but none of the methods considers simultaneous satisfaction of the aforementioned properties except in [6] where the authors have considered both optimum performance and sensor fault tolerance using *L*inear *Q*uadratic *G*aussian (LQG) control. Therefore the problem is to find the 'best' set of sensors, $\mathcal{Y}_o$, subject to the aforementioned control properties i.e. optimum performance, robustness, fault tolerance and minimum number of sensors.

The novelty in this paper relies on the fact that optimum robust performance with sensor fault tolerance is achieved by combining robust control methods, *F*ault *T*olerant *C*ontrol (FTC), *M*ulti-*O*bjective *OP*timisation (MOOP) and *M*onte *C*arlo (MC) method as illustrated in Fig. 2.

Robust control design in a practical control system has a vital role because real systems have uncertainties, disturbance inputs and other effects that affect the nominal performance of the closed-loop control system. In that context robust control theory has been developed in the last few years including $\mathcal{H}_\infty$ robust control methods [7]. Among the existing robust control methods the $\mathcal{H}_\infty$ *L*oop *S*haping *D*esign *P*rocedure (LSDP) is merged into the framework for the design of robust nominal controller [8].

Control system design for safety-critical systems [9,10] is vital for the integrity of such systems when sub-system faults occur. Therefore the scientific community developed an area where the faults can be accommodated. Fault tolerant control systems are divided into two categories, the *A*ctive FTC (AFTC) and the *P*assive

---

[*] Corresponding author. Tel.: +357 25002133.

E-mail addresses: kon_michael@ieee.org (K. Michail), a.zolotas@sussex.ac.uk (A.C. Zolotas), r.m.goodall@lboro.ac.uk (R.M. Goodall).

0019-0578/$ - see front matter © 2013 ISA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.isatra.2013.08.006

Please cite this article as: Michail K, et al. Optimised sensor selection for control and fault tolerance of electromagnetic suspension systems: A robust loop shaping approach. ISA Transactions (2013), http://dx.doi.org/10.1016/j.isatra.2013.08.006

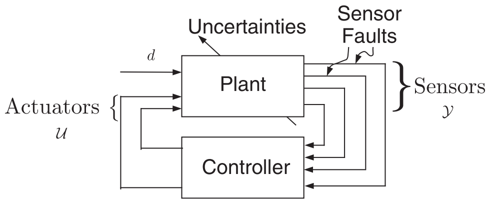

Fig. 1. A typical closed-loop control system.

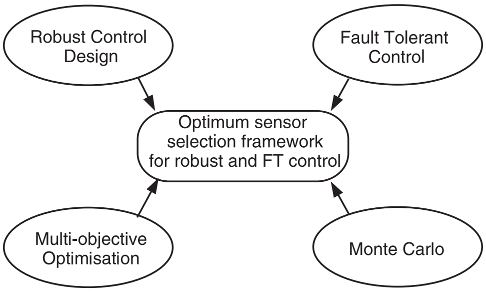

Fig. 2. The simplified diagram of the proposed framework for optimum sensor selection with robust control and fault tolerance.

FTC (PFTC) systems. In this work, the AFTC concept is introduced in order to accommodate multiple sensor faults [11–13].

Multiobjective constrained optimisation using heuristic approaches is very popular and has gained a lot of intention in the last few years [14,15]. Among the heuristic methods, *G*enetic *A*lgorithms (GAs) are favoured in control optimisation [16–18]. Since the beginning of GAs by Goldberg [19] many versions of GAs have been published all summarised in [20] with the latest version called *D*ynamical *M*ulti-objective *E*volutionary *A*lgorithm (DMOEA) been described in [21]. In this paper the *N*on-dominated *S*orting *G*enetic *A*lgorithm II (NSGAII) [22] is used for the optimisation part of the framework and shows to be a very strong optimisation tool in sensor selection for control design.

The Monte Carlo method has gained a lot of attention after the initial introduction by Metropolis [23,24]. Until today many methods have been introduced for random generation of numbers with this method [25,26]. Moreover the MC method can be used in control systems to assess the robustness in a probabilistic way [27]. In this paper the robustness against model parametric uncertainties is assessed using a combination of the MC and constraint handling functions as used in MOOP. Particularly, the MC is used to produce a number of models for the uncertainties and those are tested in closed-loop simulations using the nominal controller.

The proposed framework is assessed on an *E*lectro-*M*agnetic *S*uspension (EMS) system. The EMS systems are being used on the *MAG*netic *LEV*itated (MAGLEV) trains that have a number of advantages against the conventional wheel-on-rail trains [28]. As indicated in [29] the EMS is *N*on-*L*inear (NL), safety-critical and inherently unstable system with non-trial requirements. Such a system can easily serve as a good example for testing the efficacy of the proposed optimum sensor selection framework.

Summarizing, the novelty in this paper relies on the fact that $\mathcal{H}_\infty$ Robust Control, FTC, MC method and optimised tuning via GA concepts are combined to form a systematic framework in an attempt to simplify the selection of the best sensor set defined as, $\mathcal{Y}_o$, for the EMS system subject to optimum closed-loop performance and ensuring integrity and robustness of the system under possible sensor faults. In this context, the algorithm explores and separately optimises the performance of the EMS using all feasible sensor sets in order to identify fallback options under single or multiple sensor faults, i.e. instants of one or multiple sensors failing stability constraints but with optimum performance maintained by controller reconfiguration using the remaining healthy sensors.

The rest of the paper is separated into six sections: Section 2 explains the problem under consideration and describes the details of the proposed algorithm that leads to the optimum sensor selection for the control system design. Section 3 describes the rigorous modelling issues of the EMS system along with the disturbance inputs and multiple control objectives and constraint requirements. In Section 4 the multiobjective constraint optimisation concept as used in the algorithm is given emphasizing its usefulness and importance. Further Section 5 describes the sensor fault tolerance concept for the EMS system with the robustness assessment of the optimally tuned controller using the Monte Carlo method in combination with constraint handling technique as used in the previous section. In Section 6 data analysis is done from the realistic simulations done from the proposed framework. Finally, the conclusions of this work are given in Section 7.

2. The problem statement and description of the proposed framework

2.1. Problem statement

The plant shown in Fig. 1 has a set of control inputs (actuators) $\mathcal{U} = \{u_1, u_2, \ldots, u_{n_u}\}$, where n_u is the total number of actuators, a set of input disturbances $\mathcal{D} = \{d_1, d_2, \ldots, d_{n_d}\}$, where n_d is the total number of input disturbances, and a set of possible outputs (sensors), $\{\mathcal{Y} = y_1, y_2, \ldots, y_{n_s}\}$, where n_s is the total number of sensors, and a set of sensor sub-sets of $\mathcal{Y}$, $\mathbb{Y} = \{\mathcal{Y}_1, \mathcal{Y}_2 \ldots, \mathcal{Y}_{N_{ss}}\}$ to choose from, where N_{ss} is the total number of sensor sub-sets in $\mathbb{Y}$. The formal problem is defined as to determine the set of sensors, $\mathcal{Y}_o$, in $\mathbb{Y}$ (i.e. select $\mathcal{Y}_o \subset \mathbb{Y}(i)$), for which the system

1. satisfies a set of closed-loop performance criteria,
2. satisfies a set of fault tolerance criteria,
3. the sensor set has minimum redundancy i.e. the number of elements in $\mathcal{Y}_o$ is minimal,
4. has sufficient robustness against parametric uncertainties and
5. has low cost (although this property is not considered in the paper, its part of this problem and left for future work).

The following section gives a rigorous description of the proposed algorithm which attempts to solve this problem.

2.2. The proposed framework

The proposed framework can be summarised in the flow chart of Fig. 3. The particular points include the use of $\mathcal{H}_\infty$ loop-shaping design and the heuristic optimisation (evolutionary algorithms) method for tuning the controller subject to strict requirements (objectives and constraints) for each feasible sensor set of the EMS system. Prior to running the algorithm (initialization phase), some parameters are assigned including:

- *Formulate the model of the system*: Prior to algorithm execution formulate the model of the system to be examined, i.e. non-linearities, uncertainties, linearization, etc.
- *Generate the sensor sets*: A set, $\mathbb{Y}$, which contains all sensor sets is generated at this stage.
- *Define the control objective functions* (ϕ_i) *and constraints* (f_h,f_s): Usually, in a system's optimisation the control objectives are conflicting to each other therefore a trade-off exists between them. Also there is a number of control constraints that have to be satisfied in order for the system to have proper control

Please cite this article as: Michail K, et al. Optimised sensor selection for control and fault tolerance of electromagnetic suspension systems: A robust loop shaping approach. ISA Transactions (2013), http://dx.doi.org/10.1016/j.isatra.2013.08.006