IFAC World Congress 2017
Half-a-day Tutorial
Sunday 9th of July
14:00-17:30

Fault Diagnosis of Interconnected Cyber-Physical Systems

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Title of tutorial:
Fault Diagnosis of Interconnected Cyber-Physical Systems
Outline of the tutorial (topic and description):
Recent advances in information and communication technologies, embedded systems and sensor networks have generated significant research activity in the development of cyber-physical systems (CPS). The key motivation for the advancement of CPS is the need to better coordinate the interactions between the software and hardware designs by facilitating self-awareness in evolving environments, and the handling of a huge amount of data of different time and space characteristics (also known as 'big data'). During the last decade, the need for acquiring 'big data' has been addressed to some extend by the significant increase in the use of sensors of all kinds, which has instigated a revolution in the development of sensing devices and sensor networks. However, the acquired information is not always reliable and correct due to faults affecting the sensor devices and sensor networks. The consequences of sensor faults may cause significant damage, especially in automated decision and control scenarios. For this reason, it is necessary to apply mechanisms capable to assess the reliability of sensor information and guarantee the dependability of CPS. This tutorial will discuss the problem of the occurrence of faults in the sensors used to monitor and control a network of interconnected CPS. The goal of the tutorial will be to present a general methodology for designing model-based sensor fault diagnosis schemes, following three different architectures: centralized; decentralized; distributed. Particularly, the speakers will illustrate step-by-step the design of observer-based residuals, adaptive thresholds and decision-making logic based on analytical redundancy relations. Emphasis will be given on the isolation of multiple sensor faults, while discussing the trade-offs between the three architectures in relation to the system scale and nonlinearities, the

sensor fault detectability and multiple sensor fault isolability. A case study of monitoring smart buildings will be used to illustrate the methodology.

The topic of this tutorial matches well with the research areas and topics of the IFAC World Congress, as shown in the following table:

IFAC WC Technical Areas	**IFAC WC Keywords**
Signals & Systems	Sensor networks; Fault detection and diagnosis
Computers, Cognition & Communication	Remote sensor data acquisition
Mechatronics, Robotics & Components	Multi sensor systems; Sensor signal consolidation; Cyber-Physical Systems; Smart Sensors and Actuators; Networks of sensors and actuators; Information and sensor fusion
Power & Process Systems	Reconfigurable control, sensor and actuator faults; Estimation and fault detection; Fault diagnosis and fault tolerant control; Design of fault tolerant/reliable systems; Distributed Fault Diagnosis
Transportation & Vehicle Systems	Automotive sensors and actuators; Sensors and actuators; Decision making and autonomy, sensor data fusion; Networks of robots and intelligent sensors; Sensor integration and perception; Fault Detection, Diagnosis, Identification, Isolation and Tolerance for Autonomous Vehicles
Bio- and Ecological Systems	Wireless sensor networks in agriculture; Fault diagnosis

In the IFAC World Congress 2017, there will be several open invited tracks that deal with CPS and fault diagnosis, such as:

- Security and Privacy for Networked Multi-agent Cyber-physical systems;
- Statistical detection/isolation of cyber-physical attacks on SCADA systems;
- Cyber-physical systems for future industrial systems;
- Interoperability in Cyber Physical Smart and Sensing Systems;
- Health Monitoring and Fault Diagnosis of Complex Systems;
- Design of Fault Diagnosis and Fault-Tolerant Control methods in Unmanned Aerial Vehicle/Fleet;
- Modelling, Control and Fault Diagnosis for Building Energy Management Systems.

The tutorial will be given by Prof. Marios Polycarpou, who has extensive expertise in the area of fault diagnosis and is currently vice-chair of the IFAC SAFEPROCESS Technical Committee, and Dr. Vasso Reppa, who is an experienced researcher in the area of fault diagnosis. Due to their expertise, the speakers were invited to write a tutorial paper on sensor fault diagnosis for the journal *Foundations & Trends in Systems and Control*, which will be the basis for the proposed tutorial:

Vasso Reppa, Marios M. Polycarpou and Christos G. Panayiotou (2016), "Sensor Fault Diagnosis", Foundations and Trends® in Systems and Control: Vol. 3: No. 1-2, pp 1-248. http://dx.doi.org/10.1561/2600000007

Duration and sessions:

The tutorial will last **half-day** and will include the following sessions:

1. Introduction to Sensor Fault Diagnosis for Cyber-Physical Systems: In the first part of this tutorial, we will discuss the motivation for performing sensor fault diagnosis

(FD), and its impact on cyber-physical systems (CPS), and present the state-of-the-art of observer-based sensor FD methods. Emphasis will be given on model-based sensor FD for nonlinear systems, multiple sensor fault isolation, and non-centralized approaches.

2. Cyber-Physical Modelling for Sensor Fault Diagnosis: In the second part of this tutorial, we will present the formulation of sensor FD problem in a cyber-physical framework, and the high-level design of three model-based FD architectures, i.e. centralized, decentralized, distributed, for a network of interconnected CPS.
3. Sensor Fault Detection: In the third part, we will describe the step-by-step design of an observer-based fault detection method for a class of nonlinear systems, including the residual generation, the computation of adaptive thresholds and the decision logic in a centralized, decentralized and distributed framework. A discussion on the similarities and differences with other observer-based fault detection techniques will be provided.
4. Sensor Fault Isolation: In the fourth part, we will present the decentralized and distributed fault isolation decision making process with emphasis on the isolation of multiple sensor faults. In this part we will also give an overview of existing observer-based schemes for fault isolation, and different approaches for diagnostic reasoning.
5. Performance Analysis: In the fifth part, we will show a methodology for analysing the performance of the centralized, decentralized and distributed architecture with respect to sensor fault detectability, sensor fault propagation and multiple fault isolability.
6. Learning Approach for Sensor Fault Diagnosis: In the sixth part, we will present an adaptive approximation-based methodology for reducing the modelling uncertainty that impacts the sensor fault detectability of the observer-based diagnostic schemes.
7. Case Studies: To illustrate the overall sensor fault diagnosis methodology, we will consider all the steps of a case study for monitoring of smart buildings.
8. Challenges and Open Issues: This tutorial will be concluded with a discussion on open issues and challenges in fault diagnosis, and the intersection between cyber-security and fault diagnosis in CPS.

Description of the intended audience and the expected learning outcomes:

The proposed tutorial is oriented towards graduated students, researchers and engineers/practitioners from industry, who are interested in learning more about supervision and sensor fault diagnosis for large-scale interconnected CPS. The tutorial is also suitable for academic faculty in control systems, who would like to become more familiar with fault diagnosis.

It is expected that this tutorial will teach the participants how to design model-based techniques for sensor fault diagnosis following three different approaches: centralized, decentralized, distributed. The audience will have the opportunity to become familiar with design and real implementation challenges related to these approaches when the network of CPS is characterized by nonlinear and interconnected dynamics, its scale is large and multiple sensor faults may occur.

The participants will receive the research monograph of the speakers "Sensor Fault Diagnosis".

Desired prerequisite knowledge of the audience:

The audience is expected to be familiar with System Theory and fundamental automatic control theory. No prior expertise in fault diagnosis is required.

Tutorial speakers:

Prof. Marios Polycarpou,
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Dr. Vasso Reppa
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Brief biographies of the speakers:

Marios Polycarpou is a Professor of Electrical and Computer Engineering and the Director of the KIOS Research Center for Intelligent Systems and Networks at the University of Cyprus. In November 2016, the KIOS Research Center was upgraded by the European Commission to a Center of Excellence for Research and Innovation. Prof. Polycarpou served as the President of the IEEE Computational Intelligence Society (01/2012-01/2013) and as Editor-in-Chief of the *IEEE Transactions on Neural Networks and Learning Systems* between 2004 and 2010. He is a Fellow of IEEE and IFAC and he currently serves as Vice Chair of the IFAC SAFEPROCESS Technical Committee and as Vice President of the European Control Association (EUCA). In 2015, he served as the Panel Chair for the evaluation of proposals submitted to the ERC Advanced Grant in the area of electrical and computer engineering. Prof. Polycarpou received the Research Excellence Award from the University of Cyprus (2015) and the Cyprus Distinguished Researcher Award on behalf of the President of the Republic of Cyprus. He is the recipient of the 2016 IEEE Neural Networks Pioneer Award.

Prof. Polycarpou's teaching and research interests are in fault diagnosis, intelligent systems and control, adaptive and learning systems, computational intelligence, and distributed information processing. He has published more than 300 articles in refereed journals, edited books and refereed conference proceedings, and co-authored six books. He is also the holder of six patents. His research has received more than 12,000 citations according to Google Scholar, with an *h-index=53.* He has been an invited Keynote Plenary Speaker at more than 40 international conferences and IEEE Distinguished Lecturer in computational intelligence. Prof. Polycarpou has participated in more than 60 research projects/grants, funded by several agencies and industry in the USA and in Europe, including the prestigious European Research Council (ERC) Advanced Grant.

Vasso Reppa is a Research Associate at the KIOS Research Center for Intelligent Systems and Networks, Nicosia Cyprus. She received the Diploma and Doctorate degree in electrical and computer engineering from the University of Patras, Rio, Greece, in 2004 and 2010, respectively. Her doctoral research was on the design of process fault diagnosis methods

based on set membership identification. From 2006 to 2008 she was a Scientific Collaborator with Patras Science Park S.A., Rio, Greece, responsible for the development of knowledge-based decision support systems. In 2009, she joined the Storage Technologies Department, IBM Zurich Research Laboratory, Rüschlikon, Switzerland, as a student intern working on the sensor loss detection of intermittent contact mode scanning probe microscope. From 2011 to 2013, Dr. Reppa was a Postdoctoral Researcher with the KIOS Research Center working in the area of observer-based distributed and decentralized sensor fault diagnosis for large-scale interconnected systems, with application to building management systems and robotics. She was one of the principal researchers of the EU ICT project 'i-Sense', which dealt with the design of fault diagnosis methods for distributed unknown environments. In 2014, Dr. Reppa was among the KIOS researchers, who received the `Best paper' award for the work on contaminant event diagnosis for intelligent buildings, published in the Elsevier journal '*Buildings and Environment*'. In November 2013, Dr. Reppa was awarded the Marie Curie Intra European Fellowship for the research project 'FUTuRISM', which dealt with the design and analysis of multiple sensor fault tolerant control techniques based on positive invariance. From 2014 to 2016, she worked as a Marie Curie Research Fellow at CentraleSupélec, Gif-sur-Yvette, France.