DEPARTMENT OF SYSTEMS AND CONTROL

E-2

The department is engaged in the analysis, control and optimization of systems and processes. The activities of the department are focused on the research of new methods and algorithms for automatic control, the development of procedures and tools to support the design of control systems, the development of specific measurement and control modules, and the development and construction of complete systems for the control and supervision of machines, devices and industrial processes.

Head:
Dr. Vladimir Jovan

Basic and applied research

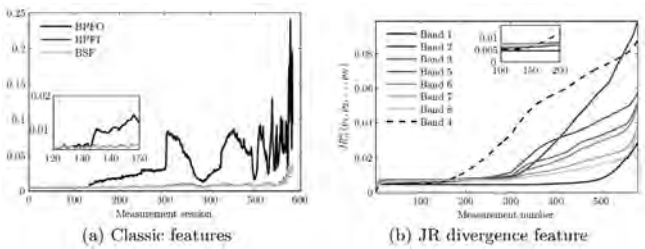
Basic and applied research in 2014 was devoted to three sub-areas: methodologies for analysis and control systems design; tools and building blocks for implementation; and applied research in the priority problem domains.

The sub-area *methodologies for analysis and control systems design* included three topics.

The first topic addressed the *modelling and identification of nonlinear and complex dynamical systems*. The research in the dynamic system modelling of Gaussian process models was directed towards the modelling of biological and environmental systems and control design based on the models. Part of the research was devoted to an alternative method, which was the modelling of dynamic systems with model-tree ensembles. A key feature of modern condition monitoring systems is the ability to predict the remaining useful life of the system or its components. To achieve this, the work on the topic of development of condition monitoring and the prediction of the remaining useful life of the system or its components continued with the development of new computational procedures that combine the sequential Monte-Carlo approach with a classical Kalman filter. The results of the work are two specifically designed algorithms for an estimation of the remaining lifetime of electrochemical energy systems, i.e., Li-ion batteries and PEM fuel-cell systems.

The second topic was *advanced control.* We have continued the work on improvements to the cascade scheme of magnetic plasma control for the Iter fusion tokamak reactor. A prototype MPC controller for the ITER plasma current and a shape controller were designed in order to assess the feasibility of its practical real-time implementation, and its control performance in the suppression of specific disturbances and in regulation near constraints was compared to a scheme based on singular perturbation decomposition.

The third topic of interest was *condition monitoring and fault diagnosis*. The emphasis in this area has been on new procedures for triggering alarms based on a feature analysis. It is an urgent problem, because in practice changes often take place in features that are not caused by injury, but due to disturbances and changes in the working conditions of the system. As a consequence, undesirable false alarms can frequently be actuated. To prevent this we have developed a robust process which – unlike the previously known processes – does not over-react to changes of the features value, but to the change of the shape of its distribution function. The "differences" between the latter and the shape in its nominal state in the presence of damage are expressed through the generalized Jensen-Renyi divergence. The procedure was successfully demonstrated for a number of experimental data obtained on bearings (Figure 1). The main feature is that its settings need a minimal amount of a priori information and that it also works successfully, even in the presence of non-measurable changes in the operating conditions. For the originality of the algorithm we received a special award at the International Conference CMMNO. Another interesting result is a solution to the problem of the detection of changes in the components of the spectrum. The basis for the solution is an effective approximation of the distribution function of the spectral component using the weighted distribution χ^2. In 2014 we also continued our work on the diagnostics of PEM fuel cells with use of impedance measurements. Based on the previous research findings, we developed a new diagnostic approach, which is based on a statistical analysis (Figure 2). The output of the approach is a condition indicator that has a direct relation to the possible faults in the PEM fuel cells. The main benefit of the approach is its ability to give results without any previous characterization measurement, which are undesirable in industrial systems. The results of this work were presented in two journal papers published in the *Journal of Power Sources*.



(a) Classic features (b) JR divergence feature

Figure 1: Comparison between the time evolution of the classical features related to bearing faults (left) and the generalised Jensen-Renyi divergence.

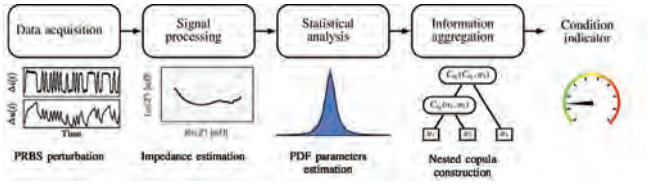


Figure 2: Schematic representation of the complete condition-monitoring process for a fuel-cell stack

In the area **tools and building blocks for the implementation**, the MAGICS methodology for the development and automatic generation of process control software has been further developed. An important part of the development environment, i.e., the ProcGraph model editor, was developed in recent years. In 2014 the development of a system for the automatic mapping of ProcGraph models into the code of the industrial controllers was in progress. At the same time, in the frame of the "Research Voucher" project, an adaptation and implementation of the methodology was continuing for a Slovenian engineering company. In 2014 we have also continued with the development of a software prototype called ProOpter, which enables the analysis of production dynamics. The commercial potential of such a tool was evaluated together with the development of a business model. Our product idea (ProOpter) was chosen as one of top-ten selected "early-stage" innovations to be presented at the Heidelberg Innovation Forum 2014 (early-stage innovations).

Applied research in the priority problem domains was the third sub-area of our interest.

In 2014 we delivered a new final-product end-quality assessment system to Domel d.o.o. (Figure 3), the main producer of motors for vacuum cleaners in the EU. The system is fully integrated into a new, centralised reporting and configuration system. The complete setup and data analysis is now performed using an internal web-based application. Additionally, we developed a platform for the endurance testing of EC motors, together with the accompanying controller units. Both systems are designed following the MIMOSA OSA-EAI standard.

Control of wastewater treatment plants is our next traditional research area. We participated in an improvement to the aeration control at the Ljubljana Wastewater Treatment Plant (Ljubljana WWTP). Several changes were made to the existing aeration control. The parameters of the common air rail pressure controller were adjusted and the air-pressure set-point controller and the airflow controller were introduced. With the improved aeration control, savings of up to 10 % in the electrical consumption are being achieved on a yearly basis.

International and national R&D projects

In the frame of three-year international project Eurostar *ProDisMon-Probabilistic Distributed Industrial System Monitor* we developed, in collaboration with the partner INEA, a test rig for validating the diagnostic and prognostic algorithms for industrial applications. Since practical usage is much conditioned on a clear economic benefit, we suggested an approach to the validation of maintenance strategies relying on a stochastic model of the degradation processes in machine components.

In 2014 the FW7 project *FCGEN-Development and on-truck demonstration of diesel-powered FC-based power unit* was in its 3rd year. In this period the complete fuel processor has been assembled and tested. In November 2014 our group has also taken over the coordination of the FCGEN project from Volvo. On the technical side our group has successfully implemented the developed control system and further optimized it (Figure 4). Besides that, the DCDC power converter and dedicated APU ECU have been developed. The former has already been tested, while for the latter, the software development is in final stages.

Figure 3: Diagnostic system for total quality control in the new production line of eco-motors at Domel

The aim of the next FW7 project *FluMaBack- Fluid Management component improvement for back up fuel cell systems* is the development and optimization of the balance-of-plant components of a fuel-cell system. The activities in 2014 include: analysis of the mechanical fault modes of the air blower and an analysis of the durability of the electrical components of the underlying controller. The results allowed the proper set up of the end-quality control line as well as a proposal for upgrading the controller, therby enhancing its durability.

From April 2014 we also participated in the third FW7 project *Diamond-Diagnosis-aided control for SOFC power systems*. The objective of the project is to improve the performance and lifetime of solid-oxide fuel-cell (SOFC) systems, by developing advanced controls and diagnosis tools that provide meaningful information about the actual state-of-the-health of the entire system. Our activities carried out in the first year of the project were related to the design of low-level controllers for system units and a soft sensor for an estimation of the maximum and minimum fuel-cell stack temperatures.

In collaboration with the consortium ENEA/CREATE from Naples, Italy, in 2014 we have successfully applied a 3-year project *"Fast Model Predictive Control for Magnetic Plasma Control - FMPCFMPC"* to the "Enabling Research" call of the EUROfusion Work Programme 2015 (part of Horizon 2020 / Euratom). The aim of the project

is to apply novel, fast MPC approaches to plasma magnetic control, where MPC is currently not applicable due to the large-scale multivariable nature of the problem and sub-second sampling rates.

Within the scope of the Slovenian Research Agency's applicative project *"Optimisation of the refrigeration energy costs in shopping centres"* in 2014 an approach was developed to evaluate defrosting needs. The approach measured the refrigerator temperatures and accordingly estimates the accumulated frost. For a cost optimisation the structure of the physical model has been determined. The developed model describes the temperature dynamics of the refrigerator and the food.

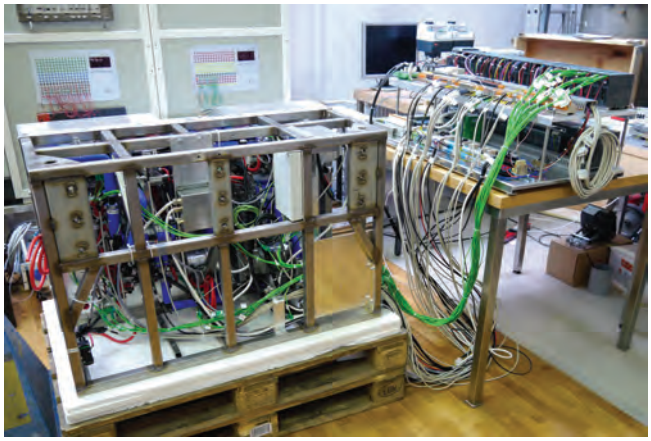


Figure 4: Testing of a fuel reformer's connections with the controller

The aim of another ongoing Slovenian Research Agency applicative project *"Development and implementation of methods for real-time modelling and forecasting air pollution"* is to develop a methodology and Gaussian-processes-based model to predict the ozone concentration above the selected, most congested, locations in Slovenia. Data from the Nova Gorica (Figure 5) and Bilje monitoring stations were used for the analysis, where we have identified the regressors with the greatest influence on the daily forecast of the ozone concentration. The data are prepared to validate the methods for the on-line learning of time-varying models, which are being developed within the project.

In 2014 we completed two projects for industrial partners and signed a new contract (with Danfoss Trata). In Domel d.o.o. we installed a new diagnostic system for the electromotors of type 458, which performs the final quality control on the production line. The system is positioned as the last stop in the production of electric motors and provides the real-time detection of errors in the produced suction units. To the Danfoss Trata d.o.o. company we delivered an electronic module and firmware software for "heavy-duty" drives valves.

Educational and training activities

Some members of the department are giving lectures and practical courses at different faculties and universities: the Faculty of Electrical Engineering, University of Ljubljana, the Faculty of Logistics, University of Maribor, the University of Nova Gorica and the "Jožef Stefan" International Postgraduate School. They also act as supervisors of Ph.D. students.

Some outstanding publications in the past year

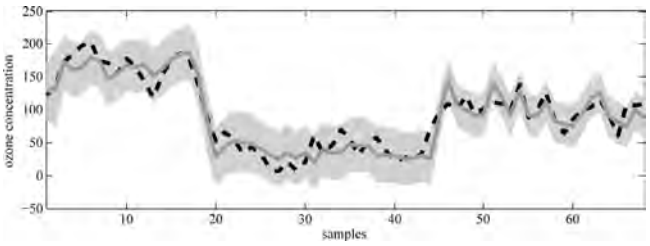


Figure 5: Daily forecast of ozone concentrations with a GP model (Nova Gorica)

1. Debenjak, A., Boškoski, P., Musizza, B., Petrovčič, J., Juričić, Đ.: Fast measurement of proton exchange membrane fuel cell impedance based on pseudo-random binary sequence perturbation signals and continuous wavelet transform. *Journal of power sources*, ISSN 0378-7753, vol. 254,112–118
2. Boškoski, P., Debenjak, A.: Optimal selection of proton exchange membrane fuel cell condition monitoring thresholds. *Journal of power sources*, ISSN 0378-7753, vol. 268, 692–699
3. Pregelj, B., Vrečko, D., Petrovčič, J., Jovan, V., Dolanc, G.: A model-based approach to battery selection for truck onboard fuel cell-based APU in an anti-idling application. *Applied energy*, ISSN 0306-2619, vol. 137, 64–76
4. Dolanc, G., Belavič, D., Hrovat, M., Hočevar, S., Pohar, A., Petrovčič, J., Musizza, B.: A miniature fuel reformer system for portable power sources. *Journal of power sources*, ISSN 0378-7753, Dec. 2014, vol. 271, 392–400
5. Leamy, D., Kocijan, J., Domijan, K., Duffin, J., Roche, R. A. P., Commins, S., Collins, R., Ward, T. E.: An exploration of EEG features during recovery following stroke - implications for BCI-mediated neurorehabilitation therapy. *Journal of neuro-engineering and rehabilitation*, ISSN 1743-0003, 2014, vol. 11, no. 9, 1–16

Some outstanding achievements in the past year

1. The development and implementation of a diagnostic system for the final quality control of electric motors in Domel d.o.o. The installed system is the eighth such system for the automatic final control of electric motors for vacuum cleaners used by Domel, which covers over 60% of the European market and produces over 3 million motors annually.

2. The prototype module ProOpter.IVS had been selected as one of top ten early-stage innovations that were presented at the Heidelberg Innovation Forum 2014 focusing on *„Smart Production and Manufacturing - Innovative ICT Solutions and Production Processes".* The module selects from the production database the most influential process variables that optimise the production process.
3. Our department members were awarded at CMMNO14 - *4th International Conference on Condition Monitoring of Machinery in Non-stationary Operations* with the *Award for an original approach to solving the problem.* The authors Boštjan Dolenc, Pavle Boškoski and Đani Juričić presented an original approach to faults diagnostics in mechanical drives by observing changes in the statistical patterns of distributions functions, i.e., the envelope distribution obtained from vibrations.
4. Our department member, Prof. Juš Kocijan, co-authored the Dictionary of Automatic Control, Systems and Robotics, released by ZRC Publisher. The dictionary contains 1,753 Slovene entries in the field of mathematical modelling, simulation of dynamic systems, automatic control and associated building blocks and robotics.
5. The „Jožef Stefan" Institute and the Danfoss Trata d.o.o. company have developed a family of intelligent valve drives. This innovative system was nominated for the H&V Award, the biggest award in the UK commercial market for HVAC systems.

Awards and appointments

1. Boštjan Dolenc was awarded with the PCT Technology Network award (Process Control Technology) for his Master's thesis entitled "Diagnostics of distributed and localized bearing faults"
2. Boštjan Dolenc was awarded for the best Diploma Thesis at Slovenian state competition on maintenance in 2014 at the 24th Slovenian Trade Fair and Conference on Technical Maintenance
3. Boštjan Dolenc was awarded for his original contribution at the 4th International Conference on Condition Monitoring of Machinery in Non-stationary Operations, CMMNO14

INTERNATIONAL PROJECTS

1. 7FP - FLUMABACK; Fluid Management Component Improvement for Back Up Fuel Cell Systems
   Dr. Pavle Boškoski
   European Commission
2. 7FP - FCGEN; Fuel Cell Based On-board Power Generation
   Dr. Boštjan Pregelj
   European Commission
3. 7FP - DIAMOND; Diagnosis-aided Control for SOFC Power System
   Prof. Đani Juričić
   European Commission
4. COST IC0806, IntelliCIS; Intelligent Monitoring, Control, and Security of Critical Infrastructure Systems
   Dr. Nadja Hvala
   COST Office
5. COST ES1202; Water_2020: Conceiving Wastewater Treatment in 2020 - Energetic, Environmental and Economic Challenges
   Dr. Darko Vrečko
   COST Office

RESEARCH PROGRAM

1. Program Systems and Control
   Prof. Đani Juričić

R & D GRANTS AND CONTRACTS

1. Prognostics and Health Management of Mechanical Drives Based on Novel MEMS Sensor Networks
   Prof. Đani Juričić
2. Development and Implementation of a Method for On-line Modelling and Forecasting of Air Pollution
   Prof. Juš Kocijan
3. Optimisation of Energy Cost for Refrigeration Systems in Shopping Malls
   Asst. Prof. Damir Vrančić
4. Competence Centre for Advanced Control Technologies: CC ACT
   Asst. Prof. Damir Vrančić
5. Probasensor: EUROSTARS; Probalistic Bayesian Soft Sensor - A Tool for On-line Estimation of the Key Process Variable in Cold Rolling Mills
   Prof. Đani Juričić

NEW CONTRACTS

1. Process Control Software Development Methodology
   Giovanni Godena, M. Sc.
   Inea, d. o. o.
2. Optimisation of Energy Cost for Refrigeration Systems in Shopping Malls
   Asst. Prof. Damir Vrančić
   Danfoss Trata, d. o. o.

VISITOR FROM ABROAD

1. Prof. Jan Cvejn, Department of process Control, Faculty of Electrical Engineering and Informatics, University of Pardubice, Pardubice, Czech Republic, 12–20 June 2014

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1. Dr. Gregor Dolanc
2. Dr. Samo Gerkšič
3. Giovanni Godena, M. Sc.
4. Dr. Dejan Gradišar
5. Dr. Nadja Hvala
6. **Dr. Vladimir Jovan, Head**
7. Prof. Đani Juričić
8. Prof. Juš Kocijan
9. Dr. Bojan Musizza
10. Dr. Janko Petrovčič
11. Dr. Boštjan Pregelj
12. Prof. Stanislav Strmčnik
13. Asst. Prof. Damir Vrančić
14. Dr. Darko Vrečko

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16. Dr. Matej Gašperin

17. Dr. Miha Glavan
18. Dr. Marko Nerat
19. Dr. Matija Perne
20. *Dr. Dejan Petelin, left 29. 09. 14*

Postgraduates

21. Andrej Debenjak, B. Sc.
22. Boštjan Dolenc, B. Sc.
23. Martin Stepančič, B. Sc.
24. *Aleš Svetek, M. Sc., left 01. 03. 14*

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25. Stanislav Černe, B. Sc.
26. Primož Fajdiga, B. Sc.

Technical and administrative staff

27. Maja Janežič, B. Sc.
28. Miroslav Štrubelj

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Original Article

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Published Conference Contribution (invited lecture)

1. Darko Belavič, Marko Hrovat, Marina Santo-Zarnik, Kostja Makarovič, Andreja Benčan, Janez Holc, Gregor Dolanc, Primož Fajdiga, Stanko Hočevar, Andrej Pohar, Franci Kovač, Marjan Hodnik, Anton Konda, Boris Jordan, Vlasta Sedlakova, Josef Sikula, Barbara Malič, "An overview of LTCC based ceramic microsystems: from simple pressure sensors to complex chemical reactors", In: *Proceedings*, EDS' 14, Electronic Devices and Systems IMAPS CS International Conference 2014, June 25-26, 2014, Brno, Czech Republic, Ondrej Hegr, ed., Brno, Vysoké učení Technické v Brně, 2014, pp. XVI-XXI.

Published Conference Contribution

1. Darko Aleksovski, Juš Kocijan, Sašo Džeroski, "Model tree ensembles for the identification of multiple-output systems", In: *ECC 14, European Control Conference, June 24-27, 2014, Strasbourg, France: final program* , [S. l.], European Control Association, 2014, pp. 750-755.
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