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RA1: Control of distributed parameter systems and complex robotic structures

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Robotics and Advanced Industrial Production
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RA1: Control of distributed parameter systems and complex robotic structures

- Three groups
  - G1: CTU in Prague – Faculty of Mechanical Eng. + CIIRC
  - G17: University of West Bohemia – NTIS
  - G18: Brno University Of Technology – CEITEC
- RO 1.1 – **Optimal control of interconnected time-delay systems** (G1, T. Vyhlídal, Z. Šika)
- RO 1.2 – **Extending the system decoupling method** (G1, V. Kučera, T. Vyhlídal)
- RO 1.3 – **Control and vibration suppression of light robotic structures** (G1, Z. Šika, T. Vyhlídal).
- RO 1.4 - **Algorithms for industrial control** (G17, M. Schlegel, O. Straka)
- RO 1.5 - **Estimation and filtering** (G18, J. Dokoupil)
- RO 1.6 – **Advanced manufacturing** (G1, P. Zeman)

RA1 people: G1 – CTU FME + CIIRC

prof. Tomáš Vyhlídal
(GL, RAL)

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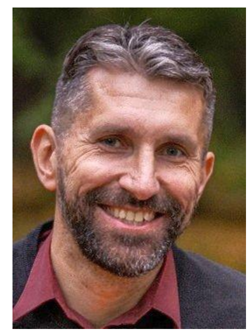
(ex. T)

prof. Zbyněk Šika
(ex. T)

doc. Pavel Zeman
(ex. TT)

Jaroslav Bušek
(PD)



Petr Beneš
(TME)

RA1 people: G1 – CTU FME – PhD students

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(PhD student)

Karel Kraus
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Can Kutlu Yuksel
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Jan Krivošej
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Juraj Lieskovský
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Martin Novák
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Michal Rytíř
(PhD student)

RA1 people: G17 - UWB

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(GL)

doc. Ondřej Straka
(ex. TT)

doc. Jindřich Duník
(ex. TT)

Ivo Punčochář
(PD)

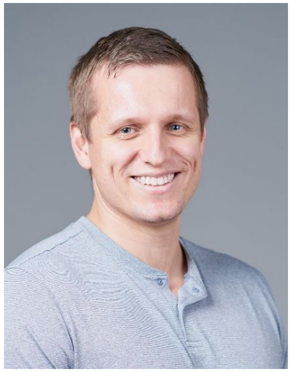
Martin Goubej
(PD)

Martin Švejda
(PD)

Michal Brabec
(PhD student)

Jan Trejbal
(PhD student)

RA1 people: G18 - BUT



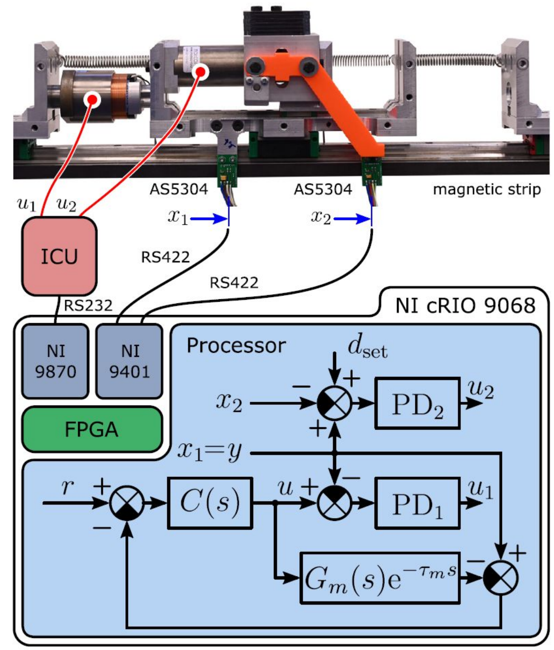
Jakub Dokoupil
(GL)

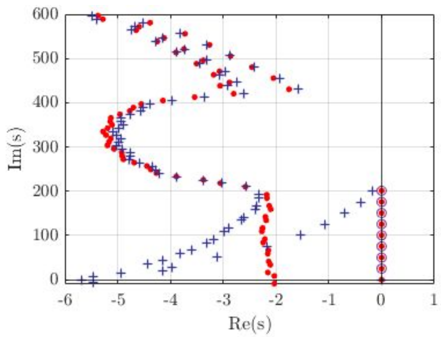
Lukáš Zezula
(PhD student)

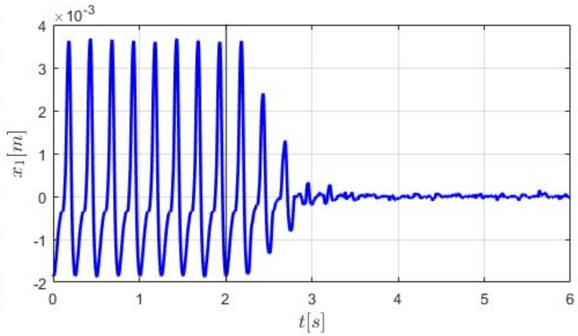
Dominik Friml
(PhD student)

RO 1.1 – Optimal control of interconnected time-delay systems

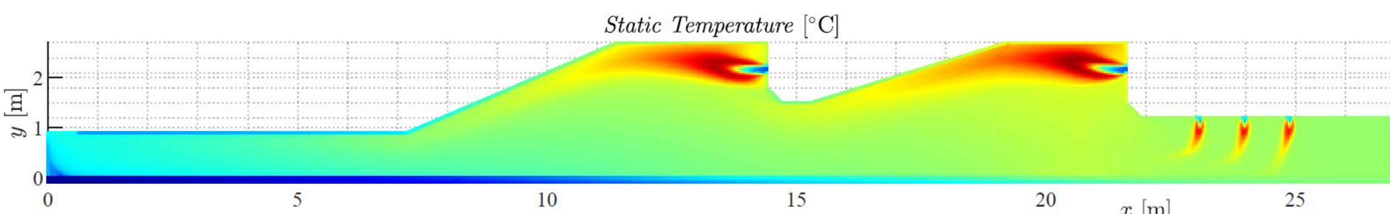
- Analysis and control synthesis of time delay systems - facing their infinite dimensionality
- Modelling of complex distributed parameter systems
- Input shaping for flexible-mode compensation and repetitive control for periodic signal suppression



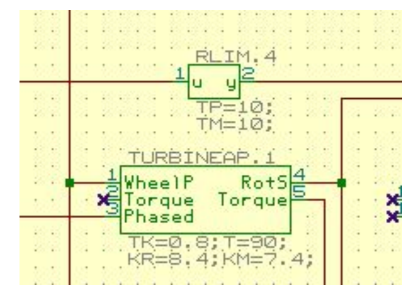




Yuksel, et al. A distributed delay based controller for simultaneous periodic disturbance rejection and input-delay compensation. ***MSSP2023***



Skopec, P., Vyhlidal, T., & Knobloch, J. Development of a continuous reheating furnace state-space model based on the finite volume method. ***ATE2024***



Hydropower plant simulator for HIL tests

RO 1.1 – Optimal control of interconnected time-delay systems

- **We will aim for:**
  - Tools for a time-delay model assembly and parameterization combining first-principle and data-driven methods
  - Optimization-based control design methods for time delay systems aiming at spectral, robustness and time domain characteristics
  - Control method implementation on Industrial platforms and Applications:
    - Heat distribution and energy systems (e.g. in smart cities, hydropower plants, building indoor-climate)
    - Industrial systems and processes (e.g. rolling mills, optimized 3D printing)
- **International collaboration:**
  - Prof. Wim Michiels (KU Leuven, Belgium)
  - Prof. Tarunraj Singh (University at Buffalo)
  - Prof. Silviu-Iulian Niculescu (L2S CentraleSupélec)
- **Cooperation with other ROs and RAs :**
  - M. Korda and D. Henrion – RA 3: non-linear constrained optimization
  - V. Kučera – RO 1.2: Extension of system decoupling methods to delay systems
  - Z. Šika – RO 1.3: Application of time delay algorithms in vibration suppression
  - M. Schlegel – RO 1.4: Repetitive control

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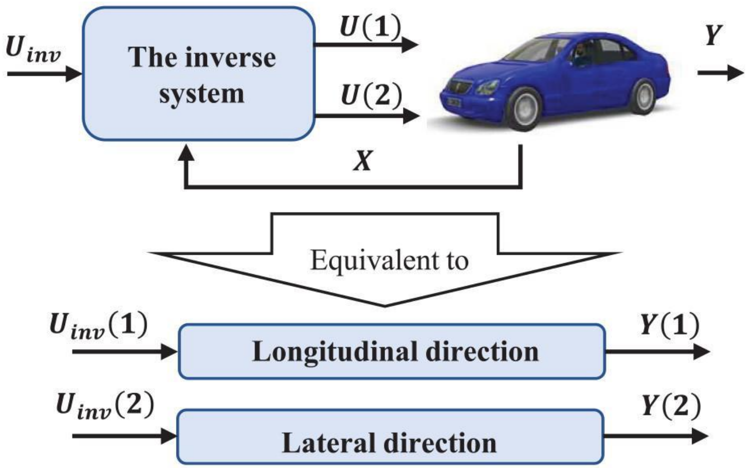
RO 1.2 – Extending the system decoupling method

A recent research breakthrough on decoupling, aka non-interactive control, of linear time-invariant finite-dimensional systems was published in

V. Kučera, "Decoupling with stability for linear systems by static-state feedback," IEEE Trans. Automat. Control, vol. 66, pp. 4684-4699, 2021.

The findings will be extended to include a broader range of linear systems:

- periodic systems
  (to decouple circular motions in robotic applications)
- time-delay systems
  (to eliminate undesirable interactions in production processes).



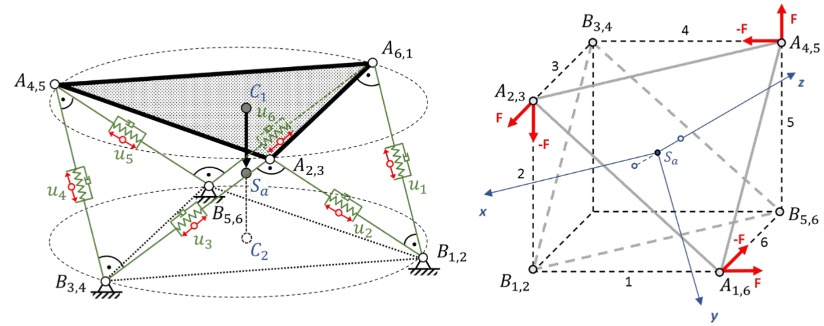
Credits: DOI 10.1177/09544070211015928

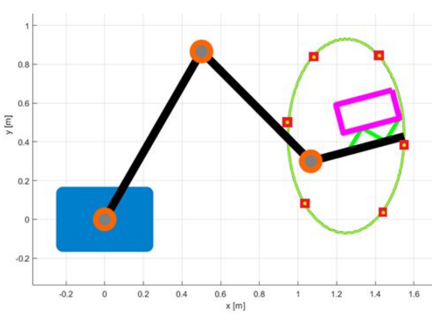
RO 1.2 – Extending the system decoupling method

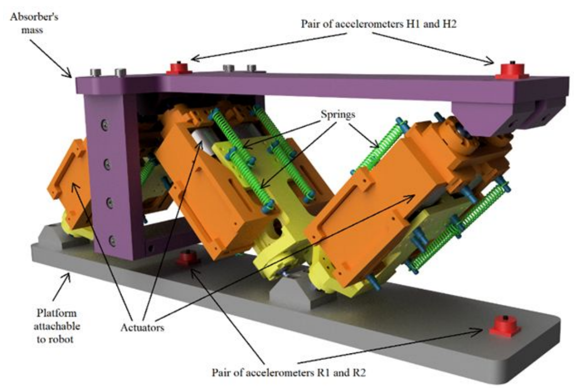
- **We will aim for:**
  - Decoupling solutions are available for systems with the same number of inputs and outputs. However, this research aims to expand the decoupling possibilities notably by allowing systems to have more inputs than outputs.
  - For periodic systems, the approach involves applying periodic feedback to make the system time-invariant. Afterward, the recently developed decoupling methodology can be used. The level of difficulty for this task is moderate.
  - For time-delay systems, the approach is based on ring models. This allows for the consideration of both retarded and neutral-type systems and both commensurate and non-commensurate delays. However, this task is extremely challenging
- **International collaboration:**
  - Prof. Patrizio Colaneri, Politecnico di Milano
- **Cooperation with other ROs:**
  - Z. Šika – RO 1.3: motion decoupling in robotic applications
  - T. Vyhlídal – RO 1.1: time delay systems

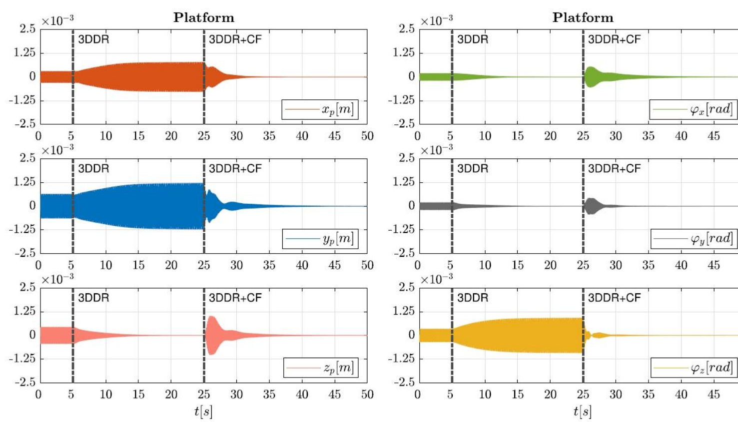
RO 1.3 – Control and vibration suppression of light robotic structures

- Reducing vibrations of robots by means of active absorbers has the advantage that it can only be realized with the help of local sensors.
- The active absorbers allow various adaptations to the highly variable dynamic properties of the robot during motion in the workspace.









K. Kraus, Z. Šika, P. Beneš, J. Krivošej and **T. Vyhlídal** *Mechatronic robot arm with active vibration absorbers.* JVC2020.

Z. Šika, J. Krivošej and **T. Vyhlídal** *Three dimensional delayed resonator of Stewart platform type for entire absorption of fully spatial vibration.* JSV2024.

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RO 1.3 – Control and vibration suppression of light robotic structures

- **We will aim for:**
  - Advanced strategies for simultaneous motion control and vibration suppression in robotic structures to increase their accuracy, energy efficiency and functionality.
  - Various control solutions will be considered, including the time-delay feedback and methods for system decoupling.
  - The robot absorbers will operate in many degrees of freedom often non-collocated with respect to the end-effector, and act on a nonlinear robot system that rapidly changes its dynamical properties along the working trajectories.
  - The experimental validation will be performed on the proposed demonstrators.
    - Set of methods for simultaneous vibration suppression and planar motion control.
    - Absorbers and methods for robot spatial motion control with vibration suppression.
- **International collaboration:**
  - Prof. Andreas Müller (Johannes Kepler University Linz, Austria)
  - Prof. Wim Michiels (KU Leuven, Belgium)
  - Prof. Martin Kozek (Technische Universität Wien, Austria)
- **Cooperation with other ROs and RAs :**
  - V. Kučera - RO 1.2: Extending the system decoupling method.
  - M. Šebek – RA 2: Control for modular sytems, structures, and materials
  - J. Zeman – RA 4: CAD, simulation and manufacturing of modular materials

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RO 1.4 - Algorithms for industrial control

PID H∞ Designer - tool for the analysis and analytical design of a wide class of controllers including

- PI,
- PD,
- PID,
- PR (proport.-resonant),
- RC (repetitive control),
- SP (Smith predictor),

based on H∞ performance and robustness constraints.

Step 1

Find the PI controller

$$C_{PI}(s) = k_p + \frac{k_i}{s}$$

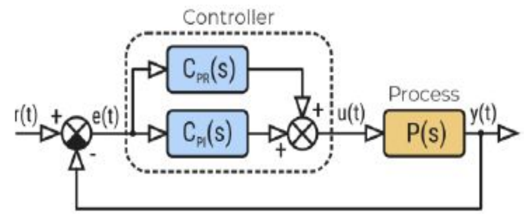
with design constraint

$$\|S(s)\|_\infty \leq 1.2$$

to track a constant reference signal.

Optimal solution (IAE)

$$k_p = 0.3554,\ k_i = 0.1714$$



Step 2

Find the PR controller parallel with the PI controller designed in step 1

$$C_{PI+PR}(s) = C_{PI} + k_q + k_r \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_0^2}$$

with design constraints

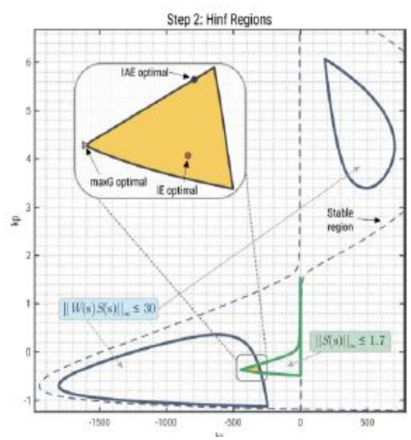
$$\|S(s)\|_\infty \leq 1.7, \qquad \|W(s)S(s)\|_\infty \leq 30$$

to attenuate a harmonic disturbance signal at the frequency 1 rad/s.

$$W(s) = \frac{s^2 + 2s + 1}{s^2 + 0.02s + 1}, \omega_0 = 1, \omega_c = 0.0004$$

Optimal solution (maxG)

$$k_q = -0.3678,\ k_r = -446.3$$

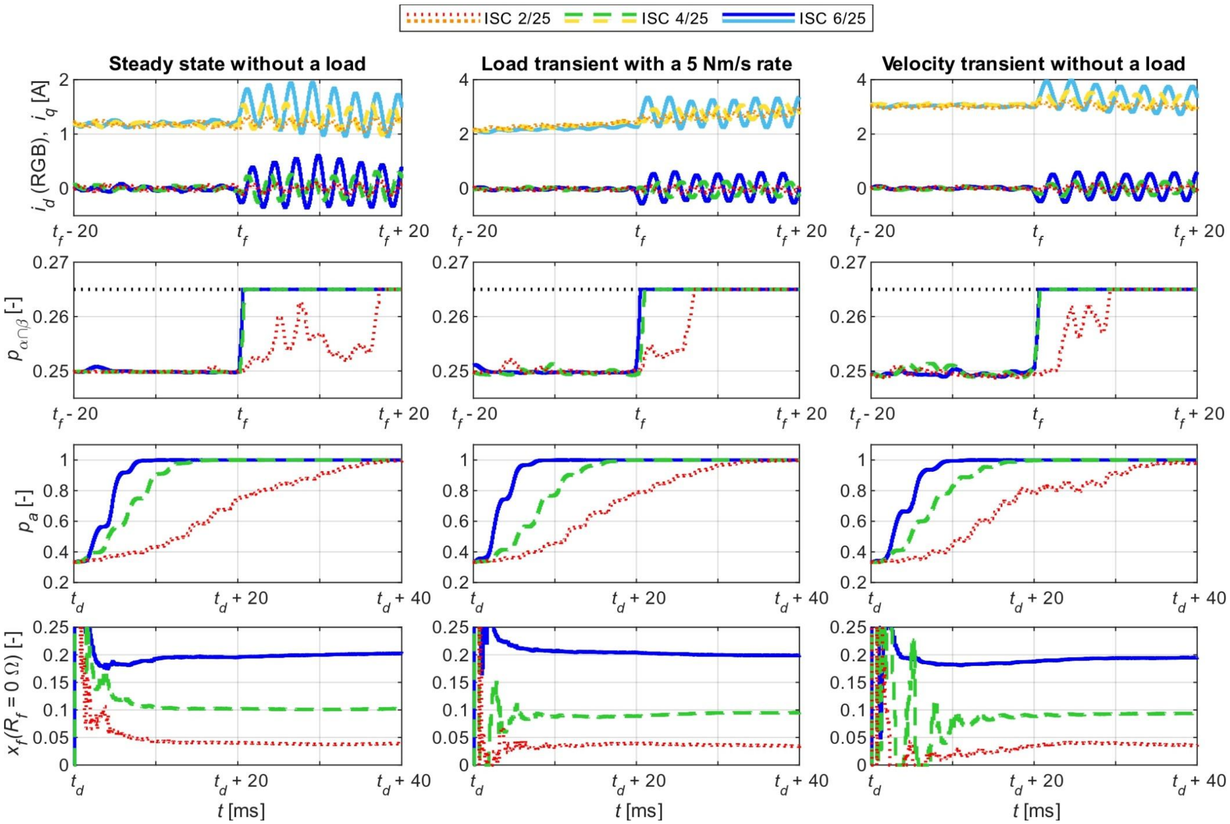


$$C_{PI+PR}(s) = \frac{(s - 0.9028)(s + 1.0321)(s + 14.8505)}{s(s^2 + 0.0008s + 1)}$$

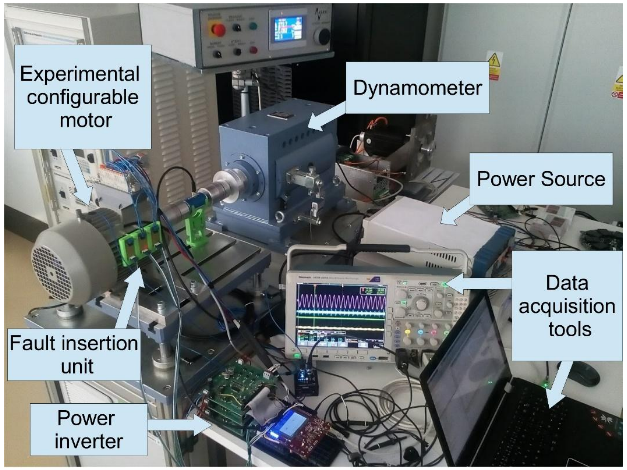
RO 1.4 - Algorithms for industrial control

- **We will aim for:**
  - Methods for systematic support in controlling and estimating electromechanical systems, power systems, and other industrial processes.
  - Methods for automatic design and tuning of control loops based on specifications capturing the essence of industrial control problems (robustness/performance trade-off, servo/regulator problem)
  - Sensor and information fusion methods that ensure high integrity, continuity and robustness, and are resilient to possible outliers, dropouts and adversary actions.
- **International collaboration:**
  - Prof. Uwe Hanebeck (Karlsruhe Institute of Technology, Germany)
- **Cooperation with other RAs:**
  - T. Vyhlídal - RO 1.1, L. Přeučil - RO 6.2: methods for automatic design and tuning of control loops,
  - J. Dokoupil - RO 1.5 : active change and fault detection algorithms
- **Industrial collaborations:**
  - ZAT a.s., Altron a.s.

RO 1.5 - Estimation and filtering



- Parameter estimation and model comparison approaches cast in a decision-making framework for fault diagnostics of electrical drives
- The Bayesian approach enables fault detection and the estimation of fault severity and location0



Jakub Dokoupil and Pavel Václavek *Recursive identification of time-varying Hammerstein systems with matrix forgetting.* [TACON 2023](#).

L. Zezula, M. Kozovsky and P. Blaha *Diagnostics of Interturn Short Circuits in PMSMs With Online Fault Indicators Estimation*. **TIE 2024**.

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RO 1.5 - Estimation and filtering

- **We will aim for:**
  - The design of a resilient data-informed forgetting strategy based on the variational Bayes method, which would operate recursively with a fixed data lag, thereby conferring the capability to confirm or negate the occurrence of potential changes (faults) and adjust their significance accordingly.
  - The combination of the previous proposal with selective (matrix) forgetting, enabling not only fault detection but also robust fault localization.
  - The design of advanced discrete models of electric drives, with consideration for adherence to the underlying stochastic contexts, thus accounting for distortion of the input signal by the inverter.
  - The experimental validation will be conducted on dual three-phase synchronous motors with permanent magnets, equipped with magnetic flux sensors, meeting high standards for the current automotive industry.
- **International collaboration:**
  - Prof. Alina Voda (Université Grenoble Alpes, France)
  - Prof. Gildas Besancon (Université Grenoble Alpes, France)
  - Prof. Alfred Hoess (University of Applied Sciences Amberg-Weiden, Germany)
  - Dr. Carlos Cardillo (University of Nevada, USA)
  - Prof. Franz Wotawa (Graz University Of Technology, Austria)
- **Cooperation with other ROs and RAs :**
  - M. Schlegel and O. Straka - RO 1.4: Algorithms for industrial control

RO 1.6 – Advanced Manufacturing

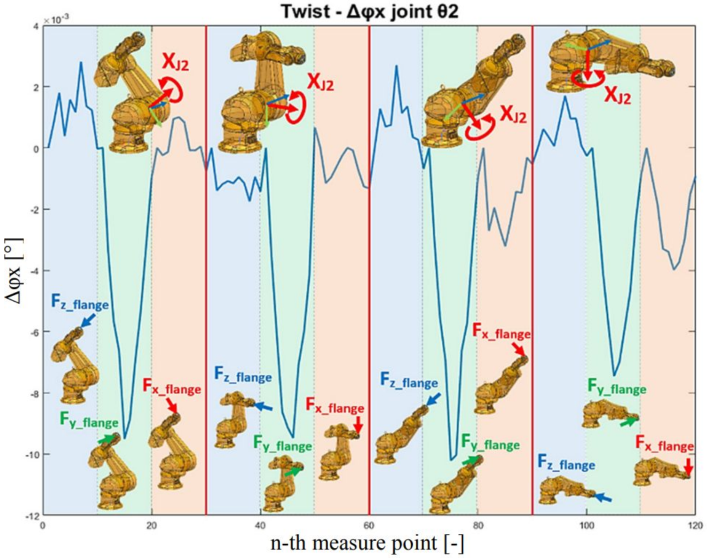
Model-based methods for optimal planning and control of:

- Robotic machining
- Robotic AM – large format printing & Laser metal deposition (LMD-wire)
- Monitoring of Laser μ-machining

Development of process models for adaptive tool path control.

Monitoring methods of process parameters and close-loop control.

High-precision control of beam-workpiece movement.



Tomas Kratena, Petr Vavruska, Jiri Sveda, Michael Valasek. *Postprocessor for Verification of Robot Movements with Additional Axis after Toolpath Optimization*, *Procedia CIRP*.

RO 1.6 – Advanced Manufacturing

- **We will aim for:**
    - Robotic machining: (i) tool-path off-line optimization based on static and dynamic stiffness models, (ii) robot energy consumption optimization using a model calculating kinetic energy along tool path.
    - Robotic AM: (i) monitoring systems and methods of process parameters and sample quality, (ii) models for tool path control and DT, (iii) control of process parameters.
    - Laser μ-machining: (i) automated and evaluation procedures for laser-material interaction, (ii) in-process measurement for the dimensions and correction assessment.
- **International collaboration:**
    - F. Bleicher (TU Vienna), M. Weigold (TU Darmstadt), H.-Ch. Möhring (TU Stuttgart), V. Stankevič (ELAS, UAB)
- **Expected cooperation within RA1:**
    - G1 T. Vyhlídal, Z. Šika
    - G17 M. Schlegel, G18 J. Dokoupil

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RA1: Industrial collaborations

- **ZAT**: Control design of energy systems
- **PTSW**: Process optimization in steel industry
- **Meopta**: Mechatronic control of optical instruments
- **Škoda Machine Tool**: Modelling and optimization
- **Altron**: Control design and parameterization of cooling systems
- **TGS**: Large format 3D printing
- **TOS Varnsdorf**: Robotic laser additive manufacturing
- **Hofmeister**: μ-machining monitoring

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