Internal Friday Seminar

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October 15, 2021

Outline

- Personal info
- Teaching
- Research
  - M-numbers
  - Distributed Control
  - Underactuated Systems

Introduction

Sweden

Lund University, LTH, Automatic control, 01\10 \2021.

- Arbetsförmedlingen → Academicum company (*Korta vägen* education) → **Practice** and **Swedish language**.
- Supervisors: Anders Robertsson and Charlotta Johnsson.

Introduction

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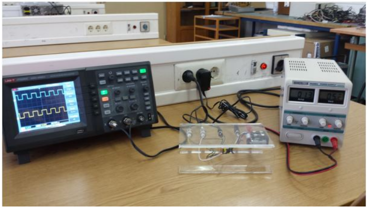
Croatia

Zagreb University, FSB[a], Automatic control [b], 2004.-2019.

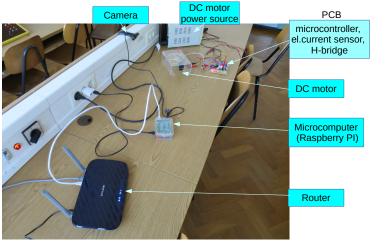
- 2003. MSc mechanical engineer, energy direction
- 2010. PhD automation (field: control system theory)
- 2004–2019. Courses: electrical engineering, programming

[a]Faculty of mechanical engineering and naval architecture, Zagreb, Croatia
[b]@ Department of Robotics and Production System Automation

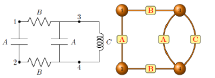
Learning basics of DC motor in **laboratory**:



Learning basics of DC motor **online**:



M-system theory[1].



- $Z_{12} = A \mid PS \mid (B \mid SS \mid ((C \mid PS \mid A) \mid SS \mid B)) =$ BCABA
- $Z_{13} = B \mid PS \mid (A \mid SS \mid B \mid SS \mid (A \mid PS \mid C)) =$ BACAB
- $Z_{14} = (A \mid SS \mid B) \mid PS \mid (B \mid SS \mid (A \mid PS \mid C)) =$ BACAB
- $Z_{23} = Z_{14}$; $Z_{24} = Z_{13}$
- $Z_{34} = C \mid PS \mid A \mid PS \mid (B \mid SS \mid A \mid SS \mid B) =$ CABA

M-system

Alphabet Γ: $\alpha < \ldots < a_1 < \ldots < a_2 < \ldots < \omega$

M-word: pairs of (concatenated,$\cdot$) symbols from Γ
ie. $(a_1, a_2) \rightarrow a_1 \cdot a_2 \rightarrow a_1 a_2$

M-logical values: the most left symbol $l(x)$
$+$ the most right symbol $r(x)$ of m-word x,
i.e. $(l_x, r_x) = q(x)$

Dual operator: $D(a_1) = a_2$, iff
$\delta(a_1, \alpha) = \delta(a_2, \omega) \rightarrow \delta(a_1, \omega) = \delta(a_2, \alpha)$

Negation operator: the unary, complement operator
$K(x) =_{def} l'(x) \cdot x \cdot r'(x) = l'_x \cdot x \cdot r'_x$
where $l'(x) = D(l(x))$ and $r'(x) = D(r(x))$

Infimum and supremum: $a \downarrow b = a$, $a \uparrow b = b$,
where $a < b$

M-logic = negation (K) + conjunction ($\wedge$)

operator	symbol	rule
negation	$\neg$	(l'_x, r'_x)
conjunction	$\wedge$	$(l_x \downarrow l_y, r_x \uparrow r_y)$
disjunction	$\vee$	$(l_x \uparrow l_y, r_x \downarrow r_y)$
p-implication	$\xrightarrow{p}$	$(l'_x \uparrow l_y, r'_x \downarrow r_y)$
s-implication	$\xrightarrow{s}$	$(l'_x \downarrow l_y, r'_x \uparrow r_y)$

Further theory development :

- Semantic of natural language[2]
- M-valued logic
- Topology of electric circuits
- Dynamical systems and optimization?

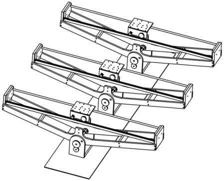
[1] Invented by Miroslav Šare: *Jorbologija*, Element Zagreb, 2000.

[2] Mario Essert, Ivana Kuzmanović, Ivan Vazler, Tihomir Žilić: *Theory of M-systems*, Logic journal of the IGPL, 25(5):836-858, August 2017.

Distributed control

Platform for education, testing and verification of real-life implementation of decentralized and distributed control solutions.

Three spring connected seesaw-cart subsystems[3].



[3] M. Lobrović, A. Jokić, V. Milić, T. Žilić, M. Jokić, J. Kasać, Z. Domitran, M. Crneković: *A Case Study in Distributed Control: Elastically Interconnected Seesaw-cart Systems.*, 25th Mediterranean Conference on Control and Automation, 2017.

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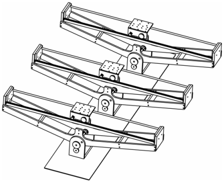
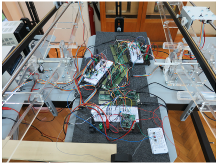


My participation:

- electronics
- programming
- micro-controllers



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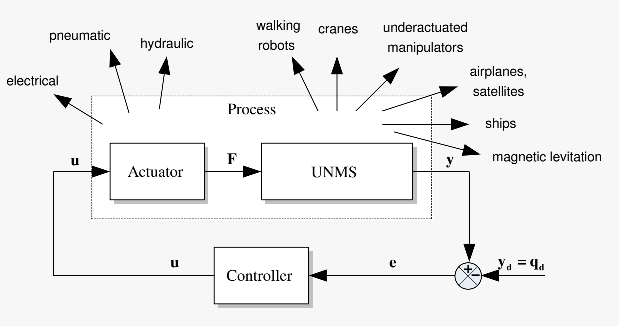
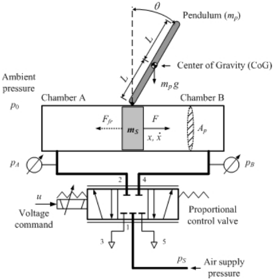
PhD research - underactuated systems

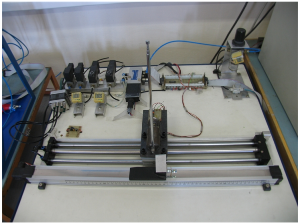
- Underactuated nonlinear mechanical systems (UNMS)
  - actuators $<$ degrees of freedom (DOF)
  - mechanical systems with input coupling
  - fully actuated but with actuators' failure $\rightarrow$ UNMS
- Included actuators dynamics. Actuators of higher orders, nonlinearities, discontinuous friction.



Pneumatically actuated slider-inverted pendulum



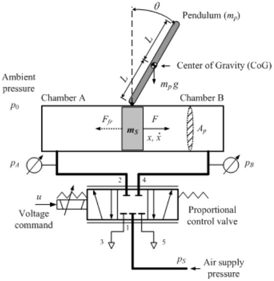
(a) Scheme



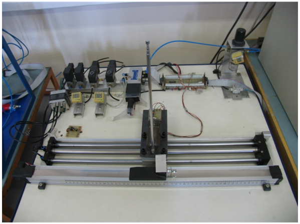
(b) Laboratory setup

PhD research - motivation

Pneumatically actuated slider-inverted pendulum



(c) Scheme



(d) Laboratory setup

Control challenge

Simultaneous stabilization and trajectory of arbitrarily selected degrees of freedom.[a]

[a] **Simultaneous stabilization and trajectory tracking** refers to a closed control loop where some DOF folow desired trajectories while simultaneously other DOF are stabilized.

Euler-Lagrange equations of UNMS

$$
\begin{aligned}
\frac{d}{dt}\frac{\partial \mathfrak{L}(\mathbf{q},\dot{\mathbf{q}})}{\partial \dot{\mathbf{q}}_a} - \frac{\partial \mathfrak{L}(\mathbf{q},\dot{\mathbf{q}})}{\partial \mathbf{q}_a} + \mathbf{F}_{dis_a}(\mathbf{q},\dot{\mathbf{q}}) &= \mathbf{H}_a(\mathbf{q})\mathbf{F} \\
\frac{d}{dt}\frac{\partial \mathfrak{L}(\mathbf{q},\dot{\mathbf{q}})}{\partial \dot{\mathbf{q}}_u} - \frac{\partial \mathfrak{L}(\mathbf{q},\dot{\mathbf{q}})}{\partial \mathbf{q}_u} + \mathbf{F}_{dis_u}(\mathbf{q},\dot{\mathbf{q}}) &= \mathbf{H}_u(\mathbf{q})\mathbf{F}
\end{aligned}
$$

$\mathbf{q} = [\mathbf{q}_a, \mathbf{q}_u]^T$, $\mathbf{q} \in \mathbb{R}^n$, $\mathbf{q}_a \in \mathbb{R}^{n_a}$, $\mathbf{q}_u \in \mathbb{R}^{n_u}$, $\mathbf{F} \in \mathbb{R}^{n_a}$
Subscripts: a - **a**ctuated, u - **u**nactuated DoF

Underactuated systems: $n_a < n$

2. order nonholonomic systems: $\mathbf{H}_a(\mathbf{q}) = \mathbf{I}$, $\mathbf{H}_u(\mathbf{q}) = \mathbf{0}$
UNMS with input coupling: $det(\mathbf{H}_a(\mathbf{q})) \neq 0$, $\mathbf{H}_u(\mathbf{q}) \neq 0$.

State space of coupled system (UNMS+actuators)

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})\mathbf{u}$$
$$\mathbf{y} = \gamma(\mathbf{x})$$

$$\overbrace{\begin{bmatrix} \dot{\mathbf{x}}_{qa1} \\ \dot{\mathbf{x}}_{qu1} \\ \dot{\mathbf{x}}_{qa2} \\ \dot{\mathbf{x}}_{qu2} \\ \dot{\mathbf{x}}_{ac} \end{bmatrix}}^{\dot{\mathbf{x}}} = \overbrace{\begin{bmatrix} \mathbf{x}_{qa2} \\ \mathbf{x}_{qu2} \\ \mathbf{f}_3(\mathbf{x}_q) + \mathbf{f}_{dis_3}(\mathbf{x}_q) + \mathbf{B}_3(\mathbf{x}_q)\gamma_{ac}(\mathbf{x}_{ac}, \mathbf{x}_q) \\ \mathbf{f}_4(\mathbf{x}_q) + \mathbf{f}_{dis_4}(\mathbf{x}_q) + \mathbf{B}_4(\mathbf{x}_q)\gamma_{ac}(\mathbf{x}_{ac}, \mathbf{x}_q) \\ \mathbf{f}_{ac}(\mathbf{x}_q, \mathbf{x}_{ac}) \end{bmatrix}}^{\mathbf{f}(\mathbf{x})} + \overbrace{\begin{bmatrix} \mathbf{0}_{n_a \times n_a} \\ \mathbf{0}_{n_u \times n_a} \\ \mathbf{0}_{n_a \times n_a} \\ \mathbf{0}_{n_u \times n_a} \\ \mathbf{g}_{ac}(\mathbf{x}_{ac}) \end{bmatrix}}^{\mathbf{g}(\mathbf{x})} \overbrace{\mathbf{u}_{ac}}^{\mathbf{u}}$$

$$\mathbf{y} = \gamma(\mathbf{x})$$

Sliding surface $\mathbf{s}$:

$$\mathbf{s} = \dot{\mathbf{e}} + \lambda_1 \mathbf{e} = \mathbf{0},\ \text{UNMS+actuator(r=0)}$$
$$\mathbf{s} = \ddot{\mathbf{e}} + \lambda_2 \dot{\mathbf{e}} + \lambda_1 \mathbf{e} = \mathbf{0},\ \text{UNMS+actuator(r=1)}$$
$$\mathbf{s} = \dddot{\mathbf{e}} + \lambda_3 \ddot{\mathbf{e}} + \lambda_2 \dot{\mathbf{e}} + \lambda_1 \mathbf{e} = \mathbf{0},\ \text{UNMS+actuator(r=2)}$$
$$\dots$$

First equation: If $\lambda_1 \succ \mathbf{0}$, then $\mathbf{e} \to \mathbf{0}$ when $t \to \infty$.
Mark r - actuator's relative degree regarding to $\mathbf{y}_{ac}$.

$$\mathbf{y} = \begin{bmatrix} \mathbf{x}_{qa1} \\ \mathbf{x}_{qu1} \end{bmatrix}, \quad \mathbf{y}_d = \begin{bmatrix} (\mathbf{x}_{qa1})_d \\ (\mathbf{x}_{qu1})_d \end{bmatrix}, \quad \mathbf{e} = \mathbf{y} - \mathbf{y}_d = \begin{bmatrix} \mathbf{e}_a \\ \mathbf{e}_u \end{bmatrix}$$

$$\ddot{\mathbf{e}} = \begin{bmatrix} \mathbf{f}_3(\mathbf{x}_q) + \mathbf{f}_{dis_3}(\mathbf{x}_q) + \mathbf{B}_3(\mathbf{x}_q)\gamma_{ac}(\mathbf{x}_{ac}, \mathbf{x}_q) - (\ddot{\mathbf{x}}_{qa1})_d \\ \mathbf{f}_4(\mathbf{x}_q) + \mathbf{f}_{dis_4}(\mathbf{x}_q) + \mathbf{B}_4(\mathbf{x}_q)\gamma_{ac}(\mathbf{x}_{ac}, \mathbf{x}_q) - (\ddot{\mathbf{x}}_{qu1})_d \end{bmatrix}$$

Eqvivalent control laws: $(\mathbf{u}_{eq})_a$ - actuated, $(\mathbf{u}_{eq})_u$ - unactuated

$$\begin{bmatrix} (\mathbf{u}_{eq})_a \\ (\mathbf{u}_{eq})_u \end{bmatrix} = \begin{bmatrix} -\left[\mathbf{B}_3(\mathbf{x}_q)\frac{\partial\gamma_{ac}(\mathbf{x}_{ac},\mathbf{x}_q)}{\partial\mathbf{x}_{ac}}\mathbf{g}_{ac}(\mathbf{x}_{ac})\right]^{-1}\left\{\mathbf{Z}_3+\mathbf{B}_3(\mathbf{x}_q)\frac{\partial\gamma_{ac}(\mathbf{x}_{ac},\mathbf{x}_q)}{\partial\mathbf{x}}\mathbf{f}(\mathbf{x})+\chi_a(\mathbf{s}_a)\right\} \\ -\left[\mathbf{B}_4(\mathbf{x}_q)\frac{\partial\gamma_{ac}(\mathbf{x}_{ac},\mathbf{x}_q)}{\partial\mathbf{x}_{ac}}\mathbf{g}_{ac}(\mathbf{x}_{ac})\right]^{+}\left\{\mathbf{Z}_4+\mathbf{B}_4(\mathbf{x}_q)\frac{\partial\gamma_{ac}(\mathbf{x}_{ac},\mathbf{x}_q)}{\partial\mathbf{x}}\mathbf{f}(\mathbf{x})+\chi_u(\mathbf{s}_u)\right\} \end{bmatrix}$$

$$\chi(\mathbf{s}) \in \{\alpha\,\mathrm{sign}(\mathbf{s}), \alpha\tanh(\mathbf{s}), \alpha\mathrm{sat}(\mathbf{s}), \ldots\},\ \alpha > \mathbf{0}$$

Proposed control law for combined control:

$$\boxed{\mathbf{u} = \varphi_a \cdot (\mathbf{u}_{eq})_a + \varphi_u \cdot (\mathbf{u}_{eq})_u}$$

φ_a, $\varphi_u \in \mathbb{R}^{n_a \times n_a}$ are diagonal weight matrices.

[1] T. Zilic, J. Kasac, Z. Situm, and M. Essert. *Simultaneous stabilization and trajectory tracking of underactuated mechanical systems with included actuators dynamics.*
Multibody System Dynamics, vol. 29, no. 1, pp. 1–19, 2013.

[2] T. Zilic, J. Kasac, Z. Situm, and M. Essert. *Application of SSTT control algorithm for underactuated: surface vessel, PPR manipulator and pneumatically actuated slider-inverted pendulum.*
Advanced Robotics, vol. 28, no. 8, pp. 545–556, 2014.

[3] T. Zilic, D. Pavkovic, and D. Zorc. *Modeling and control of a pneumatically actuated inverted pendulum.*
ISA Transactions, vol. 48, no. 3, pp. 327–335, 2009.

Thank you! Tack så mycket! Hvala vam!

Thank you! Tack så mycket! Hvala vam!

inspCoffe

Time for questions!