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Essential challenges in motion control education

M. Čech*, J. Königsmarková*, M. Goubej*, T. Oomen**, A. Visioli***

* *University of West Bohemia / NTIS – European center of excellence, Pilsen, Czech Republic (e-mail: mcech[jkonig,mgoubej]@ntis.zcu.cz).*
** *Technische Universiteit Eindhoven, Department of Mechanical Engineering,(e-mail: T.A.E.Oomen@tue.nl)*
*** *University of Brescia, Department of Mechanical and Industrial Engineering,(e-mail: antonio.visioli@unibs.it)*

Abstract: Smart mechatronic systems and applications with actively controlled moving elements face increasing demands on size, motion speed, precision, adaptability, self-diagnostic, connectivity, new cognitive features, etc. Fulfillment of these requirements is essential for building smart, safe and reliable production complexes. This, however, implies completely new demands on control *curricula* of master degree students. The aim of this paper is to identify main gaps in motion control education and industrial practice with specific focus on multi-disciplinarity, i.e., contribute to a STEM education ecosystem

Keywords: Motion control, robotics, mechatronics, control education, multi-disciplinarity

1. INTRODUCTION

An impressive number of advances in control education have been reported in recent years in terms of virtual and remote labs (Sánchez et al., 2002; Reitinger et al., 2013; Čech et al., 2013; Reitinger et al., 2014), interactive tools (Senz et al., 2015; Goodwin et al., 2011), open educational resources and repositories (De La Torre et al., 2013; Rossiter et al., 2018), etc. Unfortunately, insufficient effort has been devoted to systematic reflection of latest industrial needs and related update of the content of specific master degree courses. However, following those education drivers is essential for universities to play an expected societal role and become an university of 4th generation (Pawlowski, 2009; Lukovics and Zuti, 2015). During the last decades, a gap was identified between what students have learned and what the industrial requirements are. In many regions and applications areas, such gap is constant or even growing as the technology innovation goes faster than control education trends. Such observations are valid also for mechatronics and motion control education. This paper is focused especially on master degree *curricula* and its aim is to give an answer to the question *'What the master degree students should learn to be able to work effectively together in multi-disciplinary team with ambitions to build custom machines, optimize and design control system for them, i.e., bring machine performance close to physical limits?'*. The study is motivated by long term experience of authors' departments and also with joint applied research project (I-MECH, 2017), where high-tech mechatronic applications are being delivered in segments of semicon production, additive manufacturing, packaging, health-care robotics and other emerging fields. Here, the following preliminaries are set up:

Issue 1: *The robots size and weight are decreasing, hence their mechanical structures are becoming more flexible (Robotics, 2017; Oomen, 2018a,b)*
Consequence: The mechanical flexibility and elasticity should be considered in both modelling and control design phase as the dominant plant resonances typically overlap with target closed-loop bandwidth (see Fig. 2).

Issue 2: *The machines/robots speed is forced to be increased close to the physical barriers*
Consequence: There is a need for full utilization of more powerful HW (hardware), engineers should understand how to exploit and implement control algorithms effectively and distribute the computational burden to dedicated subsystems when necessary, e.g. by means of SoC+FPGA[1] architectures.

Issue 3: *Increasing presence of residual vibrations within the relevant frequency band*
Consequence: There is a need to teach how to design more complex controllers (more than PIDs[2]) able to attenuate resonances in the whole available bandwidth (Padula and Visioli, 2013). The students must understand the benefit of additional sensors in this 'vibrating world'. The machines are often doing repeating tasks, hence the motions, vibrations, and disturbances have a recurring signature. Thus, the engineers must know basics of repetitive and iterative learning control techniques (Bristow et al., 2006; Wang et al., 2018).

Issue 4: *The machines and robots are composed by more complex kinematic architectures, often redundant and interacting, with numerous axis to be simultaneously controlled (Smith et al., 2012)*
Consequence: There is an increasing need to include centralized control strategies into master degree courses.

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[1] System on Chip; Filed Programmable Gate Array
[2] Proportional-Integral-Derivative controller

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Moreover, these control strategies should be parameterized via more complex machine models.

Issue 5: *The machines and robots must quickly adapt to new tasks and customized production, they start to work in non-deterministic environment*
Consequence: The basic principles of self-tuning and self-adaptation should be explained to master students namely in context of variable load weight the machine caries and variable dominant modes.

Issue 6: *The machines and robots are working in fully automated multi-stage production lines that should work perfectly 24/7 (Pekarovskiy et al., 2018)*
Consequence: The engineers should understand sufficiently the components and interactions of well known MES[3] pyramid. Moreover, they should understand fundamentals and techniques of predictive maintenance and zero-defect manufacturing. Finally, they should understand the role of machine learning and deep learning in that context.

Issue 7: *Computer vision will be a key enabler for many robotic applications (Weiss et al., 2018)*
Consequence: The fundamentals of image processing should be part of control education, however also from implementation point of view (fast processing, dedicated HW leading to camera as a motion sensor)

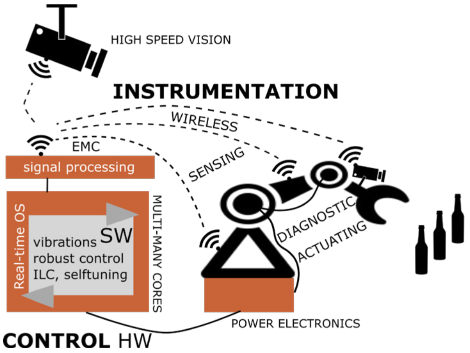

Fig. 1. Key enabling technologies (KETs) for smart motion control system

Those industrial issues define a set of key enabling technologies, see Fig. 1, and can be further mapped to numerous education challenges. This work is primarily focused on control layer (highlighted in Fig. 3) where the most important ones are:

Challenge 1: Understanding feedback loop bandwidth and all technological factors affecting it.
Challenge 2: Mastering combination of feedforward and feedback control with respect to Challenge 1.
Challenge 3: Understanding MIMO control.
Challenge 4: Learning model based design cycle with respect to robot kinematics and dynamics.
Challenge 5: Understanding the connection between control theory and practical implementation issues including all HW and SW related aspects.

In this paper, those *Challenges* are mapped into specific subtopics where the notable gaps in students knowledge have been identified. It is believed that overcoming those gaps could help to combine student technical skills with their contextualization within more complex, long-term design projects (also off-campus), see also Leshner (2018).

The paper is organized as follows: Section 2 describes the paper position within the overall control system structure. In Sections 3 and 4, the weaknesses in several key topics in control and instrumentation layer are summarized. Section 5 identifies gaps in modeling and simulation. Section 6 highlights specific mathematical background needed. Section 7 shows three mechatronic models that cover well the above defined issues. Conclusions and ideas for future work are given in Section 8.

2. AUTOMATION PYRAMID

Mechatronic systems and robots are often parts of complex production lines where they must do certain technological operations in cooperative way with maximum precision. Additional diagnostic cells then ensure zero-defect manufacturing. Finally, machines communicate lots of data for product digital thread as well as predictive maintenance of machine itself. This is often described by 5-level MES pyramid (Fig. 3) which is of highest importance in Industry 4.0 world. The paper is focused mainly at the control layer, i.e. control SW running in real-time on PACs[4]. Minor focus is devoted to instrumentation layer and control HW.

3. CONTROL LAYER

In paper context, control layer deals with core SW intelligence which is necessary to implement on real-time HW for successful feedback control applications (see Fig. 3).

3.1 Centralized Control

Many mechatronic systems exhibit multivariable dynamics coming inherently from the physical interactions between the controlled variables. Specific knowledge related to modelling and control of such systems is needed. The goal is to cover specific issues which cannot be observed in the SISO domain such as interaction analysis, decoupling and centralized control. Implementation of complex model-based controllers should be addressed as well aiming at model reduction, linearization and wind-up avoidance.

3.2 Vibration damping

Many control courses demonstrate fundamental modelling, identification and control design methods using only simple low-order systems with monotonous step and frequency response. Specific issues of oscillatory systems with several flexible modes which are encountered in the field of mechatronics should be explained explicitly. The student should be systematically prepared how to handle the unwanted vibrations using both feedback and feedforward techniques. The concepts of available bandwidth and target closed-loop bandwidth should be understand deeply. The control engineer should be able to confront the actual control objectives with the relevant plant dynamics and adopt the right strategy accordingly.

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[3] Manufacturing Execution System

[4] Programmable Automation Controller

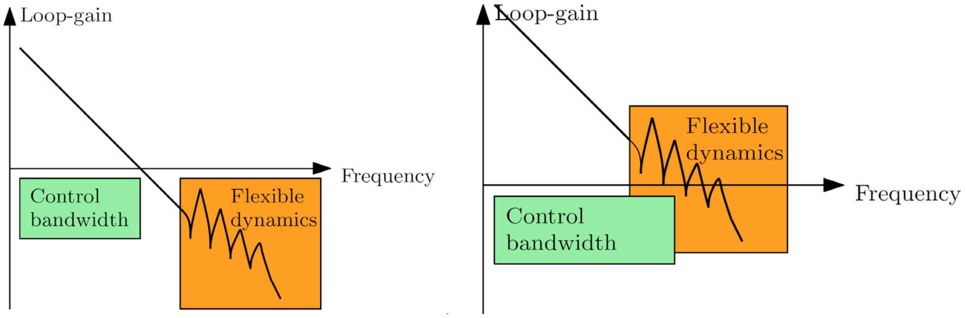

Fig. 2. Dominant resonances and anti-resonances are (left) behind control loop bandwidth; (right) overlapping with desired loop bandwidth

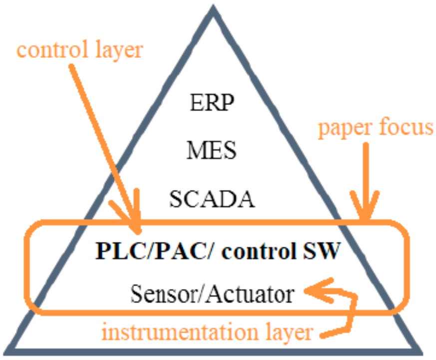

Fig. 3. Paper focus within the full automation pyramid

3.3 Repetitive and ILC

Iterative learning control (ILC) and repetitive control (RC) enable perfect performance for systems that perform the same task over and over again. A course has been developed along the lines in (Oomen2018b) that takes place after students have had a basic course in motion feedback and feedforward control. The idea of ILC and RC builds on those ideas: indeed, these add-on controller architectures essentially generate a feedforward signal during the repeated task. However, their stability analysis requires a thorough abstract analysis of the control architecture: its analysis requires 2D system theory for ILC and standard feedback control theory for RC. Students learn a formal stability analysis. Then, a design approach is developed that resembles PID tuning for feedback controllers. Furthermore, these designs are made anti-causal in an appropriate way, which challenges both their analytical skills as well as design ideas. This is complemented by theoretically strong yet practically highly relevant techniques for disturbance analysis, optimization-based design techniques, and multivariable aspects, as well as their connection with automated feedforward tuning. The students implement the techniques on a desktop printer, which has a large amount of friction. Still, the students are all able to control this printer using only a very coarse LTI model up to the encoder resolution. This is highly remarkable. Indeed, none of the students nor experience control engineers are able to achieve similar performance using traditional feedback and feedforward controllers.

3.4 Robotics

Several control courses limit themselves to linear control theory. This is inadequate with respect to the field of robotics which often introduces nonlinear dynamics coming from various physical phenomena like gravity, Coriolis and centrifugal forces or nonlinear friction. The students should have some basics in nonlinear control theory covering the concepts of controllability and observability, stability, local and global linearization. Understanding kinematics is essential in order to be able to perform transformation from joint to task space and vice versa. Newton-Euler and Lagrange formalisms are important for the derivation of dynamic plant models. Basics of trajectory planning are required to understand how robot motion can be parameterized and executed. Advanced control concepts include e.g. impedance/admittance control to employ robots in contact motions with environment interactions or visual servoing which introduces machine vision into the feedback loop.

4. INSTRUMENTATION LAYER

Many control *curricula* focus only on the algorithmic aspects of control neglecting the important instrumentation and implementation parts which every control engineer has to face when dealing with practical motion control problems. A multidisciplinary knowledge is needed including also the components of the instrumentation layer with their specific issues.

4.1 Sensors

This includes the fundamental principles of position, velocity and acceleration sensors typically used in mechatronic systems such as optical encoders, resolvers, DC tachos, magnetostrict or laser position sensors, LIDARs, inertial measurement units including MEMS accelerometers, magnetometers and gyroscopes. Data fusion and filtering techniques may be useful to extract relevant information about the motion system from the combination of imperfect measurements provided by various sensors.

4.2 Actuators

Basic awareness about electrical drives used in industry is necessary including DC, brushless-DC, synchronous, asynchronous or stepper motors or special type of actuators used for micromanipulation such as piezo and voice-coil motors. Fundamentals of their control and operational properties are also relevant since the control engineer is often forced to cooperate on the selection and dimensioning of the actuators during machine design phase.

4.3 Control HW and SW

Graduate students coming from academia often lack necessary skills for the implementation of control systems by means of industrial grade hardware and software. They often rely on Matlab/Simulink software which they know from the control courses and which is seldom available in industry. Basics of PLC programming languages according to a widely accepted IEC 61-131 standard and some knowledge of low-level C(++) may be helpful. Knowledge of FPGA platforms and their programming may be needed in specific applications requiring fast processing times and highly parallel computing.

4.4 Industrial protocols

Industrial control systems are often built upon standardized communication protocols used between the individual subsystems (see Fig.3). Their knowledge is essential for the successful integration of the control algorithms to complex automation technology. Industrial Ethernet protocols such as EtherCAT, Ethernet Powerlink, ProfiNET IRT or SERCOS are especially important for the motion control as they provide the connectivity of sensors and actuators to a supervisory control layer. The communication layer becomes more important for control engineers due to the increasing bandwidth and update rates which nowadays allow implementation of complex centralized control algorithms with high number of machine axes.

5. DESIGN CYCLE, MODELLING, SIMULATION

In last years, one can see a dramatically increased pressure to make control system deployment, update or commissioning in a very limited time in order not to block a production line (see Issue 6). Hence model based control design cycle is becoming well adopted in many industrial fields (driven mainly by automotive industry). It includes typically at least MIL (model-in-the loop), SIL (software-in-the-loop) and HIL (hardware-in-the-loop) stages. Passing through all of them minimizes errors and trials on real production plant. Students should get familiar such approaches which are, unfortunately, covered very seldom in standard control courses. However, the price of technology is nowadays at such low level, that teachers could think about HIL simulators based on e.g. pair of well-known Raspberry Pi supplied via touch screen for model visualization. Such real-time simulators could be available for every student in the lab and also for their home training. Hence the low price HIL simulators could become a disruptive technology in control education in the near future.

6. MATHEMATICAL BACKGROUND NEEDED

Mechatronics can be viewed as a multidisciplinary science composed by different areas including Control Engineering, Mechanics, Computer Science, Electronics, thus a solid mathematical background from many different areas is needed for good understanding and effective dealing with mechatronic systems and their control. Following paragraphs mention some essentials of algebra, calculus and analysis which were identified as core skills necessary for the field of control engineering. Strong emphasis is placed on complex analysis, differential calculus, numerical analysis and computation, (differential) geometry which must be more highlighted in related control courses. For these topics one can recommend e.g. (Lewis, 2003; Van Dooren and Wyman, 2012; Tenenbaum and Pollard, 2012; Holmes, 2016).

In mechatronics rather than in other control fields (process control, energetics), one deals often with the state space form, so the principles from linear algebra about vector spaces, matrices properties, especially eigenvalues and eigenvectors, singular decomposition, norms of vectors or matrices and inner product of two vectors or matrix exponentials, should be well known to understand especially the stability issues of linear dynamical systems or controllability and observability measures. For state space control design tasks, let us point out mainly the solvability of Sylvesters matrix equation and algebraic Riccati equation.

In this context, there are many prerequisites that have to be understood well, e.g. analysis and differential calculus of continuous functions of a real variable, Taylor series to be able to derive linearized models from non-linear ones. Principles from linear algebra regarding the inner product should be further generalized to the inner product of two continuous functions and norms of vectors and matrices to norms of signals and systems, so one can approach the H_∞ and H_2 optimization.

For mechatronic systems, a good explanation of their characteristic behavior in the frequency domain becomes essential. The transition between frequency and time domain shall be addressed as well. Therefore, many topics from complex variable theory must be taught carefully. One often has to deal with the instability of the dynamical system, so students are supposed to be familiar with the mathematical fundamentals which are behind the Nyquist criterion. Loop-shaping principles are often used. Therefore, the Bode theorem and the corresponding restriction which follow from it must be understood. From theorems of crucial importance let us highlight especially Cauchy theorem, the Principle argument, Parseval theorem, further Laurent series and Fourier and Laplace transform, Z-transform.

The area of differential equations plays an irreplaceable role in dealing with any dynamical system and its control design. The students should understand well the solvability of the system of linear ordinary differential equations with constant coefficients and be able to compute its analytic solution, especially with the emphasis to the role of its fundamental system. To this subject, let us put also the numerical methods for solving ordinary differential equations of linear as well as non-linear systems of equations because mechatronic systems must be often handled as highly non-linear systems. Moreover, some of the mechatronic systems evince the stiffness property, therefore the need for implicit numerical solvers should be also highlighted. Speaking about modeling and simulation, one has to be aware also about computational and numerical aspects of simulation of complex dynamical systems. Students should be familiar with various modeling software. The most widespread and preferred at many European Universities is Matlab with its toolboxes Simulink and SimScape. According to the university resources, the students could be also familiar with another software like SolidWorks or Autodesk Inventor for 3D CAD modeling and dynamic analysis, Mathematica or Maple for easy symbolic computation and modeling/simulation tasks, or OpenModelica, Simcenter Amesim or Dymola for component modeling.

From the kinematic and dynamics of systems point of view, one should understand the principles from geometry and differential geometry, matrix transformations, curves parametrization, interpolation and extrapolation methods.

7. EXAMPLES OF MECHATRONIC MODELS

7.1 Flexible beam

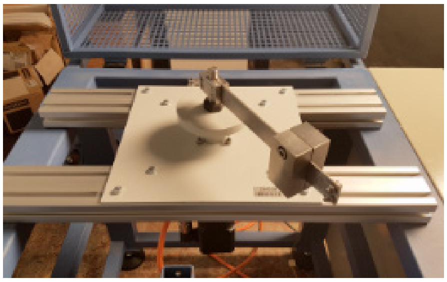

Fig. 4. Flexible beam model

This serves as an example of a simple yet very useful and demonstrative testbed (Fig. 4) which is used at the University of West Bohemia for both teaching and research purposes. The setup consists of an electrical drive (500W permanent magnets synchronous motor) and a flexible mechanical arm which can rotate freely with one degree of freedom. The model is controlled by our own developed industrial computer based on Altera Cyclone V SoC containing two ARM Cortex-A9 CPU cores and a programmable FPGA. The control algorithms are implemented in REXYGEN software tools. The system proved to be an excellent benchmark problem for testing of modelling, identification and control design methods as well as for practicing the implementation and programming skills in the industrial-grade HW and SW environment. It is essentially a distributed parameter system which can exhibit diverse dynamic characteristics allowing to emulate many practical motion control scenarios. It can mimic both rigid and mechanically compliant load with several flexible bending modes. Analytical modelling techniques can be exploited e.g. by using a Euler-Bernoulli beam theory where the white-box model can be directly confronted with the physical reality. It can be used for testing data-driven system identification methods as simple change of mass position, or arm material allows to quickly adjust the dynamics of the system. Friction phenomenon and compensation of periodic disturbances can be studied. Feedforward vibration control methods can be validated as well. Addition of a load-side sensor, e.g. a MEMS accelerometer, allows to employ advanced multivariable controllers aiming at vibration reduction and improved control performance.

7.2 Flexible shaft model

A benchmark motion system has been designed (Fig. 5) to teach loop-shaping based feedback design, followed by feed-forward tuning. The system consists of a two mass-spring-damper system, where one of the masses is equipped with a motor. Students first learn to design controllers for the collocated measurement, i.e., y_1 in Fig. 6. This situation is very easy to control, and very high bandwidths can be obtained. Subsequently, students consider the non-collocated case, which almost always occurs in mechatronic systems due to flexibilities in the actuation chain. Using Bode and Nyquist techniques, students encounter that this situation is extremely hard to control, and it is impossible to push the bandwidth far beyond the resonance mode, which is in sharp contrast to the collocated situation. Finally, students learn to tune feedforward controllers, consisting of mass-feedforward, Coulomb and viscous friction feedforward, and more advanced snap-feedforward.

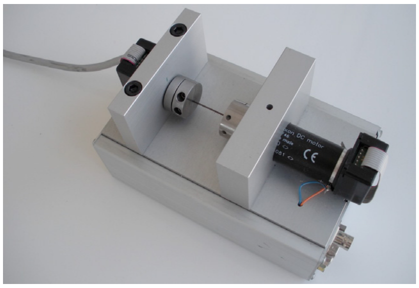

Fig. 5. Benchmark motion system: 2 mass-spring-damper system. One of the masses is equipped with a motor, whereas both of them are equipped with rotary encoders. Both a collocated or non-collocated situation can be considered.

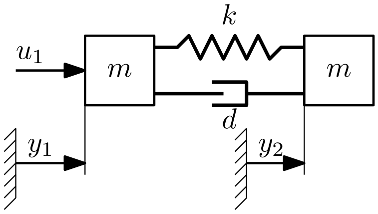

Fig. 6. Schematic representation of the benchmark system.

7.3 SCARA robot

The SCARA robot (Fig. 7) is a representative example of a nonlinear multivariable coupled system. It may serve for the demonstration of fundamental principles of robot modeling and control. The influence of reduction ratio on the coupling dynamics can be explained both qualitatively and quantitatively showing the importance of decoupling, linearization and multi-variable behavior. Position-dependent dynamics can be used for derivation of gain-scheduled, robust or nonlinear controllers. The effects introduced by non-ideal actuators such as friction, elasticity and backlash can be studied and suppressed in a systematic manner. Principles of direct and inverse kinematics can be explained easily.

8. CONCLUSIONS

In this paper, key gaps between industrial needs and master student knowledge in motion education have been

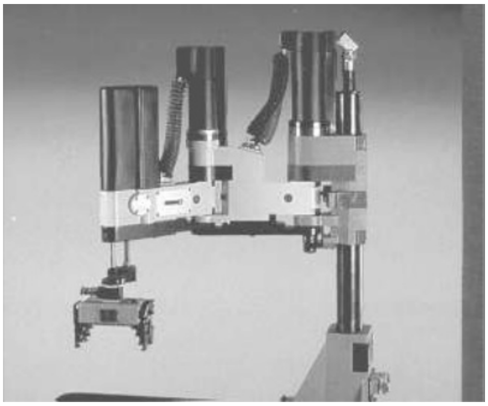

Fig. 7. SCARA robot model

addressed. It was highlighted that both control and instrumentation layer must be taken into account. Finally, simple mechatronic models have been proposed that should help to overcome identified gaps. All industrial requirements have been gathered by professionals from various industrial sectors. The authors believe that the information contained would help to adapt master degree courses in right 'student-centered' direction. In the future, the presented ideas will be elaborated into detailed 'technology driven' education scenarios, with clear time schedule and explicit relations to STEM [5] ecosystem.

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REFERENCES

Bristow, D., Tharayil, M., and Alleyne, A. (2006). Survey of iterative learning control: A learning-based method for high-performance tracking control. *IEEE Control Systems*, 26(3), 96–114.

De La Torre, L., Heradio, R., Jara, C., Sanchez, J., Dormido, S., Torres, F., and Candelas, F. (2013). Providing collaborative support to virtual and remote laboratories. *IEEE Transactions on Learning Technologies*, 6(4), 312–323.

Goodwin, G., Medioli, A., Sher, W., Vlacic, L., and Welsh, J. (2011). Emulation-based virtual laboratories: A low-cost alternative to physical experiments in control engineering education. *IEEE Transactions on Education*, 54(1), 48–55.

Holmes, M.H. (2016). *Introduction to scientific computing and data analysis*, volume 13. Springer.

I-MECH (2017). Intelligent motion control platform for smart mechatronic systems. In *H2020 ECSEL JU project*. URL `https://www.i-mech.eu`.

Leshner, A. (2018). Student-centered, modernized graduate STEM education. *Science*, 360(1), 969–970.

Lewis, A.D. (2003). *A mathematical approach to classical control*. Queens University, Kingston.

Lukovics, M. and Zuti, B. (2015). New functions of universities in century XXI towards fourth generation universities. *Transition Studies Review*, 22(2), 33–48.

Oomen, T. (2018a). Advanced motion control for precision mechatronics: Control, identification, and learning of complex systems. *IEEJ Journal of Industry Applications*, 7(2), 127–140.

Oomen, T. (2018b). Towards ingelligent mechatronic systems through iterative control. *Mikroniek*, (6), 5–11.

Padula, F. and Visioli, A. (2013). An approach for teaching automatic control in a laboratory of mechatronics. volume 10, 214–219.

Pawlowski, K. (2009). The 'fourth generation university' as a creator of the local and regional development. *Higher Education in Europe*, 34(1), 51–64.

Pekarovskiy, A., Nierhoff, T., Hirche, S., and Buss, M. (2018). Dynamically consistent online adaptation of fast motions for robotic manipulators. *IEEE Transactions on Robotics*, 34(1), 166–182.

Reitinger, J., Čech, M., and Goubej, M. (2013). Advanced input shaping filter 3D virtual laboratory. 528–533.

Reitinger, J., Čech, M., Schlegel, M., and Balda, P. (2014). New tools for teaching vibration damping concepts: Contlab.eu. volume 19, 10580–10585.

Robotics, I. (2017). ABB introduces the IRB 4600 ? the ultimate lean robot for general industry. In *Robotics Tomorrow*. URL `https://www.roboticstomorrow.com/`.

Rossiter, J., Pasik-Duncan, B., Dormido, S., Vlacic, L., Jones, B., and Murray, R. (2018). A survey of good practice in control education. *European Journal of Engineering Education*, 43(6), 801–823.

Sánchez, J., Morilla, F., Dormido, S., Aranda, J., and Ruiperez, P. (2002). Virtual and remote control labs using java: a qualitative approach. *IEEE Control Systems Magazine*, 22(2), 8–20.

Senz, J., Chacn, J., De La Torre, L., Visioli, A., and Dormido, S. (2015). Open and low-cost virtual and remote labs on control engineering. *IEEE Access*, 3, 805–814.

Smith, C., Karayiannidis, Y., Nalpantidis, L., Gratal, X., Qi, P., Dimarogonas, D., and Kragic, D. (2012). Dual arm manipulation - a survey. *Robotics and Autonomous Systems*, 60(10), 1340–1353.

Tenenbaum, M. and Pollard, H. (2012). *Ordinary Differential Equations*. Dover Books on Mathematics Series. Dover Publications, Incorporated.

Van Dooren, P. and Wyman, B. (2012). *Linear algebra for control theory*, volume 62. Springer Science & Business Media.

Čech, M., Schlegel, M., Balda, P., and Severa, O. (2013). A new extensive source for web-based control education Contlab.eu. In *Proceedings of 10th IFAC Symposium of Advances in Control Education*, 1–6. Sheffield (UK).

Wang, C., Zheng, M., Wang, Z., Peng, C., and Tomizuka, M. (2018). Robust iterative learning control for vibration suppression of industrial robot manipulators. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, 140(1).

Weiss, B., Sharp, M., and Klinger, A. (2018). Developing a hierarchical decomposition methodology to increase manufacturing process and equipment health awareness. *Journal of Manufacturing Systems*, 48, 96–107.

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[5] Science, technology, engineering, mathematics