Reasoning About Perspectives in Mechatronic Engineering Education

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Abstract. Starting from current trends in Mechatronic engineering, the paper presents upgrading prospects for a two-year curriculum for graduate students with first level degree in mechanical engineering, intended to take into account last innovations in related technological fields. Then, giving more insight into a specific aspect of the curriculum, a project work within a course in mechatronic system modelling and design is presented in detail, and its didactic features are discussed.

Keywords: Mechatronic engineering education · Simulation · Design of mechatronic systems

1 Introduction

Mechatronics is an interdisciplinary engineering field involving a large spectrum of disciplines and technological topics. In the last decades, mechatronics has gained a great relevance due to the pervasive diffusion of consumer products, automotive systems, industrial apparatuses, civil and military systems encompassing the integration of mechanical/physical components along with sensor, actuators, embedded analog and digital electronic hardware and software modules.

In parallel with the wider spread of mechatronic systems, the need for mechatronic engineering education has continuously grown. Due to the peculiar characteristics of strong interdisciplinarity of mechatronics, education in this field distinguishes from other engineering majors. The topic has been analyzed from many different points of view and, along with the evolution of the field, different needs and solutions have been proposed. An interesting starting point to update the education needs is provided by the recent trends in Mechatronic engineering, discussed in Refs. [1–5], where also education aspects are partially considered. Other relevant information can be added by analyzing the status of Mechatronic engineering education in different countries and geographic areas, as found in Refs. [6–9]. Beyond general trends, many focused contributions are available in scientific literature regarding specific aspects and methodological innovations in Mechatronic engineering education. Here we recall some of the most recent, as they are more specifically related to the trends of the sector. In Refs. [10, 11], peculiar aspects of teaching mechatronic engineering to mechanical engineering students are discussed. Some contributions [12–14] examine the adoption of different teaching

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approaches to improve the learning results in the field. Other investigations analyze the impact of using specific types of mechatronic systems, again with respect to learning results [15–18]. Finally, in Ref. [19], specific aspects related to the introduction of machine learning topics in Mechatronics curricula are discussed.

Starting from an existing curriculum, been active at the University of Genoa for the last fifteen years [8, 9], this paper discusses, in next section, how well-established tracks should be upgraded to take into account advances in technological fields that have risen to great prominence, in some cases forcibly, in the last ten years. The second part of the paper presents and analyzes in great details a specific project work, actually used within the mechatronic curriculum at the University of Genoa, aimed at synergically training students in the field of mechatronic system simulation and design.

2 Upgrading Mechatronic Engineering Curriculum

The analysis regarding curriculum upgrading is carried out with reference to the graduate mechatronic engineering program active at the University of Genoa, presented in its original form in [8]. The graduate curriculum was designed to be mainly tailored to students with first level degree with major in mechanical engineering, enhanced with some background in mechatronic foundations (i.e., introductory electronics, embedded systems and programming, see [9]), so that the graduate program courses did not need to present basic topics. Moreover, being (mostly) mechanical engineers, the graduate program assumes that students already know fundamentals of mechanics and how to apply them to the design of simple systems, have a knowledge of CAD software tools and an introduction to the MATLAB environment.

Based on these considerations, the graduate curriculum was designed as outlined in [8], but, as discussed in literature analysis, new technologies are fast becoming relevant in the mechatronic field in the last decade. So here, in Fig. 1, we propose an updated version of Fig. 1 in [8], in which new technologies have been considered (red boxes). Moreover, the figure puts into evidence that mechatronic engineer knowledge requires both "framework" knowledge (enabling technologies, system engineering knowledge) and "application field" acquaintance, as no real complex system can be successfully and competitively developed without specific knowledge regarding its context.

Figure 1 poses a well-known, but challenging question to an education system designer ([11, 12, 19]), as the breadth of knowledge to be covered is very large with respect to the student time assigned to learn it, i.e., typically a two-year program, corresponding to 120 ECTS credits [20, 21], for a master's degree in Italy. One possibility consists in realizing a broad presentation of the field, and to renounce to reach, except in very few areas, a breadth of knowledge comparable to that of specific area masters. On the other side, another way to conceive the curriculum is to accept a more limited exploration of all enabling and application technologies, to provide the students specific operative abilities. There is no easy answer to this question.

The proposal in Table 1 which constitute an improvement to the curriculum presented in [8], based on more than 10 years of experience and by considering the new technological advancements previously discussed. By analyzing it, some guidelines adopted for its definition become immediately clear:

- no credits are explicitly allocated to topics related to a specific application field, so the program is entirely devoted to enabling technologies and system engineering;
- the weight of control system engineering (6 credits), is rather limited with respect to many consolidated mechatronics curricula, as specific issues related to control synthesis and implementation are not considered central in current mechatronic systems;
- mechanical engineering courses take a significant space, as the familiarity with the physical part of a mechatronic system is considered a key feature of a mechatronic engineer with respect to a software or electronic engineer;
- new enabling technologies (IOT - Internet of Things, Edge computing, Applied AI) are explicitly considered in the program
- a suitable amount of credits is dedicated to mechatronic and system engineering, with lab activities and modelling & design courses and project works (see next section).

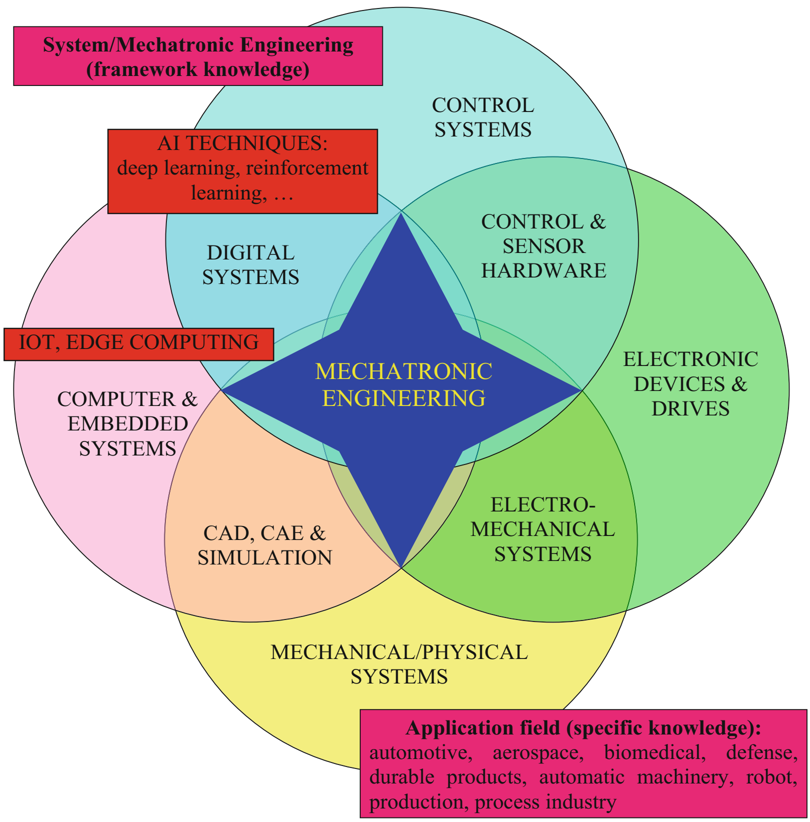

Fig. 1. Topic areas of mechatronic engineering

Table 1. Two-year graduate program in mechatronic engineering

Engineering field	Content outline	ECTS credits
Math tools	Advanced calculus, numerical methods	8
Mechanical	Production technologies and plants; Mechanics and design of machines; Thermal analysis of electronic systems	25
Electrical	Electric drives	5
Electronics	Embedded systems architecture; IOT and edge computing	10
Sensors	Sensor and signal processing systems	6
Control	Control system engineering	6
Software	Embedded systems programming; Applied AI	12
Mechatronics	Modelling and design of mechatronic systems; Laboratory of mechatronic engineering	24
Electives, Thesis		24
Total (2 years, 120 ECTS credits [20, 21])		120

3 Mechatronic Simulation and Design Project Work

To deepen the reasoning, in this section, we discuss in detail an example of project work used to enhance interdisciplinary competences of the students in the context of mechatronic system modelling. The text of a project in the field of Mechatronic system simulation and design is provided in next subsection. This kind of project is assigned to groups of 2–3 graduate students at the second year of their master's degree.

3.1 Simulation and Design Project Assignment

Modelling of mechatronic systems–Group project: Simulation & Design

Consider the system given in Fig. 2, with the following numerical data: $r_1 = 200$ mm, $r_2 = 80$ mm, $r_3 = 90$ mm, $r_4 = 180$ mm, $r_5 = 140$ mm, $r_6 = 90$ mm, $J_{D12} = 0.7$ kgm^2, (total moment of inertia of the drive and pulleys 1 and 2), $J_{34} = 0.5$ kgm^2, $J_5 = 0.3$ kgm^2, $J_6 = 0.25$ kgm^2. Pulley pairs 1–3, 4–6 and 2–5 are connected by belts that are considered axially flexible with stiffness $k_{b13} = 50000$ N/m, $k_{b25} = 60000$ N/m, $k_{b46} = 45000$ N/m. Belts (when they are considered deformable) introduce into the system also a viscous damping with numerical values of the damping coefficient c in Ns/m equal to 2% of the numerical value of the corresponding stiffness k. The system is subject to a viscous load on pulley 6 with $c_6 = 0.15$ Nms/rad and to a time-dependent periodic disturbance torque applied to pulley 5, with a square wave shape with lower value $M_{5l} = 20$ Nm (duration 6 s) and higher value $M_{5h} = 35$ Nm (duration 5 s).

Project assignments:

1. taking into account the viscous load and disturbance torque, derive the equations of motion of the system: 1-a) by assuming the belts as axially rigid, therefore functioning

as kinematic constraints between the pulleys, with the torque of the drive M_{DR} as input and the angular velocity ω_6 of pulley 6 as output (the system has 1 d.o.f.); 1-b) by taking into account the flexibility of the belts, again with M_{DR} as input and ω_6 as output (the system has 4 d.o.f.). In both cases, determine the poles of the system and discuss the presence of any particular value (e.g., null poles). For both models, neglecting the disturbance on pulley 5, determine the frequency and step responses and the static gain; compare and discuss the responses for the two models;

2. By imposing to pulley 6 the cyclical law of motion represented in Fig. 2, with period of 10 s, define a Matlab function that evaluates $\omega_6(t)$ according to the diagram in the figure. Evaluate also the values of angular position and acceleration of the same variable for arbitrary values of time; the corresponding ideal values for angle, speed $\omega_{DR}(t)$ and acceleration of the driver can be readily obtained by the kinematic transmission ratio. Generate the plot of the position, velocity and acceleration of pulley 6 for at least 3 cycles of the (ideal) system motion;
3. considering the model 1-a) (1 d.o.f.), solve the inverse dynamics, to determine the driving torque M_{DR} needed to realize the prescribed motion, in presence of the viscous load and of the disturbance torque;
4. apply the driving torque determined at the previous point as input to model 1-b) (4 d.o.f.) and determine the position and velocity behavior of pulley 6 for at least 3 cycles; compare the result obtained with the ideal law in Fig. 2, highlighting the trend of the error of the system, now operating in open cycle;
5. for the system 1-b) (4 d.o.f.), assume the drive torque M_{DR} as the control variable u and the speed of rotor 6 (ω_6, measured) as controlled variable y. For this system, appropriately documenting the choices made:
   a. identify a control scheme and the related parameters that allow to control appropriately ω_6;
   b. analyze and discuss the characteristics of the closed-loop system, showing poles, static gain and the typical step and frequency response diagrams;
6. apply to the closed-loop system, as a reference signal, the law of motion shown in Fig. 2 for ω_6 and determine the response of the system and the error between actual motion and reference one (at least 3 cycles); evaluate the driving torque required by the closed-loop system. If the closed-loop system does not behave accurately enough, review the control scheme and, if possible, improve it; then reanalyze the system and document its performances;
7. based on the results of the dynamic analyses, select a commercial gear motor and the pulleys and belts that can be used to drive the system.

Material to be delivered:

- a project report presenting a description of the system, the development of the equations and of the block-based models, the simulation results and their discussion;
- a motivation of the design choices (e.g., control system, required actuation/transmission components);
- all model files, properly commented, with synthetic instructions for their use;
- a comparison of the results obtained with different modelling approaches, with a discussion regarding the possible causes of discrepancies;
- the list of selected components, justifying their selection.

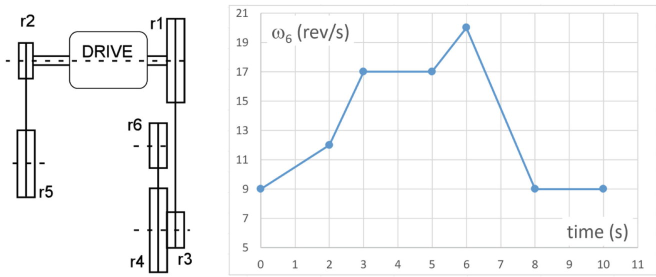

Fig. 2. Scheme of a typical system for the simulation & design project

3.2 Simulation and Design Project Didactic Features

The project assignment is conceived so that, although the complexity can be tackled by graduate students in mechatronic engineering with a background in mechanical engineering, it comprises several aspects of a typical integrated project containing mechanical system dynamics, drive and transmission component selection and design and tuning of a control system. Being in the context of a simulation and design course, no mention is made to control system implementation, for example by a microcontroller, and to sensor hardware and related signal processing requirements. Nevertheless, in case that parallel courses on embedded systems, sensors and measurements are activated (see Table 1), didactic coordination allows to "outsource" such specific aspects to their proper academic referents.

By explicit choice, the system considered in the project assignment is an LTI system, (LTI: linear time-invariant dynamic system) so that all classical control system design techniques and tools can be used. Obviously, non-linear features can be easily added, for example dry friction forces or other typical phenomena (non-linear elastic/damping components, discontinuous contact forces), but such a choice may complicate the modelling effort and it surely makes much more difficult the control design problem.

Typically, since a MathWorks Campus license is made available to teachers and students, the project assignment is solved within the MathWorks Matlab-Simulink-Simscape environment, with possible use of all required toolboxes.

A key aspect of the project assignment is evidenced in Fig. 3: the project can be faced by using several different modelling approaches, corresponding to distinct software tools. Typically, in the first part of the project, student groups are required to conceive a code-based solution. This requires that they attain a deep insight on the mathematical model of the system they have to study. In this phase, they can also analyze the system as an LTI and work on the control design problem, for example, by using the Control system toolbox within the Matlab environment. In the second part of the course, they are introduced to block-based modelling approaches, starting from Simulink and then to more advanced tools such as Simscape and Simscape multibody, so that they can study (again) their system using these tools. In this way, beyond acquiring the skills of using them, they gain sensibility regarding different modelling approaches, along with their advantages and drawbacks.

An unexpected and challenging aspect of the project is the difficulty to obtain the same results for the dynamic behavior of the system as results of simulations with different modelling approaches. In case the group is not able to achieve this nontrivial result, it is required to try to understand why differences arise due to the use of the various modelling tools.

Another interesting feature of the project assignment is that, by properly choosing numerical parameters (inertia, stiffness, damping factors), the control design problem can be rendered from very easy to highly challenging, as it happens when poorly damped natural frequencies fall within the range of working frequencies of the system.

Overall, the teaching activities and the project assignment cover an 11 ECTS course, with about 100 h of lectures and simulation labs and 150–200 h of project work by the student groups. Project complexity is usually tailored according to the number of students in the group, typically ranging from 1 to 3. Project assignment in Sect. 3.1 is an example for a group of 3 students.

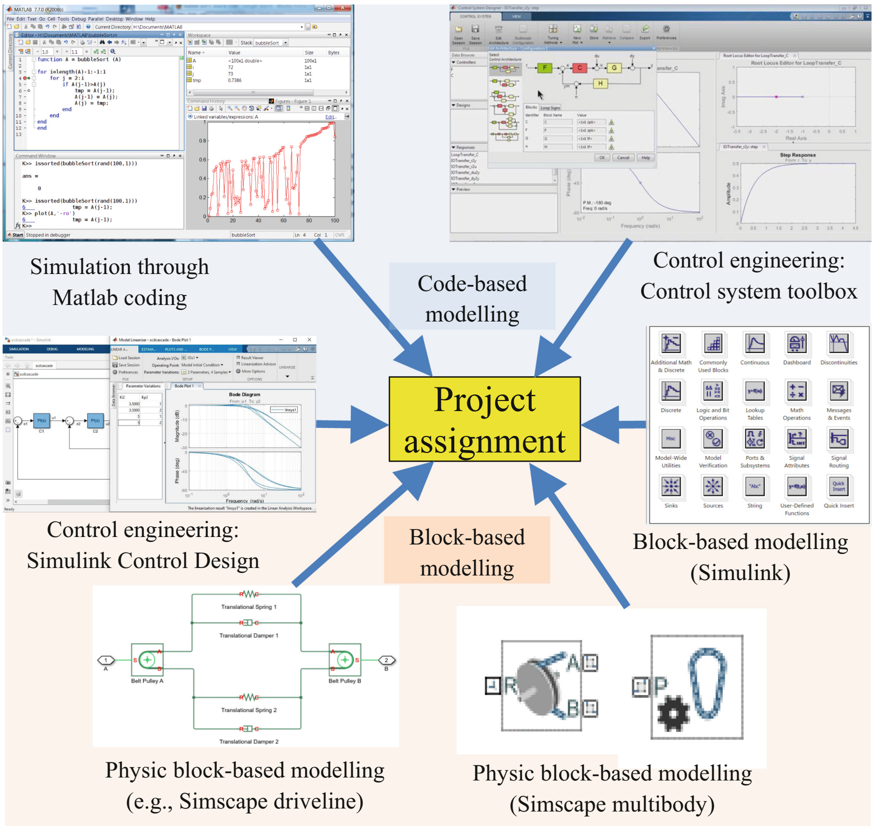

Fig. 3. Interdisciplinary project for dynamics, simulation and control design learning

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