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Control systems engineering and robotics education since Primary school

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Abstract— **Control engineering and robotics hold significant potential to support the development of valuable skills that allow the comprehension and analysis of the current real-world problems. Unfortunately, usually, education on control engineering does not start before undergraduate courses. This paper reviews some of the current experiences whose aim is to introduce control engineering education in K12 education. Subsequently, it presents a whole curriculum based on Educational Robotics that could be integrated into primary school curricula to face control engineering education. One of the key aspects in the creation of such curriculum is the co-creation of the educational curriculum with teachers and education experts. Notably, empowering teachers is essential to effectively convey the fundamental concepts of control theory, enhancing students' problem-solving and critical thinking skills in the domain of control engineering.**

I. Introduction

Control theory plays a significant role in shaping various aspects of modern society, influencing socio-technical systems, organizations, individuals, and society as a whole [1] - [3]. Recent educational policies prioritize fostering STEM competencies from primary school onwards, encouraging innovative learning methods that actively involve educators in the process of educational innovation [4] - [5]. In the landscape of the smart pedagogies [6], Educational Robotics (ER) offers an alternative approach to teaching compared to the conventional lecture-style classes [7]. It aims to enhance comprehension of mathematical and scientific concepts by actively engaging students in processes such as inquiry, planning, documentation, analysis, and interpretation. This approach frequently leads to a favorable disposition towards STEM subjects and motivates individuals to pursue further education and careers in these domains [8]. Notably, ER also holds the potential to promote control engineering education by combining the core concepts of robotics along with other essential elements of the primary school curriculum [9] - [11]. Despite the benefits that the ER approach and control engineering education could bring into the K12 (kindergarten through twelfth grade, referring to students approximately from 5- to 18-year-olds) curriculum, there are still many challenges to overcome, among which the adaptation of instructional content, the evolution of pedagogical approaches, the creation of novel educational materials, and careful planning for the future competencies. Moreover, technological advancement can fragment the educational landscape, leading stakeholders to operate independently, potentially diminishing the role of pedagogy in the process [6]. Also, the scarcity of ICT expertise and the misconception that technology and control system-related tasks exceed the capabilities of teachers [12], and the lack of trusted educational resources and validated measures of student's learning progress can hinder technology and control theory adoption.

This paper presents the design of a set of educational activities aiming to introduce control engineering into primary school curriculum using ER. Through the cooperation with teachers, the activities aim to bridge the gap between elementary education and control engineering. Drawing from active learning, experiential education, and play-based pedagogies, these activities are designed to be age-appropriate, hands-on, and relatable to the daily experiences. Key objectives include introducing students to the basics of control; exploring how familiar systems rely on control engineering; programming for automation; ethical and environmental considerations. In this context, training teachers to draw real world examples and adapt them to their classroom is pivotal for the successful use of the proposed resources. The paper is organized as follows: first, the scientific literature is reviewed to highlight the status of control engineering education initiatives with a focus on primary education; then the authors present a proposal of an educational curriculum based on ER aimed at primary school education to integrate control engineering education.

II. State of the art

Control engineering education is widely debated among professionals and academics in the field. On the one hand, there is the need to transmit the rigorous notions of the control theory. On the other hand, there is the need to adapt curricula to the skill demand of the industry. The ongoing discussion is reported in this section as a result of a thorough search on the scientific databases using ScienceDirect, Web of Science, IEEE Explorer and Google Scholar. Table I summarizes the findings and represents the current efforts and the discussions on Control Engineering education. Notably, most of the experiences are reported or promoted by the IFAC and IEEE community. This is no surprise since these are the two main organizations gathering professionals in the field of engineering and control systems.

Control engineering education has been evolving both in terms of curriculum content, design, and delivery, and in terms of technological tools that can enhance learning.

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TABLE I

SUMMARY OF THE EXPERIENCES IN CONTROL ENGINEERING EDUCATION

Paper	Aim	Impact	Target population
Rossiter (2022) [13]	report the ongoing discussion about the control curriculum at university	propose a reflection along two main dimensions (content and delivery) of control courses	university
Serbezov et al. (2022) [14]	setting up and share a repository of resources based on an IFAC and IEEE joint initiative	provide a list of multimedia and multimodal resources and resource collections	university
de la Peña et al. (2022) [20]	review of the main trends in control education	identify major challenges	university
Knorn et al. (2022) [16]	propose a course for undergraduate	detail the process of restructuring a control course	university
Liotino et al. (2022) [17]	propose a novel taxonomy to describe and quantify the difficulty levels of exam questions and exercises encountered in engineering-related contexts	testing a taxonomy for classifying exercises along 2 dimensions (using, explaining) to overcome the issue of subjective interpretability	university
Mohammadi et al. (2022) [18]	develop a database promoting the exchange of exercises among teachers for STEM subjects	provide an open database and associated handbook	university
Rossiter (2020) [15]	set up a framework for a modern course delivery on control theory	highlight number of core components of a benchmark control course	university
Dörschel & Abel (2022) [1]	develop an interactive teaching format to sensitize prospective engineers to ethical challenges	propose a 90-minutes seminar intended for a control engineering class	university
Bauer & Heskebeck (2022) [19]	address the issue of low female participation in engineering disciplines at university and career	propose resources for a 90-minute-lecture workshop in the classroom	university
Rosas & Fernández (2022) [21]	provide the pedagogical framework for developing mindtools that improve the understanding of the fundamentals of dynamical systems	provide the theoretical basis to use simulations from different perspectives, including cognitive, psychological, pedagogical, and philosophical	university
Shavetov et al. (2022) [22]	propose the student advising service to align academic performance and career planning with the students' personal goals, ambitions, and capabilities	provide examples of academic advisors supporting students in organizing their educational pathway and practical training	university
Axelson-Fisk et al. (2022) [24]	convey basic understanding and awareness of automatic control	propose an escape room composed of 10 challenges about automatic control	general public
Ramos-Teodoro et al. (2022) [10]	present a series of workshop about robotics	engage students during scientific dissemination events	high school
Hoyo et al. (2022) [25]	describe a series of workshops on programming, control engineering and robotics	increase participation in the fields explored by the workshop	secondary school
Duncan et al. (2022) [23]	development of innovative and accessible STEM curricula using ML and AI methods with biomedical and public health applications	integrate into the classroom real data and novel tools deriving from university-level laboratories to motivate students to study STEM	K12
Patiño-Escarcina (2021) [11]	propose a three steps methodology for Robotics in Education to guide projects to either use it alone or to teach robotics with other topics.	organize robotics contents into five core disciplines: Robotics and Society, Mechanics, Electronics, Programming, and Control Theory; define the level of knowledge to achieve based on Bloom's Nomenclature	K12
Screpanti et al. (2022) [9]	describe how to support educational robotics lessons	provide personalized feedback by means of learning analytics	K12
Giacomelli et al. (2022) [30]	show the benefits of using control systems	provide a lesson about control engineering using a GUI for simulating the behavior of an overhead crane	10 - 25 years old
Di Benedetto et al. (2021) [27]	target underrepresented population in control engineering	provide a format workshop available in 20 languages with open online resources	10 - 15 years old
Jackson et al. (2021) [28]	target underrepresented population in control engineering	provide a format workshop available in 20 languages with open online resources	10 - 15 years old
Johnsson et al. (2023) [29]	support gender diversity and inclusion with role models for the future control engineers	provide two portraits of female control engineering professionals and ideas on how to use the resource	Not specified
Li & Yu (2022) [26]	help students open the door of "control"	design a control systems course of 8 lectures in biology curriculum	secondary school
Scaradozzi et al. (2019) [31][31]	Propose a curriculum based on ER to teach the fundamentals of Robotics, IoT and control strategies, also relating the marine environment	Notions about robotics and control theory are aligned with the national guidelines for developing competences at primary schools	Primary school

Nowadays, control engineering is increasingly facing the challenges of keeping students motivated, adequately preparing them to face the problems in modern industry, and tailoring teaching methods and resources to current students, not those of yesteryear [13]. The issue of restructuring the first course in control engineering at university is widely debated and many proposals arouse to align the pathway of the course educational contents [14] - [16], as well as the assessment of the learning outcomes [17], [18]. Also, innovative workshops were proposed to promote the ethical challenge in automatic control [1] and to support gender diversity and inclusion [19]. Many studies report the effectiveness of modern technologies like Massive Open Online Courses (MOOCs), Learning Management Systems (LMS) or other web-based multimodal

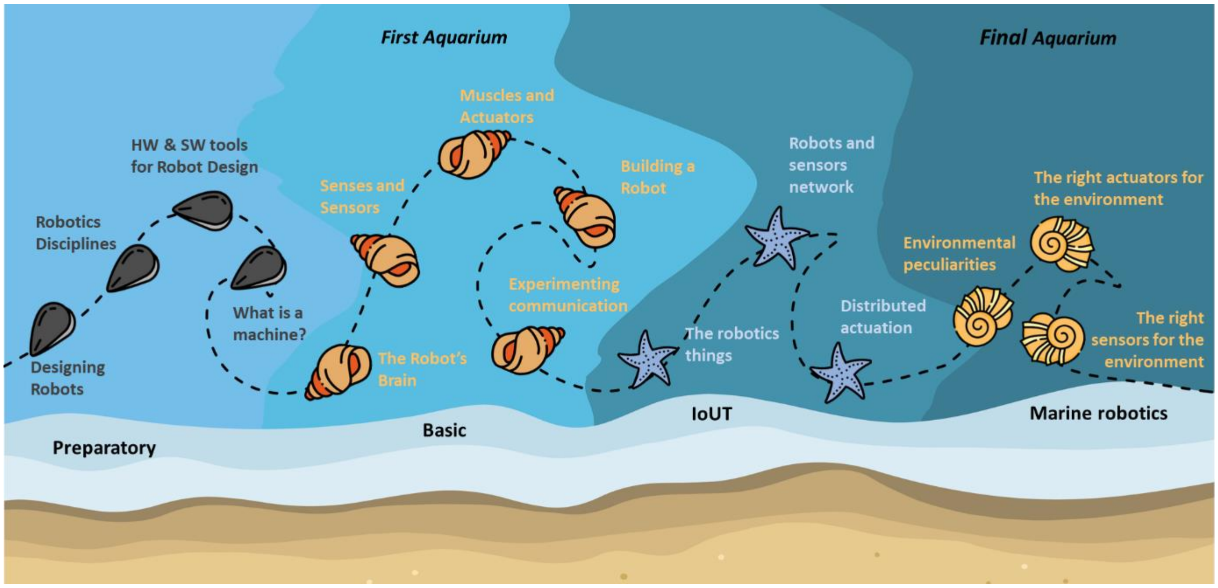

Fig. 1.: A graphical representation of the proposed curriculum and its topics.

resources to enhance students' learning [13] - [15], [18], [20], [21]. Over the years, many educational resources have been developed by researchers and lecturers to keep students interested and facilitate their understanding of the notions of control theory. To exploit the wide range of quality materials created so far by the control community, IFAC and IEEE sponsored initiatives to create a platform and a framework where a lecturer can find a set of trustworthy resources [14], [16] - [18]. The pedagogical framework underlying the control engineering classroom proposes to align the curriculum on active learning and continuous assessment [16], to endorse authentic assessment and lecture flipping [15], to ground the use of simulations in the theory of mental models [21], and to provide mentoring programs [22].

If on the one hand there is a lively discussion on how to bring quality control engineering education to university students, on the other hand, only few studies focus on how to bring introductory courses on control engineering in K12 education. K12 education is usually targeted by special programs outside the traditional school curriculum, like outreach activities [23] or dissemination activities [10],[24]-[29]. Only four studies (Table I) mention and explain educational activities focusing on primary school [9], [11], [30], [31]. Three of these studies include the presentation of a tool whose aim is to provide either a mechatronic toolkit for robotics activities [31], or a software to demonstrate concepts by means of simulations [30], or an evaluation support system that detects trajectories of students' learning [9]. All of them propose at least one associated educational activity. Only two studies provide a proposal for the organization of control theory's notions into the primary school curriculum using ER: one organizes the curriculum around the five main disciplines of robotics and proposes activities' evaluation based on Bloom's Taxonomy [11]; the other proposes a path of activities developing according to the growing abilities of primary school students and relies on the national assessment for the evaluation of the curriculum [31]. From the analysis of the previous work, it seems that most of the studies focus on improving existing curricula and resources dedicated to university students. K12 education seems to benefit mainly form outreach activities or workshops held during special events, mostly targeting high school or secondary school students. Only few activities focus on the development of educational activities for primary school education and, usually, it involves a top-down approach: experts plan a set of tools and educational contents, then they also carry out the activity. Moreover, despite a few initiatives have been already established to build a community of practice [32] among control engineering experts and lecturers, there are no sustainable trajectories for primary school teachers' professional development on control engineering education. Finally, only few studies report to include environmental themes during the activities.

Starting from these considerations the present paper aims to present a curriculum that could be integrated into the curricular pathway of primary school students. The curriculum and the activities are not entirely developed by control engineering experts, but they are co-created with education experts and teachers. Teachers themselves are first trained on the main principles of control engineering and robotics, then involved in the development of the final resources that they will bring into the classroom. The results of this kind of approach are a community of practice among teachers, and a set of activities that could be arranged to carry out seldom activities, if necessary, but that unleash the whole potential when combined in a systematic series of workshop integrated with the other subjects into the school timetable. The proposed curriculum includes environmental themes both as a boost for the inclusion and engagement of all students, and to foster reflections about sustainability.

III. Control Engineering Education in Primary School

Primary schools are increasingly prioritizing STEAM education (STEM subjects and Arts) to foster students' interest and skills in science, technology, and interdisciplinary

TABLE II
CONTROL THEORY FUNDAMENTAL CONCEPTS EMBEDDED INTO THE ER CURRICULUM

Concept	Topic (Module)	Example activity (skill)
Control Theory	2. Robotics' disciplines (Introductory)	A. a meeting with the expert (role modeling) B. find examples of control engineering applications in the real world (contextualize concepts in the real world) C. role playing (gamified cooperative learning)
System/ Subsystems	3. Hw and Sw tools 4. My first machine 5. The robot brain (Introductory)	A. observing a technological tool and identify its main parts and how they interact to accomplish a task (computational thinking) B. use the robotic toolkit to assemble a machine and assign it a behavior (constructionism) C. observe real world phenomena, take notes, represent the phenomenon by means of connected blocks (computational thinking, scientific inquiry)
Input	6. Sense and sensors 8. My first Robot (Introductory) 1. Environment peculiarities 3. The right sensor for the environment (Marine Robotics)	A. establish a connection between the senses of the human body and the sensors integrated in the robot's structure B. generalize the concept of sensing the environment to other realm and environments (generalization)
Output	7. Muscles and actuators 8. My First Robot (Introductory) 1. Environment peculiarities 2. The right actuators for the environment (Marine Robotics)	A. establish a connection between the muscles of the human body and the actuators integrated in the robot's structure (reinforces the objectives of the national guidelines for the curriculum for primary school) B. observe and analyze the different propulsion structures in relation to the different environments (analytical skills, generalization skills)
Open loop/closed loop control	4. My First Machine 5. The robot brain 8. My First Robot (Introductory) 3. Distributed actuation (IoT)	A. observe the behavior of a simple robot programmed without control statements and compare it with the behavior of a robot programmed using a control statement B. Use the Flow diagram to represent the behaviors in activity A (generalization skills, algorithmic thinking) C. Use the Block diagram to represent the subsystems in activity A (generalization skills, abstraction)
SISO vs MIMO systems	8. My First Robot (Introductory) 9. Listening and communication 1. The robotics things 2. Robots and sensors network 3. Distributed actuation (IoT)	A. invent a simple behavior for a robot using one sensor (microphone) and one actuator (speaker) and present it to the classroom (storytelling, creativity, digital competence) B. invent a collaborative story using multiple sensors, one core unit and multiple actuators and present it on a digital ebook (project-based learning, cooperation, digital skills)
Central control vs distributed control	1. The robotics things 2. Robots and sensors network 3. Distributed actuation (IoT)	A. build a simple tune using the central controller and the speaker unit (digital competence, art) B. realize a simple tune using more controllers each equipped with a speaker unit (digital competence, artistic skill)
Ethical issues	1. The robot's design job (Introductory) 2. Environment peculiarities (Marine Robotics)	A. read the Asimov's laws of robotics and explain them using the toolkit B. read the 7 principles of ocean literacy and imagine how to use the RoboFISH toolkit to explain them to your friends (Green competence) C. design your own robot(s) that could help citizens in achieving sustainability (active citizenship skills, green competences)

learning. Coding and programming concepts are also being promoted at this level to equip students for future employment opportunities. The proposed curriculum integrates STEAM and environmental education while emphasizing automation theories, often overlooked in educational initiatives. The authors aim to introduce robotics and control theory, as these concepts are essential for understanding autonomous artificial life and highlighting automation concepts is crucial for a valid educational robotics curriculum. In the early design of authors' research, the curriculum was divided in two sets of modules: the basic modules (preparatory and basic topics of Fig.1) and the advanced modules (IoT and Marine Topics of Fig. 1). Each module is made of several topics and each topic provides a key concept related to robotics and control engineering as well as a hands-on activity using a robotic toolkit. The following sub-sections describe the underlying approach to developing the educational pathway, the pedagogical methodology to bring activities into the classroom and the overall organization of topics and activities within the curriculum.

A. *Bottom-up approach*

The creation of the curriculum has a dual purpose: first, to equip teachers with the knowledge and skills in robotics and control theory, enabling them to create customized educational experiences tailored to their classroom requirements; second, to encourage students to delve into robotics concepts and engage in hands-on exploration of complex problems by means of robotics.

Considering the broad spectrum of students at differing cognitive development levels when crafting educational activities for primary school, a close collaboration with experts in the field is essential. Building upon this premise, specialists in control theory and robotics initiated a strategic partnership with the experts in the field of learning and education science as well as primary schools' staff to outline essential subject matter. The education science experts shaped instructional guidelines, engineers selected robotics and control theory related topics, while teachers and schools' staff offered diverse insights about the introduction of innovation into their daily activities, thus influencing the co-design of curriculum activities. As a first step, teachers enrolled in a training program where they aligned with the pedagogies underlying ER and the basics of robotics and control theories. After the training, they were able to reuse, remix, or adapt the lesson topics and activities they were presented with during the training, so to create a set of lesson plans that could suit the cognitive development and the learning objectives of their classroom. Notably, the evaluation of students' learning was designed using a playful approach, thus quizzes and games were embedded at the end of each module. Finally, teachers tested the activities in the classroom.

B. The methodology

To establish an engaging and efficient learning environment, the activities include the following pedagogical methods:

- Experiential learning: hands-on learning sessions let students build, program, and interact with robots. This promotes active engagement and problem-solving.
- Authentic learning: students explore real-world examples using a robotic toolkit. This encourages critical thinking and problem-solving skills.
- Constructionism: manipulating hardware and software help students understand concepts by thinking with the object; designing and customizing robots, continuously refining designs and programs based on testing and feedback, allowing for personalization and self-expression, encourage students to explore their creativity [33].
- Social Constructivism: sharing the experience with peers promotes the process of building knowledge.
- Inquiry-based learning: asking questions, exploring, experimenting, and learning through inquiry foster a sense of curiosity and self-directed learning.
- Teachers and students assess progress and reflect on their experiences, promoting self-awareness and metacognition.
- Interdisciplinary learning: it promotes the sustainability competences, which are necessary to think, plan, and act with empathy, responsibility, and care for both our planet and public health [34].

C. The curriculum

Table II summarizes some of the key concepts in control theory applied throughout the curriculum; they are presented in relation to the topics of the curriculum shown in Fig. 1. The preparatory module defines a set of preliminary activities whose aim is to familiarize with the world of robotics. The first concept is that to create a robot it takes several skilled professional from key disciplines in robotics, among which control engineering. Then, students explore the concepts of "machine" starting from the reflection on familiar objects like household appliances and cars. At the end of the activity, they are familiar with the notion of system and subsystem, they are able to analyze technological objects by their purpose and scope, mechanical structure, power system, interfaces with the environment and with humans. This approach to robotics education aligns with the Reverse Engineering Pedagogy (REP) [35] and with the assessment of technological literacy in the context of the maker approach [36]. Then, students focus on learning the basics of robotics, first, reflecting on the differences and similarities between machines and robots, then, learning about the concept of autonomy. The simple statement *if… else..* is the first kind of control students explore. They also learn how to integrate information from sensors into the strategy for controlling the robot's behavior. They explore what happens when the robot's behavior is not restrained by a closed loop control. The use of block diagrams helps student abstract, generalize, and build the concept of the whole process. Finally, communication between robots and humans, and among robots is presented.

As depicted in Fig.1, the advanced modules propose two pathways: IoUT (The Robotics thing, Robot Sensors Network and Distributed Actuation) and Marine Robotics (Environmental peculiarities, The right actuators for the right environment and the right sensors for the right environment). The lessons on IoUT concepts extend from the foundational communication lessons in the basic module. The lessons introduce the notion of smart things and their capability to connect with each other, and explore sensor networks and distributed actuation. Example activities involve programming a smart traffic light system and establishing a network of smart buoys to monitor the ocean temperature. The fundamentals of Control System Theory principles are reviewed (dynamical systems, open-loop control, and closed-loop control) and extended to include notions about distributed automation. The module about marine robotics explores by comparison the different earthly environments, emphasizing the ocean. Lessons are organized as scenarios. Each scenario guides the student toward the exploration of the environment focusing on relevant physical variables that can describe the state of the environmental system or on the relevant actuation mechanism.

IV. Discussion and Conclusion

The proposed curriculum was first piloted in the years 2020-2022 within the Erasmus+ project Robopisces. Teacher training and activity in the classroom spanned over 2 years. Due to pandemic related issue the teacher training was delivered only online. Its duration was of 25 hours (basic modules), 40 hours (Marine topics) and 35 hours (IoT topics). The full report of the project's results is available as Open Educational Resources (OERs) at www.robopisces.eu. Interestingly, teachers' observations reported a marked increase in students' acquired knowledge in specific dimensions like "Understand the basic programming principles" or "understand how to add sensors, engine, battery" [37]. Moreover, students' motivation in STEAM subjects seemed to be improved, along with their interest and participation [37].

The proposed work recognizes the vital role of primary education in shaping students' perceptions of STEM fields aiming to demystifying the complexity of control engineering. By providing an engaging and accessible foundation, the curriculum aims to inspire the next generation of engineers. This paper outlined the rationale behind the proposed activities and discussed the expected outcomes in terms of student learning in control engineering. This work will be extended in the future expanding the set of available activities and including possible connections with the experiences presented in Table II. For example, promoting the inclusive dimension with the 'Girls in Control' initiative [28][27], [28] or by [19], [29]. Moreover, the final gamified evaluation strategy of the curriculum could involve other remarkable initiatives, like [25].

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