LUCAS RIBEIRO MATA

Considerations about the design and development of remote laboratories for cyber-physical systems in engineering courses

SÃO PAULO

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Master's thesis presented to the Escola Politécnica - Universidade de São Paulo

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Corrected Version

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Dedicated to Brazilian people.
May engineering help Brazil to find its way for social,
technological, environmental and economic development.

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RESUMO

MATA, L.R. Considerations about the design and development of remote laboratories for teaching cyber-physical systems in engineering courses. 2022. 188 p. Thesis (Master of Science). Escola Politécnica, Universidade de São Paulo, São Paulo.

A disseminação das tecnologias digitais mudou profundamente a dinâmica das atividades humanas em todos os aspectos da vida. Atualmente, a transformação digital é o principal desafio para diversos setores produtivos em todos os países. Um dos fatores mais importantes nesse processo é a formação de engenheiros que devem ser capazes de integrar equipes multidisciplinares para projetar e desenvolver soluções de engenharia baseadas em tecnologias digitais. As instituições de ensino devem fornecer ambientes de aprendizagem nos quais os alunos possam explorar conceitos e experimentar atividades práticas relacionadas ao uso e desenvolvimento de tecnologias digitais. Plataformas educacionais remotas podem ser uma solução para compartilhar recursos entre instituições, aumentar a disponibilidade de equipamentos e garantir a continuidade das atividades de aprendizagem mesmo durante surtos de doenças infecciosas, como aconteceu durante a Pandemia da Covid-19. Este trabalho investigou os principais aspectos relacionados ao projeto e desenvolvimento de laboratórios remotos para o ensino de sistemas ciberfísicos em cursos de engenharia. Primeiramente, foi feita uma revisão de literatura para identificar objetivos de aprendizagem, competências e estratégias educacionais relacionadas a sistemas ciberfísicos e indústria 4.0 no ensino de engenharia. Foram realizados três estudos de caso sobre plataformas educacionais utilizadas para ensino e pesquisa de sistemas ciberfísicos. Em seguida, foi apresentada uma proposta de diretrizes para o projeto de plataformas educacionais remotas para o ensino de sistemas ciberfísicos. Uma prova de conceito foi implementada com base nessas diretrizes. Cinco professores de engenharia foram convidados a avaliar esta prova de conceito. Finalmente, foram feitas algumas considerações sobre o projeto e desenvolvimento de laboratórios remotos de sistemas ciberfísicos. Os resultados apresentados neste trabalho contribuem e demonstram a facilidade de implementação de plataformas educacionais flexíveis, baseadas em tecnologias de código aberto e aprendizagem híbrida, que podem ser usadas para desenvolver múltiplas competências em cursos dedicados à introdução e design de sistemas ciberfísicos.

Palavras-chave: laboratórios remotos, sistemas ciberfísicos, ensino de engenharia.

ABSTRACT

MATA, L.R. Considerations about the design and development of remote laboratories for teaching cyber-physical systems in engineering courses. 2022. 188 p. Thesis (Mater of Science). Escola Politécnica, Universidade de São Paulo, São Paulo.

The spread of digital technologies has profoundly changed the dynamics of human activities in all aspects of life. Nowadays, digital transformation is the main challenge for several productive sectors in all countries. One of the most important factors in this process is the education of engineers who must be able to integrate multidisciplinary teams to design and develop engineering solutions based on digital technologies. Educational institutions must provide learning environments in which students can explore concepts and experience hands-on activities related to the use and development of digital technologies. Remote educational platforms can be a solution to share resources among institutions, increase the availability of equipment, and ensure the continuity of learning activities even during outbreaks of infectious diseases, as happened during the Covid-19 Pandemic. This work investigated the main aspects related to the design and development of remote laboratories for teaching cyber-physical systems in engineering courses. First, a literature review was carried out to identify learning objectives, competencies and educational strategies related to cyber-physical systems and industry 4.0 in engineering education. Three case studies were carried out on educational platforms used for teaching and researching cyber-physical systems. Then, a proposal for guidelines for the design of remote educational platforms for teaching cyber-physical systems was presented. A proof of concept was implemented based on these guidelines. Five engineering professors were invited to assess this proof of concept. Finally, some considerations were made about the design and development of remote laboratories for cyber-physical systems. The results presented in this work contribute and demonstrate the ease of implementation of flexible educational platforms, based on open-source technologies and hybrid learning, which can be used to develop multiple competencies in courses dedicated to the introduction and design of cyber-physical systems.

Keywords: Remote laboratories, Cyber-physical systems, Engineering education.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABET – Accreditation Board for Engineering and Technology

API – Application program interface

CITI – Interdisciplinary Center in Interactive Technologies

CPPS – Cyber-physical production system

CPU – Central processing unit

DC – Direct current

ESC – Electronic-speed-controllers

FCU – Flight control unit

GPIO – General purpose input/output

GPU – Graphical processing unit

HTTPS – Hypertext transfer protocol secure

IIoT – Industrial internet of things

IoT – Internet of things

IDE – Integrated development environment

LAB – Laboratory

LDR – Light dependent resistor

LED – Light emitting diode

LIDAR – Light detection and ranging

MBSE – Model based systems engineering

MDF – Medium-density fiberboard

MOOC – Massively open online course

OSEPP – Open-Source Electronics Prototyping Platform

PLC – Programmable logic controller

PMU – Power management unit

POM – Polyoxymethylene

PWM – Pulse width modulation

QR – Quick response

RAM – Random-access memory

ROS – Robotic operating system

SBC – Single board computer

SDF – Simulation description format

SSH – Secure socket shell

SysLCM – Systems Life Cycle Remote Laboratory

TRIZ – Theory of inventive problem solving

TTL – Transistor-transistor logic

UART – Universal asynchronous receiver/transmitter

UAV – Unmanned aerial vehicles

UK – United Kingdom

USA – United States of America

USB – Universal serial bus

USP – Universidade de São Paulo

xCPS – Explore Cyber-Physical Systems

SUMMARY

1 INTRODUCTION

The history of human development is marked by overcoming challenges through the creation and application of technologies. The scientific and technological advances that occurred after the Scientific Revolution led to an unprecedented expansion of human knowledge, with the natural consequence of its division into specific fields. In this sense, engineering emerged as a profession devoted to the application of human knowledge in the development of artifacts for solving problems in different contexts, a knowledge area that focuses on how to overcome different challenges in order to improve quality of human life (FEISEL; ROSA, 2005). At first, engineering gained great relevance in the military sphere in the creation of fortifications and armaments, but then it expanded to the civil context (TELLES, 1994).

The first institutions dedicated to engineering education were established at the end of the 18th century. Initially, its main role was to instruct engineers with a solid technical basis, transmitting the set of technical knowledge mastered at the time. The introduction of a scientific basis in engineering education gave rise to the 2+3 model, in which the first two years are dedicated to basic scientific studies, such as mathematics, philosophy, chemistry and physics, and the last three years focus on technical and specialized studies. This model was created in France and used as a reference by many countries in the establishment of engineering schools (GRIMONI, 2006). In the same period, the industrial revolution took place, a milestone that divides human history in different stages. Until the 18th century, the process of transforming raw materials into artifacts was mostly handcrafted (STEARNS, 2021). The processes were characterized by intensive use of human force as main energy input. The creation of the first steam machines in the weaving sector led to a technological break in production processes, also known as the first industrial revolution. It allowed a sudden increase in productivity and standardization of product quality (STEARNS, 2021).

In the 19th century, electricity opened up a new opportunity for technological reinvention of manufacturing processes (TELLES, 1994). Electric machines transformed the industrial sector as well as people's way of life, establishing a new landmark known as the second industrial revolution (STEARNS, 2021). Despite the leading role of electricity, considerable advances in other areas such as chemistry, production management, biology, agriculture, materials and transport, were also important in this technological transformation. The expansion of knowledge and technological evolution led engineering, previously divided into two contexts - civil and military, to gain new fields of specialization, such as mechanics, chemistry and electrical engineering. Civil engineering has become an area of expertise focused on buildings and interventions in nature (GRIMONI, 2006).

In the middle of the 20th century, the development of semiconductors and computers enabled the automation of manufacturing processes, leading the industry to take a new technological leap known as the third industrial revolution (STEARNS, 2021). Since then, scientific production has grown in an extraordinary way and technological innovations have emerged ever faster. New fields of specialization emerged in engineering.

Engineering with its practical character has a central role in technological and industrial development. It can be described as a profession dedicated to the use and modification of the three fundamental resources that humankind has available - energy, materials and information - for the creation of all technology (FEISEL and ROSA, 2005).

In the initial phase of industrialization, the most relevant aspect in engineering education was mastering the basic scientific knowledge and technical content related to the area of specialization. The rapid changes in science and technology shifted this paradigm. The competency-based approach became essential in order to teach engineers capable of solving problems, making decisions, working in multidisciplinary teams and communicating the results of their work (KAMP, 2016).

Currently, the diffusion of digital technologies in everyday life and in productive activities has caused profound changes in the economy. This process of disruption is often known as the fourth industrial revolution, and it is characterized by the development and application of advanced technologies such as cloud computing, industrial internet of things (IIoT), synthetic biology, big data, virtual reality, 3D printing, artificial intelligence, and cyber physical systems (SCHWAB, 2016). Contrary to the previous industrial revolutions, this one integrates multiple technologies that are leading to unprecedented changes in the economy and society at an exponential pace (KAMP, 2016; SCHWAB, 2016). In the manufacturing sector, the term “industry 4.0” has been used to describe the new technological stage that can be achieved by the implementation of these technologies, which are expected to lead to more efficient, sustainable, and flexible manufacturing processes (TERKOSKY; FRYE; MAY, 2020).

In this new stage, data becomes one of the fundamental resources for engineering, and engineering systems are being formed by a deep integration of physical and virtual components, which is described as cyber-physical systems. This brings a new challenge for engineering education that should instruct engineers how to design, improve and maintain this new kind of systems. Thus, it is fundamental to rethink the instructional design process in order to focus on the development of competencies and skills that enable engineers to lead the technological transformation in different economic sectors and cope with cyber physical systems.

Laboratories are an essential part of the learning process in engineering education where students can experience the reality of the concepts, interact with real phenomena and learn how to design solutions for problems in different contexts (VIEGAS et. al, 2018). Lab environments can leverage hands-on activities that allow students to explore concepts and learn by doing, opening up opportunities for the adoption of active learning.

Active learning is an educational approach based on the constructivism theory, which emphasizes learning as a construction of knowledge structures through the progressive internalization of actions (FERNANDEZ, 2017). This approach consists of educational strategies that encourage students to interact, reflect, explore, apply and share their experiences. Students play the main role in a dynamic learning process in which knowledge is socially constructed linking theory and practice (SANTOS et. al, 2020). In this way, students are better able to analyse, evaluate and synthesise ideas, achieving the higher-order skills in the cognitive domain (CAMBRIDGE ASSESSMENT, 2021).

The engineering education for this new technological and social context must include the development of skills to solve real problems (KAMP, 2016). One of the most important aspects for engineering education is to develop learning-to-learn skills that teach engineers to deal with unknown and complex problems (KAMP, 2016).

The excellence in engineering education is linked to significant learning, which involves the learning of concepts and also develops a set of diverse and complex skills, attitudes and values (SANTOS *et. al*, 2020).

The adoption of learning methods that focus on skills development, such as hands-on activities, is essential to prepare engineers who should be able to solve 21st century societal and engineering challenges. This is not a novel educational approach, many studies were carried out addressing the design and validation of diverse strategies based on skills development. However, it requires a change of attitude by students, instructors and professors. Professors and instructors should redesign the teaching and learning processes, taking on the role of facilitators, while students should be encouraged to take on the responsibilities for their own learning. On the other hand, institutions should provide resources and infrastructure that enable a wide range of hands-on activities for diverse learning objectives. In this way, professors can select, combine and adapt educational strategies that best suit the learning objectives.

Advances in digital technologies have enabled the development of simulation and remote laboratories that allow students and professors from different institutions to conduct hands-on activities using a common environment. Simulation laboratories are virtual platforms that emulate physical environments for exploration of concepts (Balamuralithara and Woods, 2009), while remote laboratories are virtual environments that connect users to a real laboratory, allowing them to interact remotely and instantaneously with the lab systems (VIEGAS *et. al*, 2018). Through remote labs, students can safely interact and get measurements and conduct tests in real systems, exploring different design solutions and learning by experimenting.

Remote and virtual labs are solutions that can be used to amplify opportunities and to overcome the lack of specific laboratories or logistical restrictions, providing environments in which students can experience the real world and construct their own knowledge on their own time schedule and rhythm. In engineering education, remote labs are gaining relevance as remote solutions due to permitting students and teachers to conduct experimental activities remotely and safely, and institutions to share laboratories and resources.

The COVID-19 pandemic has caused, at the same time, significant negative and positive impact on education. The health measures of social distancing required the use of virtual and remote resources as the main environment for the instructional process. The inequalities were amplified and those without access to devices and/or connectivity were left far behind, causing severe damages for education for all ages. On the other hand, many institutions accelerated their digital transformation, adopting digital technologies, including remote and virtual labs solutions. Many aspects of the response to the pandemic will probably be retained by teachers and institutions. The hybrid mode of delivery of experiential learning activities can gain great importance after that. This mode is characterized by the combination of hands-on activities with remote delivery (BHUTE *et al.*, 2021). In this scenario, the use of virtual and remote labs will be part of the instructional process in many engineering disciplines.

Remote labs can offer a flexible environment with high availability (24/7). Furthermore, the sharing and integration of educational resources can reduce the differences among well equipped and disadvantaged institutions. Virtual and remote labs can be used as solutions to the lack of laboratory equipment, logistics problems, economic constraints, and distance learning. Several authors have advocated that virtual environments in which students can interact with real-distant engineered systems are essential for teaching industry 4.0 (BENIS; NELKE; WINOKUR, 2021) (TERKOSKY; FRYE; MAY, 2020) (BORDEL; ALCARRIA; ROBLES, 2019).

The investigation of the use of remote labs in engineering education is an important research topic that can provide the background and understanding needed to adopt it as a potential environment for hands-on activities and skills development in different disciplines. In the context of the fourth industrial revolution, it is relevant to analyse how remote labs can support learning activities that intend to engage engineering students in the construction of knowledge about industry 4.0.

1.1 Objective

The objective of this work is to investigate the design and development of remote laboratories for hands-on activities that enable engineering students to acquire competencies and construct knowledge about cyber-physical systems.

1.2 Specific objectives

In order to achieve the general target, the following specific objectives were defined:

1) Analyse the role of laboratories in engineering education and investigate the use of remote laboratories.
2) Identify core competencies for industry 4.0 and review studies using remote labs for teaching industry 4.0 to investigate its capabilities, potential applications, and challenges.
3) Identify learning objectives, competencies and educational strategies related to cyber-physical systems in engineering education.
4) Develop case studies to investigate the educational platforms that can support learning and research activities in cyber-physical systems.
5) Propose design guidelines for remote laboratories which can support practical activities in the development of conceptual understanding and design of cyber-physical systems.
6) Develop a proof of concept of a remote laboratory for teaching the concept and design of cyber-physical systems in engineering courses.
7) Make considerations about the design and development of remote educational platforms for teaching cyber-physical systems.

1.3 Methodology

This work is categorized as applied research due to its investigative and purposeful nature. The problem investigated was approached qualitatively. As for its objectives, the research is considered exploratory. The technical procedures adopted were: (1) bibliographic research to identify needs and define requirements; (2) case study to analyze examples of educational platforms; and (3) experimental research to develop a proof of concept. Table 1 summarizes the methods adopted in this research.

Table 1 - Classification of the research process

Aspect	Type
Nature	Applied research
Problem approach	Qualitative research
Objectives	Exploratory research
Technical procedures	Bibliographic research
	Case study
	Experimental research

1.4 Thesis organization

The text of this master's thesis is organized into seven chapters. Chapter 1 presents the context and the problem addressed in this work, states the general and specific objectives, and presents an overview of the methods adopted. Chapter 2 details the literature review, undertaken to investigate the role of laboratories in engineering education, core competencies and learning objectives related to industry 4.0 and cyber-physical systems, and academic courses aimed at teaching cyber-physical systems to engineering students. Chapter 3 describes the methodology used to conduct the case studies, build guidelines and develop a proof of concept. Chapter 4 details three case studies of educational platforms. Chapter 5 presents guidelines for developing remote labs for cyber-physical systems. Chapter 6 describes the proof-of-concept of a remote lab of a cyber-physical system, from design conceptualization to prototype analysis. Finally, Chapter 7 presents the conclusions of the work, as well as contributions and recommendations for further research and development.

This thesis also includes four appendices, which bring together procedures and documents used in the analysis of the prototype, and programs embedded in the experimental setup.

2 LITERATURE REVIEW

This chapter aims to present a review about the use of remote laboratories for teaching industry 4.0 and the current status of cyber-physical systems in engineering education. A brief overview of the role of laboratory environments in engineering education is described in section 2.1. Section 2.2 introduces the concepts of remote and virtual laboratories. Competencies required for industry 4.0 are described in section 2.3. Section 2.4 presents a framework of studies that sought to investigate or describe the use of remote laboratories for teaching industry 4.0. Cyber-physical systems are described in section 2.5. Section 2.6 analyses the teaching of cyber-physical systems in engineering education. Section 2.7 presents the competency framework for industry 4.0 and cyber-physical systems.

2.1 Laboratories in engineering education

Laboratories are environments where students can explore the nature of science, interact with real phenomena, develop inquiry skills, acquire teamwork abilities, and cultivate interest in science, gaining knowledge that goes beyond pure theory (JONG; LINN; ZACHARIA, 2013). Since engineering is a profession devoted to the creation of technologies using knowledge, data, energy and materials, laboratory activities are a fundamental part of undergraduate and graduate courses. Engineering laboratories can support activities with different purposes. Feisel and Rosa (2005) categorized them into three main types: development, research, and instructional. Development laboratories are used in the product development process to get data for the design process and check whether the design meets the prescribed requirements. Research laboratories are environments intended to generate scientific and technological knowledge. Instructional laboratories are learning environments for practical activities in engineering courses.

This research focuses on instructional laboratories, thus the terms “laboratory” and “lab” are used to refer to “instructional laboratory” throughout this text.

The Accreditation Board for Engineering and Technology (ABET), which is an internationally recognized agency that accredits programs in science and engineering, promoted a colloquy in 2002 for discussing the fundamental objectives of engineering instructional laboratories. Engineering educators from different disciplines and institutions attended the colloquy that resulted in a list of thirteen learning objectives (FEISEL; ROSA, 2005). The objectives, which are shown in table 2, describe what engineering students are expected to learn with laboratory activities and cover knowledge in cognitive domain, psychomotor domain, and affective domain (FEISEL; PETERSON, 2002).

Table 2 - Fundamental objectives of engineering instructional laboratories

Objective	Description	Domain of learning
Instrumentation	Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.	Cognitive
Models	Identify the strengths and limitations of theoretical models as predictors of real-world behaviors. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.	Cognitive
Experiment	Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.	Cognitive
Data analysis	Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.	Cognitive
Design	Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.	Cognitive
Learn from failure	Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions.	Cognitive and affective
Creativity	Demonstrate appropriate levels of independent thought, creativity, and capability in real world problem solving.	Cognitive and affective
Psychomotor	Demonstrate competency in selection, modification, and operation of appropriate engineering tools and resources.	Psychomotor
Safety	Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.	Cognitive and affective
Communication	Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.	Cognitive and affective
Teamwork	Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.	Cognitive and affective
Ethics in the laboratory	Behave with highest ethical standards, including reporting information objectively and interacting with integrity.	Cognitive and affective
Sensory awareness	Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real world problems.	Psychomotor

Source: Feisel and Peterson (2002)

Despite the importance of instructional laboratories in education, some issues, such as time and space constraints, larger number of students per class, lack of laboratory assistants, insufficient equipment and materials, and maintenance problems, can hamper its adoption in the instructional process (ESPOSITO *et al.*, 2021). Alternatives to overcome these issues are the use of lab networks, which is the integration of two or more laboratories through web platforms, and virtual or remote labs.

2.2 Virtual and remote laboratories

Technological advances in communication and computing have opened space for the development of new educational resources, such as virtual classrooms, learning platforms, and simulation software. Currently, practical activities can be carried out by students at home, using computers and accessing the internet. For laboratory activities in engineering, two approaches have been used: virtual laboratories and remote laboratories. Virtual labs are learning platforms designed to emulate the real world in order to provide an environment where students can explore concepts and conduct virtual experiments (JONG; LINN; ZACHARIA, 2013). Balamuralithara and Woods (2009) highlighted that these platforms are as effective as physical labs for explaining and reinforcing concepts.

On the other hand, remote labs are physical laboratories that can be remotely controlled and monitored in real time through a virtual platform (VIEGAS *et al*., 2018). Remote labs allow students to conduct experiments using real equipment and instrumentation, interacting with real phenomena in practical activities (BALAMURALITHARA; WOODS, 2009). The main components of remote labs are actual laboratory equipment, equipment control software and hardware, video cameras and sensors, and remote access system (BHUTE *et al*., 2021). The effectiveness of remote labs is highly influenced by the level of immersion and user interactivity (BALAMURALITHARA; WOODS, 2009; BHUTE *et al*., 2021).

Robotics and control were the first engineering fields to adopt remote labs in the instructional process, then other fields started to use these as educational resources (BALAMURALITHARA; WOODS, 2009). Nowadays, there are many commercial and open solutions available for different purposes. The Virtual Instruments Systems In Reality (VISIR), for instance, is an open remote lab that allows students to conduct experiments in electrical and electronic circuits (VISIR+, 2018). It was developed by Blekinge Institute of Technology (BTH) in Sweden and is currently used by more than ten higher education institutions across the world (VIEGAS *et al*., 2018).

Stefanovic (2013), through a literature review and case studies conducted in Serbian Universities, defined the following general requirements for remote and virtual labs:

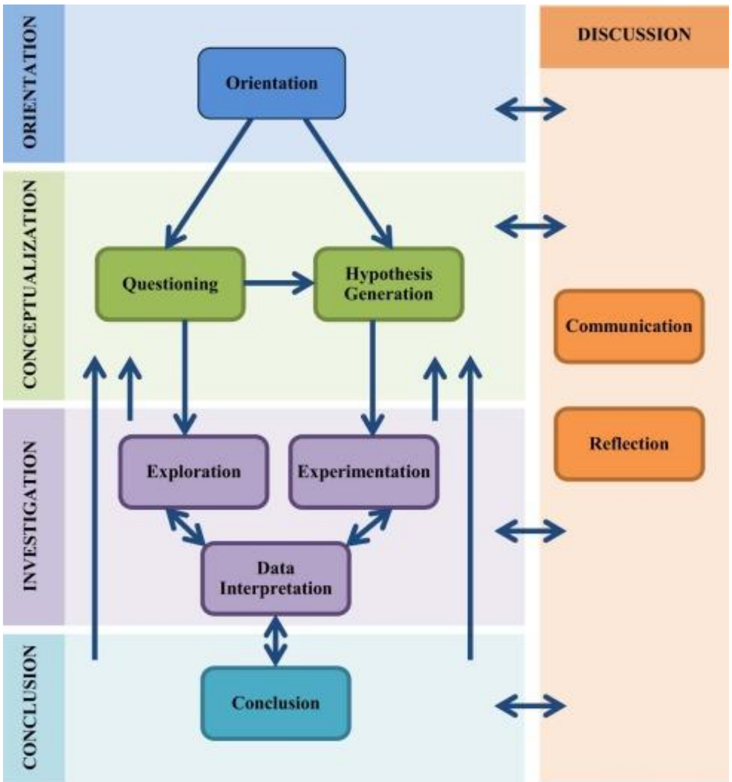
- Easy understanding and usage.
- Incorporation of traditional didactic materials in a new context.
- On-line supervision and monitoring of the laboratory environment.
- Flexible control algorithm.
- Existence of parameters for quality of service.
- Easy installation and maintenance of client/server software.
- Management of changes and distribution of new versions.
- Multi-platform client software.
- Free client software or low cost client software.
- Security of client-side application.
- Laboratory experiments and all results should be stored in a database.
- Storage and download of experimental data.
- Easy access to a library of examples.
- Use of physical real problems.
- Connection with specific learning objectives.
- Self-paced learning.

The richness of the representation of experiments, the extent of live interactivity and the perceived reality of experiments are the main dimensions of student-experiments interaction that have a direct impact on the effectiveness of the remote lab (LOWE *et al.*, 2009). Lowe *et al.* (2009) advocates that collaboration among students should be included as a feature of remote labs due to its recognized importance on hands-on activities in labs.

Pedaste *et al*. (2015) introduced an inquiry-based learning framework that can serve as a basis for the development of virtual and remote labs. The framework consists of five phases: (1) orientation, (2) conceptualization, (3) investigation, (4) conclusion, and

(5) discussion. The orientation phase aims to instigate curiosity and interest in the phenomenon under study. Conceptualization focuses on understanding the concepts related to the phenomenon. This process is formed by two steps: questioning and hypothesis generation. The investigation phase is characterized by the exploration of the research questions, test design, experimental activities, and data collection and analysis. It consists of three main steps: exploration, experimentation, and data interpretation. Conclusion is a process of analytical examination for the generation of conclusions based on the study findings. Discussion is the phase in which findings and conclusions obtained in the study are presented, feedback and recommendations are received, and reflection about the knowledge construction process is carried out.

Figure 1 - Inquiry-based learning framework.



Source: Pedaste *et al.*(2015)

Tawfik *et al*. (2014) introduced the concept of “laboratory as a service” for remote labs. The concept is based on the service-oriented architecture, consisting of the modularization of the laboratory components and the delivery of the entire laboratory functions as a set of services. The main idea is to share laboratory resources among different institutions, providing access via the internet to a large set of specialized equipment.

2.3 Competencies for industry 4.0

The profound changes caused by the fourth industrial revolution require a new education model. It is not only for preparing future workers for the industry 4.0 environment, but rather for enabling people to create a more inclusive, cohesive and productive world (WORLD ECONOMIC FORUM, 2020). This new model should focus on the development of competencies at all educational levels. The World Economic Forum defined eight critical features in learning content and experience that lead to a high quality learning in the fourth industrial revolution, these are (WORLD ECONOMIC FORUM, 2020):

- Global citizenship skills: to prepare students to play an active role in the global community, building awareness about the wider world and sustainability.
- Innovation and creativity skills: to foster skills required for innovation, including complex problem-solving, analytical thinking, creativity and systems analysis.
- Technology skills: to prepare students for the use of digital technologies in their daily lives and work.
- Interpersonal skills: to develop soft skills such as interpersonal emotional intelligence, including empathy, cooperation, negotiation, leadership and social awareness.
- Personalized and self-paced learning: to create a new educational system in which students can select the content in accordance with their interests and progress at their own pace.
- Accessible and inclusive learning: to guarantee access to learning environments for everyone.
- Problem-based and collaborative learning: to adopt problem-based and collaborative learning as educational strategies.

- Lifelong and student-driven learning: to create a system where people can continuously improve on existing skills and acquire new ones based on their individual needs.

Hecklau *et al*. (2016) developed a competency model to identify the core competencies that employees must have in order to work in a new technological environment created by the fourth industrial revolution. The competencies were classified into four categories that are technical, methodological, social, and personal. Table 3 shows the competencies mapped by the authors.

Table 3 - Core competencies for working in the context of the Fourth Industrial Revolution

Category	Competencies
Technical competencies	- State-of-the-art knowledge - Technical skills - Process understanding - Media skills - Coding skills - Understanding IT security
Methodological competencies	- Creativity - Entrepreneurial thinking - Problem solving - Conflict solving - Decision making - Analytical skills - Research skills - Efficiency orientation
Social competencies	- Intercultural skills - Language skills - Communication skills - Networking skills - Ability to work in a team - Ability to be compromising and cooperative - Ability to transfer knowledge - Leadership skills
Personal competencies	- Flexibility - Ambiguity tolerance - Motivation to learn - Ability to work under pressure - Sustainable mindset - Compliance

Source: Hecklau *et al.* (2016)

A research group composed by professors and researchers from Portugal, Finland and Poland investigated the competencies required for succeeding in the industry 4.0 environment, in order to rethink the role of the universities in this new context (UNIVERSITIES OF THE FUTURE, 2019). The group conducted a literature review and thirty interviews with industrial managers and industry 4.0 experts. They identified discipline-specific competencies, which are required for specific fields of work, and general competencies, which must be possessed by all professionals. Table 4 summarizes these competencies.

Table 4 - Competencies required for succeeding in the industry 4.0 environment

Discipline-specific competencies			**General competencies**
Engineering	**Business**	**Design**	
- Data science - Human-machine interface - Advanced simulations and virtual plant modeling - Data communications and networking - System automation - Artificial intelligence - Cyber-physical systems - Robotics - Programming - Real-time inventory and logistical optimization systems	- Technology awareness - Change management and strategy - Novel talent management and strategy - Organizational structures and knowledge - Role of manager as facilitators - Tech enable process	- To understand the impact of technology. - Human-robot interaction - User interfaces - Tech-enabled product and service design - Tech-enabled ergonomic solutions and user experience	- Problem solving - Soft skills - Systems thinking - Business thinking - Technological literacy

Source: UNIVERSITIES OF THE FUTURE (2019)

Terkosky, Frye and May (2020) conducted a systematic review to identify competencies that should be developed by students in order to be able to work in industry 4.0. The authors grouped the competencies, which are shown in table 5, into three categories: domain specific and generic technical competencies; social competencies; self-competencies.

Table 5 - Fundamental competencies for industry 4.0

Category	**Competencies**
Domain specific and generic technical competencies	- To act and collaborate in interdisciplinary contexts. - To flexibly adapt business processes to changeable conditions to new technologies. - To design IT processes in the context of production and to use IT components for human-machine interaction. - To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes). - To establish a connection between a digital twin and its physical reality. - To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data). - To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior. - To initiate and to implement innovation processes. - To control the legal context of the entrepreneurial act•to act strategically in a company-specific way.

	- To use the appropriate evaluation tools in complex decision-making situations
Social competencies	- To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations). - To act confidently and effectively in social (including intercultural) contexts. - To lead production units and teams with goal orientation. - To design digitally supported interaction and cooperation processes.
Self-competencies	- To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action. - To act self-determined and self-organized. - To act on the basis of one's own open mindedness and creativity. - To design and implement your own lifelong learning.

Source: Terkosky, Frye and May (2020)

2.4 Remote laboratories for teaching industry 4.0

This review selected and analysed fifteen studies that sought to investigate the use and development of remote labs for teaching industry 4.0. These studies were searched on Scopus and Web of Science adopting the search string "*industry 4.0*" AND ("*remote lab*" OR "*remote laboratory*"). This search resulted in fifty-one studies that were examined in terms of their research focus. It consisted in reviewing the abstracts to understand the focus of each study, which selected fifteen papers that focused on the topic of interest for this review.

The use of remote laboratories can be an important educational strategy for preparing students for industry 4.0. Benis, Nelke and Winokur (2021) highlighted that remote working and management are a new reality that engineers and managers should be able to deal with. In this sense, the authors argue that the adoption of virtual platforms in which students interact with real-distant systems is essential for preparing the next generation of engineers. Terkosky, Frye and May (2020) also highlighted that the adoption of digital laboratories based on the concept of cyber-physical systems is an important strategy to foster the competencies required by the industry 4.0.

Analysing instructional laboratories with respect to the industry 4.0 competencies, Terkowsky, Frye and May (2019) suggested that remote laboratories should be designed in a cross-disciplinary context, connected with other laboratories under a common, wider problem, and used for solving problems in practical contexts. The authors' suggestions aim to create a comprehensive teaching-learning environment, and foster the students' ability to deal with complex and networked structures.

Bordel, Alcarria and Robles (2019) described their experience of the adoption of industry 4.0 methods and tools on engineering education. The authors developed a remote lab for teaching microcontroller programming in telecommunication engineering and bioengineering degree programs. The lab was based on the problem solving approach. Students had to create a code solution for a problem proposed by the system and execute it in a remote real hardware platform, which could be monitored and controlled by the students in real time. After three years of use, the authors observed that students improved their academic performance, increased their motivation, and could acquire industry 4.0 competencies.

Wanyama, Singh and Centea (2018) developed a remote laboratory in McMaster University (Canada) based on industry 4.0 remote data access technologies to teach PLC programming, PLC automation data access, software applications integration, and Human Machine Interface (HMI) development. The laboratory could also be used onsite for teaching hardware configuration. The authors underlined the adoption of industry 4.0 technologies in engineering education as an imperative strategy that prepares students to work with cyber-physical systems. Additionally, they also noted that remote labs can encourage teachers to include practical experiments into their lectures.

The Open Digital Lab for You (Digilab4u) is a cross institutional project that aims to provide laboratory environments to students and teachers for teaching, learning and researching in the field of industry 4.0 and IoT (PFEIFFER; UCKELMANN, 2019). The main objective is to create a cross institutional network of educational resources and laboratory infrastructure, which can be accessed remotely, that can support hands-on activities and instructional strategies for the development of industry 4.0 competencies and skills. The project integrates six laboratories from three different institutions: RFID Lab and Supply Chain Management Game Lab - University of Parma (Italy); Smart Building Lab and RFID Lab - Stuttgart Technology University of Applied Sciences (Germany); Position Lab - Bremen Institute for Production and Logistics (Germany) (DIGILAB4U, 2019).

The Excellent Teaching and Learning in Engineering Science (ELLI) was a German cooperative project developed by three universities: RWTH Aachen University, Ruhr-Universität Bochum and TU Dortmund University. Its objective was to investigate and develop different kinds of remote and virtual labs for engineering education in the context of industry 4.0 (ELLI2, 2019). Remote labs for material characterization, flow measurement and manufacturing processes were developed in TU Dortmund University, allowing students to create and test design solutions remotely and teachers to adopt industry 4.0 technologies and methods into their lectures (GRODOTZKI; ORTELT; TEKKAYA, 2018).

In France, the FIT IoT-LAB testbed is an open access and open-source platform in which researchers, developers, students, and engineers can conduct experiments with large-scale wireless IoT technologies. The remote testbed consists of 2728 low-power wireless nodes and 117 mobile robots distributed in six sites across France (ADJIH *et al.*, 2015).

Based on the concepts of laboratory as a service and IoT systems, Komarov and Sarafanov (2021) developed a methodology to design multi-user distributed measuring and control systems for training students and engineers in electronic instrumentation in the context of industry 4.0.

Angrisani *et al.* (2019) proposed an IoT-oriented platform as a training tool for remote programming of automatic test equipment and development of measurement and automation applications. It can be used by students and practitioners in order to understand concepts related to measurement science and its application in industry 4.0.

Kans, Campos e Håkansson (2020) proposed a remote condition monitoring and maintenance laboratory environment to support the development of instructional activities in maintenance 4.0. They argued that remote labs can be used by students and practitioners to learn technical, managerial and practical aspects of maintenance in the context of industry 4.0.

2.5 Cyber-physical systems and embedded systems

The term cyber-physical systems defines a new generation of engineered systems that are formed by a deep integration of computational and physical elements and that can interact with humans through diverse modalities (BAHETI; GIL, 2011). Lee (2015) defined it as “an orchestration of computers and physical systems”, underlining that it integrates engineering methods and models from diverse disciplines with the methods and models of computer science. The concept of cyber-physical systems can be utilized in different products and environments: a factory can be a cyber-physical system, as well as simple medical devices such as glucose monitors. With the advances in computing and communication technologies, it is expected that the application of cyber-physical systems across different fields will increase exponentially in the next few years. It is one of the most important concepts related to industry 4.0 (SCHWAB, 2016).

Embedded systems are usually described as the forerunners of cyber-physical systems. MARWEDEL (2021) argues that cyber-physical systems is a new term for embedded systems which emphasizes the link to physical processes and the corresponding physical environment. In this sense, cyber-physical systems are formed by the integration of an embedded system and a dynamic physical environment. MARWEDEL (2003) defined embedded systems as “information processing systems embedded into enclosing products”.

The importance of cyber-physical systems in engineering turned it into a fundamental discipline in engineering departments in order to have qualified engineers for the development of systems in industry and other specialized applications (YETIS; BAYGIN; KARAKOSE, 2016). In terms of research and development, publications related to cyber-physical systems have been increasing significantly since 2011.

Yetis, Baygin and Karakose (2016) described cyber-physical systems as a practice of specialized disciplines such as embedded systems, simulation and visualization, real time programming, control, robotics, sensors, network and communication. In that sense, the educational strategy for its teaching should be based on practical activities and laboratories are an essential environment for its learning. The use of remote and virtual laboratories were cited by Nair *et al.* (2020) as a potential educational strategy for cyber-physical systems courses in institutions where physical resources are not available.

2.6 Cyber-physical systems and engineering education

Teaching how to design, implement, operate, and maintain cyber-physical systems demands the integration of different domains of engineering with computer science. Engineers should master the use of information and communication technologies in order to be able to cope with cyber-physical systems. Some authors argue that engineers in the context of industry 4.0 should master knowledge and skills from diverse disciplines spanning various domains of engineering. Nair *et al.* (2020) pointed out that the cyber-physical systems paradigm is poised to disrupt the way that engineering disciplines are taught.

Jeganathan *et al.* (2018) defined designing cyber-physical systems as one of the functional domains of engineering education 4.0. It was described as the study, design, development, and maintenance of cyber-physical systems. The authors highlighted that there are seven essential knowledge domains for engineering education 4.0, these are: designing, modularity, interoperability, virtualization, decentralization, real time capability, and service orientation. In the virtualization domain, cyber-physical systems were included as a technology that enables the creation of virtual copies of the real world. In the decentralization domain, cyber-physical systems were highlighted as systems with the ability to work autonomously.

Broo, Boman and Törngren (2021) described cyber-physical systems as an inherently cross-disciplinary scientific and technological field. They suggested the integration of sustainability, human-machine interaction, data ethics, and social issues with cyber-physical systems in the engineering curriculum. This integration can empower engineering education with a fully multidisciplinary perspective in which societal, engineering, and sustainability related outcomes and solutions are considered together.

Antkowiak *et al.* (2017) developed a cyber-physical production system (CPPS) course aiming to prepare students for smart factories. The course is based on the automation pyramid and constructivism theory. It was divided into four modules: (1) “*integration of programmable logic controllers (PLC) controlled field devices*” - focuses on the fundamentals of PLC and machine level information modelling; (2) “*data acquisition and data modeling*” - teaches how to connect single devices controlled by PLCs and create the related digital representation for the implementation of a CPPS; (3) “*data storage and data integration*” - aims to analyse how to integrate the acquired data into a central storage; (4) “*perform data analysis to optimize production systems*” - focuses on the use of data analysis in the operation, decision support and optimization of production systems.

Wade *et al.* (2015) described the systems engineering of cyber-physical systems program at Stevens Institute of Technology (New Jersey, US). This program is based on the development of abilities that enable students to conceptualize, design, test, validate, deploy and sustain cyber-physical systems. Conception of cyber-physical systems, Design of cyber physical systems, Implementation of cyber-physical systems, and Sustainment of cyber physical systems are the four courses that form the core of the program, covering the entire lifecycle of cyber-physical systems. The courses are integrated using the project-based learning as the integrative educational strategy. The students use the Systems Modeling Language (SysML) for systems design and their final implementation must include human interactions, embedded software and hardware, sensors, real time behavior, and distributed control.

Makio *et al.* (2017) reported an international cooperation project for teaching cyber-physical systems that was carried out by ITMO University (Russia) and University of Applied Sciences Emden / Leer (Germany). The project created a pedagogical concept for teaching cyber-physical systems, which was called task-centric holistic approach, and implemented it in an international setting. The concept is a result of the combination of five pedagogical approaches: perceptual learning, problem based learning, project-based learning, research oriented, and face-to-face. Its central component is the development of a cyber-physical system project. The concept was implemented in a cyber-physical course that was attended by students from both universities. During the course students had to develop a smart production plant, which consisted of palettes, shop floors, robots, and building blocks, working on the concept of cyber-physical systems. The course stressed the development of soft skills that were pointed out as fundamental for cyber-physical systems development projects.

Makio-Marusik (2017) carried out a literature review to identify competencies related to cyber-physical systems that are required by industry and academia for engineers. The identified competencies, which are shown in table 6, were grouped into three categories: technical knowledge and skills, social knowledge and skills, and attitudes. The review also pointed out that project-based learning in teams, face-to-face teaching and hands-on laboratory activities were the mostly used educational strategies in cyber-physical systems courses and curricula.

Table 6 - Competencies required by industry and academia for cyber-physical systems engineers

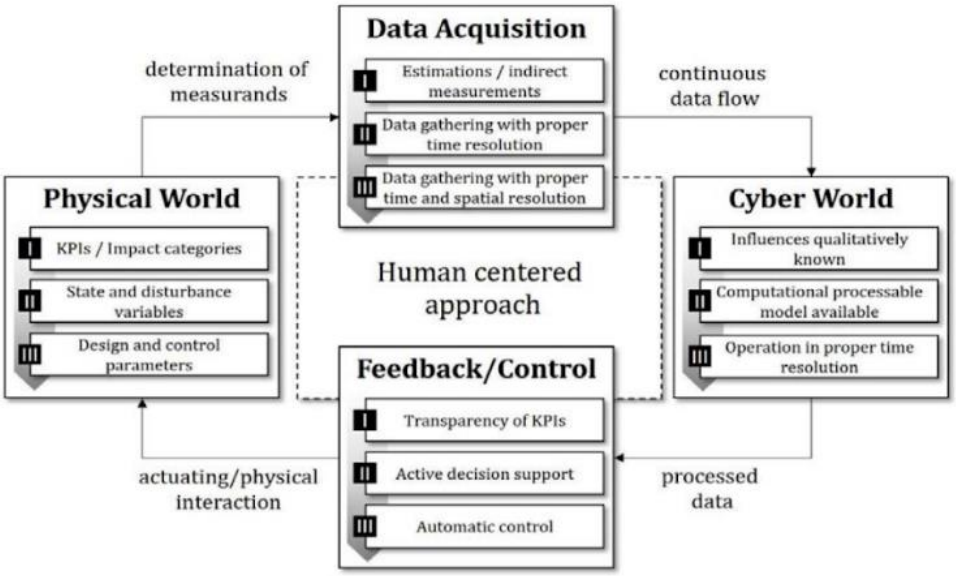
Category	Subcategory	Description
Technical knowledge and skills	General	- Solid foundations together with multidisciplinary awareness. - Broad knowledge and skills of multiple areas of engineering expertise. - Practical experience in product development process including state-of-the-art technologies, tools and best practices.
	Cyber-physical systems basis	- Computing concepts, computer science, software engineering. - Computing for the physical world: sensors, actuators, embedded systems. - Discrete and continuous mathematics. - Cross-cutting application of sensing, actuation, control, communication, and computing. - Modeling of heterogeneous and dynamic systems integrating control, computing, and communication. - Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.
	Non-functional characteristics of cyber-physical systems	- Security and privacy. - Interoperability. - Reliability and dependability. - Power and energy management. - Safety. - Stability and performance. - Human factors and usability.
	Systems engineering	- System-level approach. - Systems integration across domains. - Systems of Systems.
	Engineering	- Engineering Process. - Industrial automation, plant modeling. - Statistical methods and mining techniques. - Physics.
	Business and humanities	- Project management. - Antropoly, sociology. - Economics. - Legislation.

Social knowledge and skills	- Collaboration in heterogeneous interdisciplinary multicultural teams. - Collaboration with customers. - Communication within heterogeneous interdisciplinary multicultural teams and with customers. - Presentation. - Technical writing.
Attitudes	- Flexibility to manage rapidly evolving technologies. - Definition as well as solving problems. - Analytical skills. - Creativity. - Entrepreneurship. - Critical thinking and critical attitude towards technological developments. - Cross-disciplinary thinking. - Lifelong learning.

Source: Makio-Marusik (2019)

The use of virtual learning environments is gaining increasing significance in engineering education due to its effectiveness for the development of competencies in manufacturing and production systems. In this context, Thiede, Juraschek and Herrmann (2016) proposed a framework for the implementation of cyber-physical production systems in learning factories aiming the construction of knowledge and practical skills on cyber-physical systems. The framework was based on the four main elements of cyber-physical systems: physical world, data acquisition, cyber world, and control. Figure 2 depicts the framework developed for building up cyber-physical production systems in learning factories.

Figure 2 - Framework for the development of cyber-physical production systems in learning factories



Source: Thiede, Juraschek, and Herrmann (2016)

2.6.1 Cyber-physical systems in engineering programs

Cyber-physical systems are commonly described as a technological evolution of embedded systems in which physical and computational elements are deeply integrated. The evolution of sensors, network technologies and nanoelectronics have opened space for the development of cyber-physical systems. In many universities, cyber-physical systems have become a research pipeline related to embedded systems in electrical and computer engineering programs. The growing importance of cyber-physical systems in digital transformation processes has led to the creation of courses, modules and master tracks that aim to instruct students, professionals and researchers in the development of these systems.

In order to analyze the current situation of the topic of cyber-physical systems in engineering education, catalogs of courses from different universities in Brazil, France, Germany, Japan, Netherlands, Norway, USA and UK were collected and studied in this research. Courses, modules or learning paths involving the topic of cyber-physical systems were identified. Most universities include cyber-physical systems as a topic in courses related to embedded systems.

The Institut Polytechnique de Paris (France) has created a master track for cyber-physical systems in the computer science program aiming to train researchers and professionals in the development of cyber-physical systems. The course is divided into two years. The first year is dedicated to the development of essential skills in cyber-physical systems, it also includes a semester-long research project in the laboratories of the institute. In the second year, students focus on specific topics related to cyber-physical systems, such as robotics, embedded systems, real-time systems, and do a semester-long research internship (INSTITUT POLYTECHNIQUE DE PARIS, 2020).

The Technische Universität München (Germany) offers regular courses related to cyber-physical courses for master's students in different programs. The "*cyber-physical systems course*" includes the following topics: verification of cyber-physical systems, new control concepts in cyber-physical systems, planning in cyber-physical systems, modeling and simulation of cyber-physical systems, and applications to automated cars, power systems, and human-robot collaboration (TECHNISCHE UNIVERSITÄT MÜNCHEN, 2021). The "*Formal methods for cyber-physical systems* *course*” has as previous knowledge expected the “*Cyber-physical systems course*” and aims to teach the use of formal methods to verify, control, observe, and identify cyber-physical systems (TECHNISCHE UNIVERSITÄT MÜNCHEN, 2021). On the other hand, “*Cyber-physical production systems in the smart factory course*” aims to teach the needed skills to implement basic automation projects with programmable logic controllers using different types of sensors and microcontrollers in the factory environment, set up OPC unified architectures (client / server) for factories, implement databases for the data management of production plants, implement dashboards for the visualization of relevant data in the factory, and work with several project teams in the complex environment of a data acquisition project in production (TECHNISCHE UNIVERSITÄT MÜNCHEN, 2021).

Columbia University (USA) has created a course dedicated to cyber-physical systems called “Topics in cyber-physical systems” for PhD and master’s students. The main goal of the course is to foster new ideas and encourage students to develop projects that lead to publications in cyber-physical systems. Its content includes the current state of art in cyber-physical systems research and principles required for future cyber-physical systems. Students are assessed based on oral presentations and project ideas development (COLUMBIA UNIVERSITY, 2019).

The Illinois Institute of Technology (USA) offers courses that focus on cyber-physical systems for undergraduate and graduate students in electrical and computer engineering. The “Internet of things and cyber-physical systems course” aims to introduce students to the fundamentals of internet of things and embedded systems, including the related security and privacy issues. The “*Cyber-physical systems security and design course*” addresses the security and privacy issues in the implementation of cyber-physical systems in different contexts. The “*Cyber-physical systems - languages and systems course*” aims to promote a discussion about the challenges in cyber-physical systems and to explore possible solutions from the perspectives of systems specification, system modeling, programming languages, systems design, and software engineering (ILLINOIS INSTITUTE OF TECHNOLOGY, 2021).

The Bradley Department of Electrical and Computer Engineering of the Virginia Polytechnic Institute and State University (USA) offers “*cyber-physical systems course*” for graduate students. The course has the following learning objectives:

categorize the essential modeling formalisms of cyber-physical systems; analyze the functional behavior of cyber-physical systems based on standard modeling formalisms; implement specific software cyber-physical systems using existing synthesis tools; design cyber-physical systems requirements based on operating system and hardware architecture constraints; analyze and verify the correctness of cyber-physical systems implementations against system requirements and timing constraints (VIRGINIA TECH, 2021).

The Institute of Industrial Science in the University of Tokyo (Japan) has a social cooperation program that focuses on the use of cyber-physical systems for the development of sustainable environments. It is called "*Cyber-physical architecture for the sustainable built environment*" and addresses the development of systems that interconnect physical space, society and cyberspace in order to enhance the sustainability of the built environment (INSTITUTE OF INDUSTRIAL SCIENCE, 2021).

Newcastle University (UK) has included in its module catalogue "Real-time and cyber-physical systems" that aims to introduce students to the fundamentals of real-time and cyber-physical systems, providing the understanding of the need for multidisciplinary approach to the design of these systems and developing their skills in modelling and programming them (NEWCASTLE UNIVERSITY, 2021). The course is based on a set of teaching methods formed by structured guided learning, guided independent study, scheduled learning, and teaching activities. Students' tasks include project work, practical activities, reading activities, structured research, and assessment preparation and completion.

The University of Twente (The Netherlands) offers the "*Cyber-physical systems core module*" for undergraduate students in all engineering programs aiming the development of skills that enable students to: describe and explain the concepts, challenges, methods and applications related to cyber-physical systems; apply design methods relevant to cyber-physical systems to simple systems; design, analyze, and verify cyber-physical systems; describe, explain, and apply the contents of each of the mini-tracks (formal specification and hybrid systems, cooperative autonomous driving, physical system modelling and controller design - for TCS, embedded control systems implementation, wireless sensor and actuator systems, real-time operating systems) relevant for analyzing, evaluating and designing cyber-physical systems. During the module, students work in teams to develop projects based on their own project ideas that can be taken from a variety of application fields. The final assignment includes a functional prototype, project report and final presentation. The module also includes lectures and written assignments (UNIVERSITY OF TWENTE, 2021).

The Norwegian University of Science and Technology (Norway) has included cyber-physical systems as a topic in many of its courses related to industry 4.0. The university also offers three courses that focus on cyber-physical systems for undergraduate students. "*Design of cyber-physical systems*" addresses the development of efficient and dependable software solutions for distributed cyber-physical systems using formal specifications expressed in the language UML. "*Simulation of cyber-physical systems*" teaches the use of digital tools for simulation of cyber-physical systems aiming to develop competencies that enable students to: reflect about the usefulness of simulations of cyber-physical systems for creating sustainable solutions; formulate scientific problems, propose solutions, and present results both orally and in writing to a technical audience; make evaluations about societal and ethical aspects of technological developments. "*Real-time cyber-physical systems*" focuses on the development of skills that allow students to: develop of real-time applications in object-oriented development environments; implement real-time solutions locally and in distributed systems; integrate real-time mechatronics solutions; design user interfaces for system interaction in real-time. The three courses are taught using the constructivist approach that includes project-based learning, problem solving and practical application of theory (NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY, 2021).

In Brazil, embedded systems courses at Universidade de São Paulo for undergraduate students in electrical engineering and computer science include cyber-physical systems as a topic in the content. The course "Embedded systems design" at the Department of Electronic Systems Engineering in Escola Politécnica is based on the active learning approach in which students are stimulated to develop projects in a collaborative way. Its main purpose is to instruct students how to plan, develop and validate embedded systems design (USP E-DISCIPLINAS, 2020). The classes are a combination of hands-on activities, theory sessions, and question & answer sessions.

The University of California, Berkeley (USA) adopted a similar approach including cyber-physical systems as an advanced set of embedded systems in the course "*Introduction to Embedded Systems*" for undergraduate students in electrical engineering and computer science. The course aims to introduce the basic concepts and techniques of modeling, analysis, and design of embedded, cyber-physical systems (UC BERKELEY, 2021). The main learning objective is that students learn how to integrate computation with physical processes to reach intended requirements (UC BERKELEY, 2021). The classes are divided equally into theoretical and practical.

Table 7 – Educational initiatives focused on cyber-physical systems.

Country	University	Educational initiatives
France	Institut Polytechnique de Paris	Master track for Cyber-physical systems
Germany	Technische Universität München	Courses for master's students: - Cyber-physical systems course; - Formal methods for cyber-physical systems course; - Cyber-physical production systems in the smart factory course.
USA	Columbia University	Course for Phd and master's students: - Topics in cyber-physical systems.
USA	Illinois Institute of Technology	Courses for bachelor and master's students: - Cyber-physical systems security and design course. - Cyber-physical systems - languages and systems course.
USA	Virginia Polytechnic Institute and State University	Course for graduate students: - Cyber-physical systems course.
Japan	University of Tokyo	Social cooperation program dedicated to Cyber-physical architecture for the sustainable built environment.
UK	Newcastle University	Real-time and cyber-physical systems module.
The Netherlands	University of Twente	Cyber-physical systems core module for undergraduate students in all engineering programs.
Norway	Norwegian University of Science and Technology	Courses for undergraduate students: - Design of cyber-physical systems; - Simulation of cyber-physical systems; - Real-time cyber-physical systems.

Table 7 summarizes the main findings about educational initiatives focused on cyber-physical systems in different universities. Based on these findings it is possible to verify that the most common learning objectives related to cyber-physical systems in engineering education are that students should be able to:

- understand and describe cyber-physical systems;

- use techniques and methods for the design of cyber-physical systems;
- implement cyber-physical systems in different contexts;
- test and validate cyber-physical systems in different contexts.

2.6.2 Educational resources for teaching Cyber-physical systems

In terms of educational resources for teaching cyber-physical systems, the Explore Cyber-Physical Systems (xCPS) platform is an educational and research tool, which was developed in the Eindhoven University of Technology (The Netherlands), that allows students and researchers to explore and grasp the complexity of cyber-physical systems (ADYANTHAYA *et al.*, 2017). The platform consists of a small-scale machine that emulates a production line from software-level to servo-level, it can assemble and disassemble small cylindrical objects of different shapes and colors.

Cybersim is a virtual lab based on LabView developed at the University of California, Berkeley (USA) to support a massively open online course (MOOC) on cyber-physical systems. The lab includes a realistic robot simulator, a framework to develop and debug using low- and high-level programming methods, controllers for both simulation and real hardware (SESHIA, 2021).

The Mobile Open Platform for Experimental Design (MOPED), which was developed by researchers and professors from the Swedish Institute of Computer Science (Sweden), is an open educational platform for hands-on activities in the design of cyber-physical systems. The platform consists of a model car chassis controlled by a set of three control units running the automotive software standard AUTOSAR (AXELSSON *et al.*, 2014). It is open to extensions in hardware and software, enabling the implementation of new functionalities.

The Cyber-Physical Systems Lab was an educational environment implemented at the *Technische Universität Hamburg* (Germany) that enables students to develop simple cyber-physical systems using robot kits, computers and specification tools (MATLAB/Simulink, LabVIEW, C++). The lab aims to introduce the conceptual basis of cyber-physical systems and techniques that can be used for their specification (models of computation, hierarchical automata, data flow models, petri nets, imperative approaches) (INSTITUTE OF EMBEDDED SYSTEMS, 2021). At this university, cyber-physical systems are part of the embedded systems course.

2.7 Proposed competency framework

Laboratories are often described as fundamental learning environments for the development of competencies related to the design, modeling, and analysis of engineered systems. Students have the opportunity to acquire knowledge and experience of how to combine scientific theory, technologies, techniques and tools for the application of design and creativity to science. However, the use of practical environments should be previously planned and connected with learning objectives to allow the development of intended skills and competencies.

In this sense, based on the literature findings, this research work proposes a framework that links the fundamental objectives of engineering instructional laboratories with the competencies required for industry 4.0 (Table 8) and cyber-physical systems (Table 9). The competency framework indicates which activities can be proposed for the accomplishment of each competency, highlighting domains of learning involved in each one.

Table 8 - Competency framework for industry 4.0.

Category	Competencies	Related learning objectives of engineering laboratories	Domain of learning
Technical competencies	To act and collaborate in interdisciplinary contexts.	Models, design, safety, teamwork, ethics in laboratory and experiment.	Cognitive and affective
	To flexibly adapt business processes to changeable conditions to new technologies.	Learn from failure, models, and creativity.	Cognitive and affective
	To design IT processes in the context of production and to use IT components for human-machine interaction.	Design, experiment, and models.	Cognitive
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	Design, experiment, models, instrumentation, sensory awareness, learn from failure and psychomotor.	Cognitive, affective and psychomotor
	To establish a connection between a digital twin and its physical reality.	Design, models, instrumentation, experiment, sensory awareness, and psychomotor.	Cognitive and psychomotor
	To deal with large amounts of data and to use appropriate statistical skills (including	Data analysis, models, and experiment.	Cognitive

	recognizing the importance of algorithms and the management of sensitive data).		
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Models, data analysis, and design.	Cognitive
	To initiate and to implement innovation processes.	Creativity, models, and design.	Cognitive and affective
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	Design, ethics in the laboratory and safety.	Cognitive and affective
	To use the appropriate evaluation tools in complex decision-making situations.	Data analysis, models, sensory awareness, instrumentation, safety, psychomotor, and ethics in the laboratory.	Cognitive, psychomotor and affective
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Design, teamwork, and communication.	Cognitive and affective
	To act confidently and effectively in social (including intercultural) contexts.	Ethics in laboratory, sensory awareness, and communication.	Cognitive, psychomotor and affective
	To lead production units and teams with goal orientation.	Teamwork and communication.	Cognitive and affective
	To design digitally supported interaction and cooperation processes.	Design, creativity, instrumentation, and models.	Cognitive and affective
Self-competencies	To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action.	Design, models, and creativity.	Cognitive and affective
	To act self-determined and self-organized.	Psychomotor, sensory awareness, learn from failure, safety, and ethics in the laboratory.	Cognitive, psychomotor and affective
	To act on the basis of one's own open mindedness and creativity.	Creativity, models, and design.	Cognitive and affective
	To design and implement your own lifelong learning.	Creativity, models, design, and experiment.	Cognitive and affective

Source: Based on Terkosky, Frye and May (2020) and Feisel and Peterson (2002).

Table 9 – Competency framework for cyber-physical systems

Category	Subcategory	Description	Related learning objectives of engineering instructional laboratories	Domain of learning
Technical knowledge and skills	General	Solid foundations together with multidisciplinary awareness.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective
		Broad knowledge and skills of multiple areas of engineering expertise.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Design, instrumentation, experiment, models, data analysis, creativity, and learn from failure.	Cognitive and affective

	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective
		Computing for the physical world: sensors, actuators, embedded systems.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective
		Discrete and continuous mathematics.	Models, experiment and data analysis.	Cognitive
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Models and design.	Cognitive
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective
	Non-functional characteristics of cyber-physical systems	Security and privacy	Design, models, experiment, data analysis, and ethics in the laboratory.	Cognitive and affective
		Interoperability	Design, models, instrumentation, learn from failure and experiment.	Cognitive and affective
		Reliability and dependability	Design, models, instrumentation, learn from failure and experiment.	Cognitive and affective
		Power and energy management	Design, models, instrumentation, and experimentat.	Cognitive
		Safety	Design, models, experimentation, safety, data analysis, and ethics in the laboratory.	Cognitive and affective
		Stability and performance	Design, models, instrumentation, learn from failure and experimentation.	Cognitive and affective
		Human factors and usability	Safety, ethics in the laboratory, experiment, design, models, instrumentation, sensory awareness, creativity, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Design, creativity and models.	Cognitive and affective
	Engineering	Engineering Process	Data analysis, models, design, experiment, instrumentation, sensory awareness, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective
		Industrial automation, plant modeling.	Data analysis, models, design, experiment, instrumentation, sensory awareness, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective
		Statistical methods and mining techniques	Data analysis, models, and design.	Cognitive
		Physics	Data analysis, instrumentation,	Cognitive

			experiment, models, and design.	
	Business and humanities	Project management	Design, creativity, teamwork, communication, and models.	Cognitive and affective
		Antropoly, sociology	Models, teamwork and design.	Cognitive and affective
		Economics	Models, design, experiment, and data analysis.	Cognitive
		Legislation	Models, design, experiment, safety, ethics in the laboratory.	Cognitive and affective
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Communication, teamwork, creativity, experiment, and design.	Cognitive and affective
		Collaboration with customers.	Communication, teamwork, experiment, and design.	Cognitive and affective
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.	Communication, teamwork, creativity, experiment, and design.	Cognitive and affective
		Presentation	Communication	Cognitive and affective
		Technical writing	Communication	Cognitive and affective
Attitudes		Flexibility to manage rapidly evolving technologies.	Data analysis, design, models, experiment, instrumentation, and learn from failure.	Cognitive and affective
		Definition as well as solving problems.	Creativity, design, instrumentation, and experiment.	Cognitive and affective
		Analytical skills	Design, models, experiment, creativity, data analysis, sensory awareness, learn from failure, psychomotor, and communication.	Cognitive, psychomotor, and affective
		Creativity	Creativity	Cognitive and affective
		Entrepreneurship	Design, models, experiment, creativity, communication, and teamwork.	Cognitive and affective
		Critical thinking and critical attitude towards technological developments.	Creativity, models, design, data analysis, learn from failure and experiment.	Cognitive and affective
		Cross-disciplinary thinking	Design, models, creativity, and experiment.	Cognitive and affective
		Lifelong learning	Creativity, models, design, learn from failure and experiment.	Cognitive and affective

Source: Based on Makio-Marusik (2017) and Feisel and Peterson (2002).

2.8 Concluding remarks

This chapter reviewed the theoretical framework on which this research work is based and analysed how different universities are addressing cyber-physical systems in engineering courses. The core competencies required for dealing with industry 4.0 and cyber-physical systems were examined. It also presented an overview about the use of remote laboratories for teaching industry 4.0. Cyber-physical systems are mainly considered as an evolution of embedded systems, which have been researched and taught in laboratories and courses related to electronic engineering. There are two main focuses for addressing cyber-physical systems in engineering: systems design and hardware or software development. In terms of systems design, the main objective is to instruct students how to design and develop a cyber-physical system as an engineered solution for a problem. The other approach focuses on the development of hardware or software in the context of cyber-physical systems. The approach adopted in this research work is the systems design due to its comprehensiveness, which involves all engineering disciplines.

3 METHODOLOGY

This chapter explains the methods applied in this work and is divided into three sections. Section 3.1 presents the methodology used in the study of educational platforms that were developed or designed for teaching cyber-physical systems in engineering education. Section 3.2 explains the approach adopted in the definition of the guidelines. The approach and materials applied for the development of a proof of concept of a cyber-physical systems remote lab are detailed in Section 3.3.

3.1 Case studies

The case study is a research approach that focuses on understanding the dynamics present within single settings in order to generate descriptions, test or build theories (EISENHARDT, 1989). Crowe *et al.* (2011) defined case studies as a research strategy that is used to investigate an issue or phenomenon in order to obtain an in-depth and comprehensive knowledge about it. Case studies can involve single or multiple cases, and different levels of analysis which usually deploy data collection methods such as interviews, observations, archives, and questionnaires (EISENHARDT, 1989). Although case studies can be described in different ways, Crowe *et al.* (2011) and Yin (2014) highlighted that the main tenet of case studies is to investigate an event or phenomenon in depth and in its real context. Yin (2014) described a case study as an empirical investigation in which the limits between phenomenon and context can usually not be clearly defined. In this sense, the context in which the phenomenon is investigated has a relevant influence on the findings and conclusions.

The use of case studies is related with explanatory research questions such as “how”, “what” and “why” which are formulated to capture information for the development of descriptions or refinement of theories (CROWE *et al.*, 2011). Case studies can be conducted in diverse science fields using different approaches. In natural sciences, the most common approach is positivism which usually focuses on testing and refining theory on the basis of case study findings (CROWE *et al.*, 2011). YIN (2014) argued that this approach does not take into account that the role performed by researchers can influence findings.

YIN (2014) defined that the selection of case study as a research strategy is based on three aspects:

I. Research question: questions such as “how” and “why” which aim to explain a current phenomenon, and/or questions that require a detailed description of social phenomena.
II. Control: researchers usually can not control the analysed phenomena, or can control just few aspects of them.
III. Object of study: the analysed phenomena are contemporaneous.

VOS *et al.* (2002) highlighted the triangulation with multiple means of data collection as an essential strategy to increase the internal validity of case studies. The authors defined that case studies can be used for different purposes:

I. Exploration: investigation of uncover areas for research and theory development.
II. Theory building: identification of key variables, linkages between them, and “*why*” these linkages exist.
III. Theory testing: verification of theories developed previously and prediction of future outcomes.
IV. Theory extension or refinement: to better structure theories in light of the analysed findings.

The adoption of case study as a research method in this work is based on the relevance of the context in the phenomenon, its contemporaneity, and the impossibility of its control. The phenomenon analysed by this work consists in the use of remote labs for teaching cyber-physical systems in engineering courses. The context is the spread of digital technologies that are profoundly changing the way of life, production and working around the world, that is also known as Fourth Industrial Revolution. Thus, the case study approach fits properly the investigation of this phenomenon in its real context.

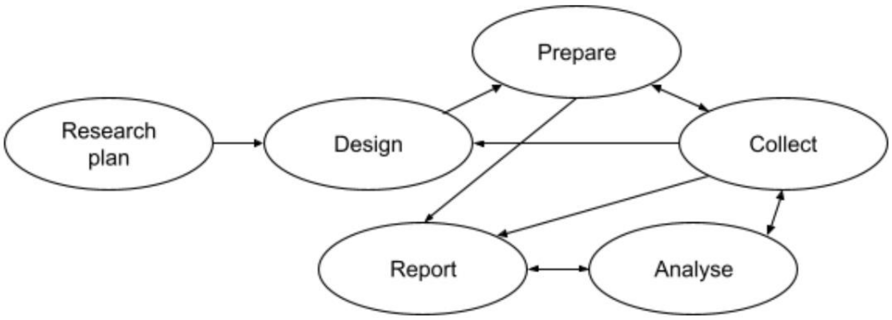
CROWE *et al.* (2011) defined six main steps of a case study, these are: case definition; case(s) selection; data collection and analysis; data interpretation; and reporting findings. These steps should be carried out observing good practices and strategies described in the literature.

The definition of a case includes the formulation of research questions based on the existing literature and prior analysis of the theoretical issues. The case should have a predefined boundary which establishes the scope and time period covered by the study, the relevant social group, the physical area of interest, the types of evidence, and the guidelines for data collection and analysis (CROWE *et al.*, 2011). A predefined boundary defines the main requirements for the case(s) selection. In the case selection, the authors highlighted that researchers should also take into account ethical issues and risks related to the human participation in the research, and accessibility of the study sites.

STAKE (1994) pointed out the importance of multiple sources of data and different ways for collecting data in order to conduct an analysis of the same issue from different perspectives and develop a holistic view of the phenomenon. The collected data can be quantitative or qualitative. CROWE *et al.* (2011) recommended the framework approach for the data analysis step, highlighting the theoretical framework as an important strategy that can integrate multiple sources of data and examine emerging themes.

YIN (2014) emphasized the need for scientific rigour and the relevance of planning in case studies. The author proposed a model for the conduction of case studies formed by a set of linear and iterative processes, which is shown in Figure 3. The first step is the research plan which consists in the definition of research questions and selection of the research method. The second step is the case study design.

Figure 3 - Processes in the development of case study research



Source: Yin (2014)

This work adopted the model proposed by YIN (2014) and observed the suggestions proposed by the authors mentioned over the present section. The first process in this model is the elaboration of a research plan which is formed by the definition of a boundary between the phenomenon and its context, formulation of research questions, and selection of a research methodology. The phenomenon and its context were previously defined in this text. The conduction of a case study in this work aims to investigate the following research questions:

1) What fundamental objectives of engineering instructional laboratories can be developed using the educational platform?
2) What competencies related to the industry 4.0 can be developed using the educational platform
3) What competencies related to cyber-physical systems can be addressed using the educational platform?
4) How can the educational platform be used in order to develop the fundamental objectives of engineering instructional laboratories, competencies related to the industry 4.0, and objectives related to cyber-physical systems?

The next process in the development consists in designing the case study, which is described in the following section.

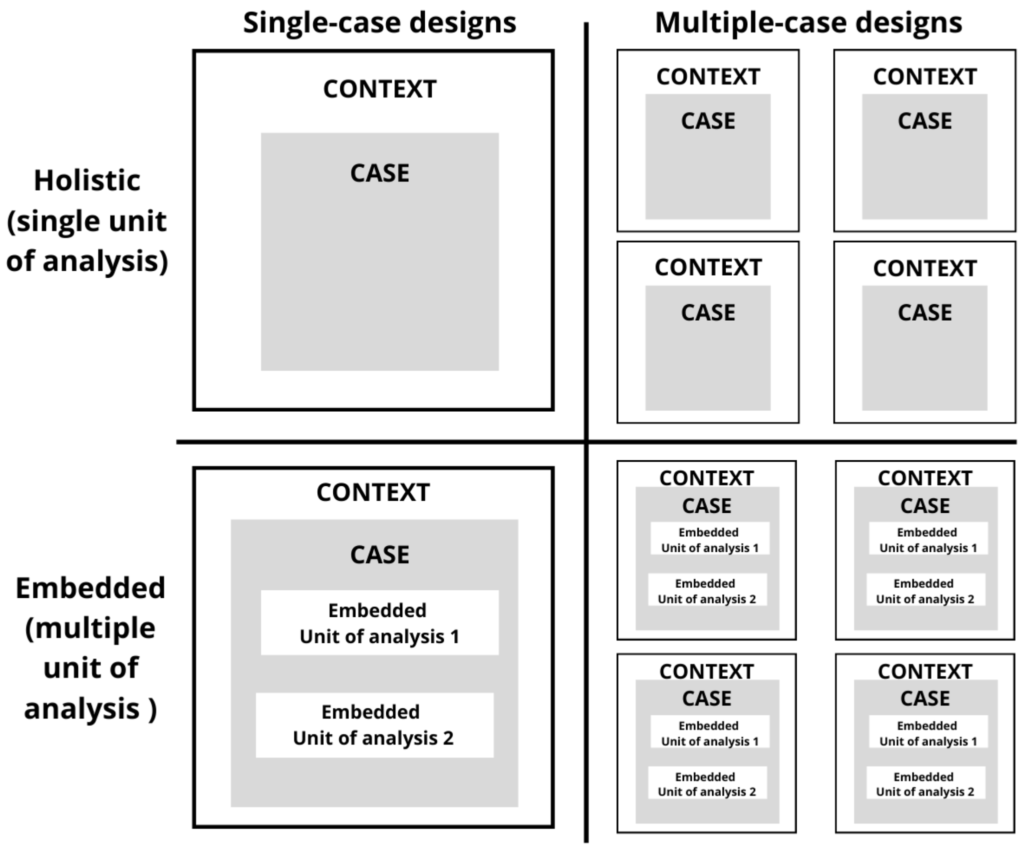
3.1.1 Case study design

The case study design is a process that comprises definition of unit of analysis and selection of cases, development of the theory in the research domain, selection of the type of design, and definition of criteria for assessing the quality of the research (YIN, 2014). As educational platforms are developed in diverse learning environments for different purposes, it is important to define the unit of analysis of each case selected in order to clarify the case boundary. In this research, the unit of analysis is an educational platform that can be used for teaching cyber-physical systems in a remote way. The selection of cases thereby were not restricted to laboratories that allow students to use educational platforms remotely. Platforms developed just for in-site use, but could be converted into a remote educational resource were also considered as a possible case for study. The case selection was based on the research questions presented in the previous section, and the access to different data sources for the development of this research. In this sense, three cases from different universities were selected: Systems Life Cycle Remote Laboratory at the University of Twente (Netherlands), eXplore Cyber-Physical Systems platform at the Eindhoven University of Technology (Netherlands), and the Skyrats platform at the Universidade de São Paulo (Brazil). These cases include educational platforms that could be used for teaching cyber-physical systems in remote mode. Two of them are used for learning activities in projects in electrical engineering programs and one is a platform still in development.

The development of the theory that forms the conceptual framework of this research was presented in Chapter 2 - Literature Review. The starting point for the theoretical construction was to investigate the role of laboratories in engineering education. Then, the use and design of virtual and remote labs, competencies required by industry 4.0, and the teaching of cyber-physical systems in engineering courses were analysed.

YIN (2014) described four types of design for case studies and arranged them in matrix format, which is shown in Figure 4. The matrix defines two dimensions of design: single- versus multiple-case study designs and holistic versus embedded case studies. The author argued that the use of single-case designs is appropriate just for critical, unusual, common, revelatory, or longitudinal cases. In other circumstances, the selection of multiple-case designs is strongly suggested in order to reduce the risk of misrepresentation and the potential vulnerability of the case study research. In this research, the cases considered for the study could not be classified as critical, unusual, common, revelatory, or longitudinal. Thus, multiple-case designs were selected as one of the design dimensions. The other dimension is related to the approach of analysis. If the case analysis involves units at more than one level, it is categorized as an embedded study case. The units of analysis were analysed using a holistic approach in this study.

Figure 4 - Types of design for case study research



Source: Yin (2014)

The definition of criteria for assessing the quality of the research was based on four tests proposed by YIN (2014): construct validity, internal validity, external validity, and reliability. Construct validity test aims to identify correct operational measures for the concepts that are under investigation. Internal validity seeks to define a causal relationship, it is valid just for explanatory and causal studies. Thus, it can not be used in this research that is more related to descriptive and exploratory studies. External validity defines whether research findings can be generalizable beyond the case studies. The author suggested the use of replication logic as a strategy to ensure the external validity for multiple-case studies. Replication logic for case studies follows the same logic used in experimental research in which multiple experiments under similar or different conditions are conducted in order to reach robust findings. A proper theory development is highlighted as an essential strategy for ensuring external validity. Reliability aims to ensure reproducibility of research. The strategies proposed for each test are described in Table 10.

Table 10 - Strategies for ensuring the quality of a case study research

Tests	Case study strategies	Phase of research in which strategy occurs
Internal validity	- do pattern matching - do explanation building - address rivals explanation - use logic models	- data analysis - data analysis - data analysis - data analysis
External validity	- use theory in single-case studies - use replication logic in multiple-case studies	- research design - research design
Reliability	- use case study protocol - develop case study database	- data collection - data collection

Source: Yin (2014)

3.1.2 Preparation, data collection and analysis, and reporting findings

The main activity in the preparation process for case studies is training researchers who will conduct the study in order to ensure that they master the basic skills, good practices and knowledge related to case study research. Although there are no tests for assessing whether a researcher is ready, YIN (2014) suggested a list of desired attributes that should be mastered by case study researchers. The author recommended that case study researchers should have the ability to: formulate clear questions; interpret answers fairly; be a good listener; stay adaptive; pursue a good understanding of the issues being investigated; conduct the research activities in an ethical manner; be sensitive to contrary evidence; and avoid biases.

Other tasks included in the preparation process are the case definition, the approval for data collection and the case study protocol development. The cases defined were introduced in Section 3.2.1 - Case study design. YIN (2014) suggested that a case study protocol consists of at least four elements: overview of the case study, data collection procedures, data collection questions, and guidelines for reporting findings. During this case study research, the good practices for data collection and analysis, and reporting findings recommended by YIN (2014) were analysed and considered.

EISENHARDT (1989) and STAKE (1994) described that case studies should collect data from diverse sources such as archives, interviews, questionnaires, and observations in order to develop a holistic view of the phenomenon. This strategy is fundamental for data triangulation. YIN (2014) analysed six sources of evidence that can be used for data collection in case study research, the analysis is shown in Table 11. The six sources of evidence mentioned are documentation, archival records, interviews, direct observations, participant-observation, and physical artifacts.

Table 11 - Analysis of sources of evidence for case study research

Sources of evidence	**Strengths**	**Weaknesses**
Documentation	- Stable: can be reviewed repeatedly - Unobtrusive: not created as a result of a case study - Specific: can contain exact names, references, and details of an event - Broad: can cover a long span of time, many events, many settings	- Retrievability: can be difficult to find - Biased selectivity, if collection is incomplete - Reporting bias: reflects bias of any given document's authors - Accessibility: may be deliberately withheld
Archival records	- *Same as mentioned for documentation* - Precise and usually quantitative	- *Same as mentioned for documentation* - Accessibility: privacy issues
Interviews	- Targeted: focuses directly on case study topics Insightful: provides explanations as well as personal views	- Bias due to poorly articulated questions - Response bias - Inaccuracies due to recall - Reflexivity: interviewee gives what interviewer wants to hear
Direct observations	- Immediacy: covers actions in real time - Contextual: can cover the case's context	- Time-consuming - Selectivity: broad coverage is difficulty without a group of observers - Reflexivity: actions may be proceed differently because they are being observed - Cost-hours needed by human observers
Participant-observation	- *Same as mentioned for direct observations* - Insightful into interpersonal behavior and motives	- *Same as mentioned for direct observations* - Bias due to participant-observer's manipulation of events
Physical artifacts	- Insightful into cultural features - Insightful into technical operations	- Selectivity - Availability

Source: Yin (2014)

The combination of sources of evidence adopted for each case was different due to the difference of accessibility conditions. Documentation, archival records and interviews were sources of evidence for all cases. Physical artifacts were included as sources of evidence in two cases (University of Twente and Universidade de São Paulo) in which the educational platforms were available for analysis. Direct observation and participant-observation were included in one case in which the researcher could follow the development of the educational platform (University of Twente). Bachelor’s thesis, blueprints, course materials, diagrams, figures, master’s thesis, papers, videos and websites related to the educational platforms analysed were analysed. Archives that describe the design, implementation or use of the educational platforms were also analysed. Interviews were adopted in order to clarify the lack or divergence of information. The approach adopted for the interviews were based on a guided conversation in which a line of inquiry is designed to be fluid, without rigid guidelines. This type of interview is also known as “*in-depth interview*” or “*unstructured interview*” (YIN, 2014).

The reliability and construct validity were ensured by the use of multiple sources of evidence, development of convergent evidence, and creation of a database for each case analysed. Peers, key informants and participants were asked to review the draft report in order to guarantee the consistency and precision of information and increase the overall quality of the study. Table 12 summarizes the definitions previously presented and defines the case study protocol adopted in this research.

Table 12 - Analysis of sources of evidence for case study research

Case study overview	
Research objective	To investigate the use of remote laboratories for teaching cyber-physical systems in engineering courses.
Research questions	1. What fundamental objectives of engineering instructional laboratories can be developed using the educational platform? 2. What competencies related to the industry 4.0 can be developed using the educational platform? 3. What competencies related to cyber-physical systems can be addressed using the educational platform? 4. How can the educational platform be used in order to develop the fundamental objectives of engineering instructional laboratories, competencies related to the industry 4.0, and objectives related to cyber-physical systems?
Unit of analysis	Educational platforms used or designed for teaching cyber-physical systems in engineering courses.
Type of design	Holistic and multiple-cases designs

Cases selected	1. Systems Life Cycle Remote Laboratory at the University of Twente (Netherlands). 2. eXplore Cyber-Physical Systems platform at the Eindhoven University of Technology (Netherlands). 3. Skyrats platform at the Universidade de São Paulo (Brazil).
Sources of evidence	• Documentation, archival records and interviews for all cases. • Physical artifacts for cases (1) and (3). • Direct observation and participant-observation for case (1).
Strategies for ensuring the quality of research	
External validity	• Construction of a solid theoretical basis. • Use of replication logic.
Construct validity	• Use of multiple sources of evidence. • Development of convergent evidence. • Review the draft case study.
Reliability	• Creation of a case study database. • Development of convergent evidence.
Data collection and analysis	
Process	**Description**
1 - Evidence collection	Identification and collection of evidence: archives, bachelor's thesis, blueprints, course materials, diagrams, figures, master's thesis, papers, videos, websites, etc. Development of the case study database.
2 - Case contextualization	Contextualization of each platform analysed. Identification of the institutions, laboratories and programs linked with the platforms. Evidence analysis.
3 - Structure	Analysis of the structure of each platform. Description of the structure in terms of mechanical, electrical and software components. Evidence analysis and unstructured interviews key-informants. Key-informants were asked to review the description of the structure.
4 - Educational use	Identification of the possible educational uses of the platforms in their respective institutions and departments. Evidence analysis and unstructured interviews key-informants. Key-informants were asked to review the educational uses.
4- Analysis	Investigation of the use of each platform in the development of skills and competencies related to the fundamental objectives of engineering instructional laboratories, industry 4.0, and cyber-physical systems. Classification and comparison of the platforms. Peer review.
5 - Report	Reporting the case studies in this master's thesis.

3.2 Definition of design guidelines

Stefanovic (2013) stated that remote and virtual labs should be designed as part of the scope of a course in order to support the achievement of specific learning outcomes, with a well-defined role in assessment methods and grading policy. The central question that should be addressed in the design process of a remote lab is "what students will be able to do by completing the designated laboratory in a course syllabus". In this sense, the first step in the design process is to define the fundamental objectives for the remote lab. The next steps are the definition of requests for the remote lab from different stakeholders' points of view and the selection of architecture for implementation.

The guidelines aim to provide a foundation for further development of remote labs which can support hands-on activities in cyber-physical systems. The process of definition of guidelines was based on the analysis of learning objectives and competencies related to cyber-physical systems in engineering education in order to identify the fundamental objectives for a cyber-physical systems remote lab. The analysis of pedagogical models and approaches adopted for teaching cyber-physical systems showed that team project-based learning is the most common method used by teachers. It can enhance the development of competencies and prepares students for real world problems. In this sense, the guidelines considered the adoption of this teaching method. The framework adopted as the basis for the guidelines was the inquiry-based learning proposed by Pedaste *et al.* (2015), which was described in Section 2.2 - Virtual and remote laboratories.

The conduction of case studies provided examples of educational platforms developed in different universities for teaching concepts and technologies related to cyber-physical systems. The analysis of competencies addressed in these platforms and how students can use them also supported the formulation of the guidelines.

3.3 Proof of concept study

Proof of concept is a term that describes a practical process developed in the early stage of a project or experiment aiming to demonstrate the feasibility of a design concept, business proposal, or technological solution (KENDIG, 2016). This process is frequently adopted as an essential step in the product development process for the creation of digital solutions. In terms of business, the term can also refer to the idea of a minimum viable product that is the simplest version of a product able to meet the requirements defined through the analysis of stakeholders' needs.

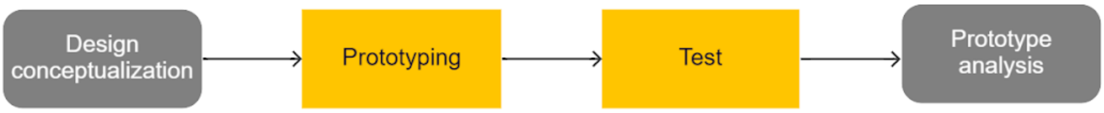
The conduction of a proof of concept study is particularly useful in situations such as lack of clarity or high level of complexity of requirements, new fields of research, high-risk projects, development of high cost products, and lack of previous experience on the concept. It helps designers, developers and researchers to understand better solution concepts, project requirements, and how to integrate multiple requirements into the final product. The study is an essential step to gain experience and knowledge in new fields of research and complex problems, especially when researchers do not have previous experience on the topic.

In terms of contribution, the main findings that are provided by proof of concept studies are evidence of validity and usability of solution concepts, and recommendations for further research and development. Evidence and recommendations collected from a proof of concept study can be important design guidelines and considerations to researchers, developers and designers in other related projects and fields of research.

The development of a remote lab is a project that demands a multidisciplinary work team in order to be able to implement the basic requirements and features described in Section 2.2 Virtual and remote laboratories. Team members should have different professional expertises such as graphical design, information security, user experience, robotics, software engineering, and communication and interaction technology. In addition to the basic requirements which are common to all remote labs, there are specific requirements related to the purpose of the remote lab in development. A remote lab that is able to improve the students' learning experience should meet a long list of requirements. It may be seen as a barrier for the development of remote educational platforms. The acquisition of communication devices, computers, instruments, lab equipment, and specialized services forms the main part of the upfront investment costs.

In the perspective of a master's thesis, the development of a remote lab is a complex and expensive project, requiring multiple resources, tasks and abilities. Due to this fact, this work adopted the proof of concept study for the investigation about the development of remote labs dedicated to cyber-physical systems in engineering education. The study aimed to provide evidence and recommendations that can support professors, coordinators, designers, and institutions in the design of cyber-physical systems remote labs. It also helps to understand the level of complexity and requirements associated with the development of these labs.

Figure 5 - Design of the proof of concept study



The proof of concept study conducted in this work was divided into four phases: design conceptualization, prototyping, test and prototype analysis. Design conceptualization consists in defining the simplest design solution that is able to demonstrate the basic features of the concept. Prototyping is the implementation process of the design concept, creating a prototype that should be tested in the test phase. Different tests can be conducted to assess the feasibility of the concept such as usability, security, functional, and performance testing. The test phase provides evidence that allows the analysis of the concept. Prototype analysis is the phase in which the concept is analysed and a final report is elaborated. The final study report should detail the materials, methods, tests, results, and considerations. The proof of concept study is described in Chapter 6 Cyber-physical systems remote lab proof of concept. Figure 5 illustrates the phases involved in the proof of concept study.

3.4 Concluding remarks

This chapter summarized the methodology, considerations and approaches adopted for the conduction of this research work. Case studies have been used in different fields of research, it was possible to find a wide range of references that sought to establish a methodology for the conduction of these studies. On the other hand, proof of concept studies are still a methodology that requires further development in order to establish frameworks and guidelines for the conduction of these studies. Based on the analysis of good engineering practices, this research work developed a framework for the proof of concept study.

4 CASE STUDIES

This chapter discusses the case studies conducted in the present research. The methodology adopted was introduced in chapter 3 (section 3.2). Section 4.1 describes the case of development of a proof of concept of a remote lab for teaching digital twin, digital thread and internet of things at the University of Twente. Section 4.2 presents the case of a platform created for research and education in cyber-physical systems at the Eindhoven University of Technology. Section 4.3 presents the case of Skyrats platform adopted in the embedded systems design course at the Escola Politécnica in the Universidade de São Paulo (Brazil). Section 4.4 synthesizes the key findings of the three case studies investigated in this work.

4.1 Systems Life Cycle Remote Laboratory - Contextualization

The Systems Life Cycle Remote Laboratory (SysLCM Lab) is a project that is being developed at the University of Twente as a proof of concept of a remote laboratory for supporting courses in which digital thread, digital twin and model-based systems engineering are part of the learning content. The main purpose is to create a learning environment where students from different engineering programs can experiment and conduct case studies. Thus, the remote lab will allow students to remotely interact with devices using internet of things, sensors and actuators, and reflect on the effects through the respective digital twins. The intended availability of the environment is 24/7, that is high in order to offer a flexible use.

The developmental context is characterized by the new skills and competencies required by the industry 4.0 and the need for the adoption of a multidisciplinary approach in engineering education. The development team is formed by two professors from the Faculty of Electrical Engineering, Mathematics and Computer Science, one professor from the Faculty of Engineering Technology, one computer science master's student, and one mechanical engineering master's student.

The University of Twente is a research university located in the city of Enschede (The Netherlands). It is composed of five faculties: Engineering Technology, Electrical Engineering, Mathematics and Computer Science, Science and Technology, Behavioural, Management & Social Sciences, and Geo-Information Science and Earth Observation. These faculties administers a wide range of programs from pre-university education to in company training sessions. The programs are concentrated in fields such as technical medicine, robotics, information technology, business & public policy, chemistry and engineering science, earth observation, natural and social sciences (UNIVERSITY OF TWENTE, 2021).

The university is distinguished by the Twente Education Model (TOM), which is followed by all the Bachelor's programs at the university. TOM is characterized by the modular approach of the programs, the adoption of project-based learning as the main educational strategy, and student-driven learning, which means that students are stimulated to make their own choices under the supervision of a teacher (UNIVERSITY OF TWENTE, 2021). Each module of a program has a specific theme and combines different subjects and learning activities. Project-based learning is the central component of each module, students should work in teams in order to address a real-world problem (UNIVERSITY OF TWENTE, 2021). This education model is strongly based on hands-on activities that engage students to put theory into practice, developing a diverse range of skills and competencies.

4.1.1 Systems Life Cycle Remote Laboratory – Structure

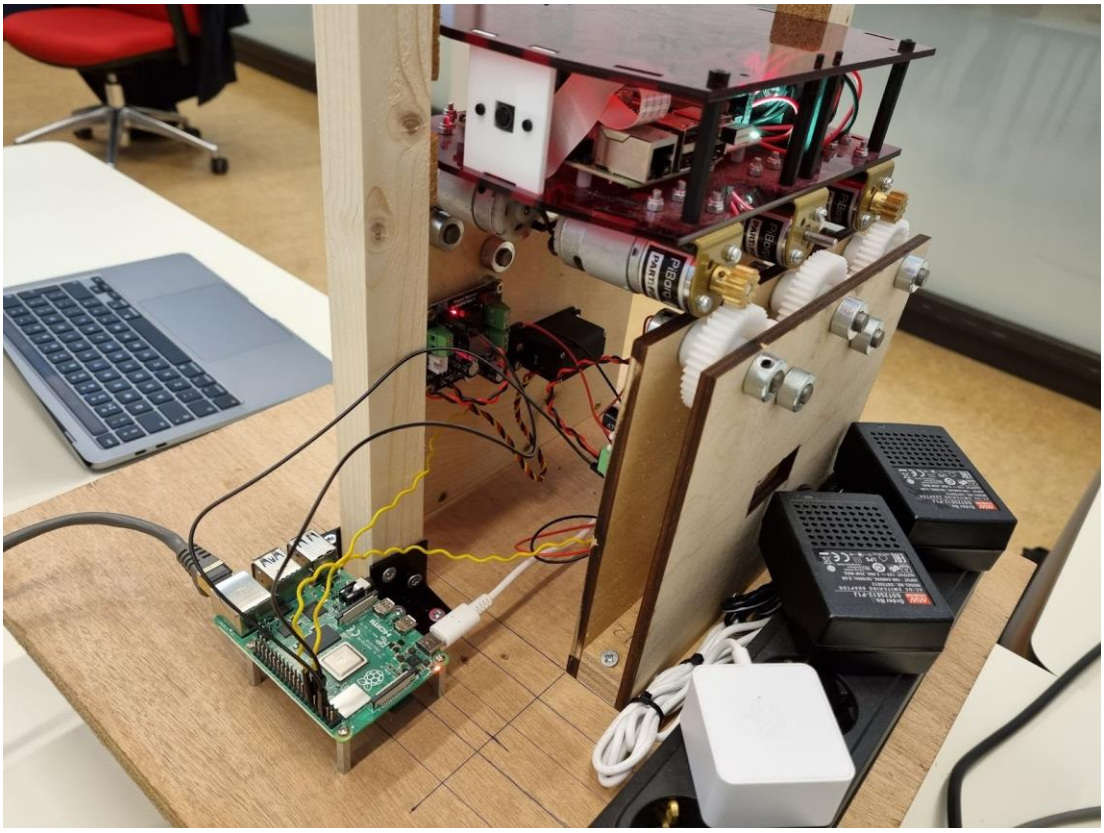
The prototype consists of a small remote-controlled vehicle, a treadmill and a RESTful application program interface (API). The RESTful API is a software architecture based on representational state transfer that aims to connect users, computers and computer programs. This architecture is characterized by the use of hypertext transfer protocol secure (HTTPS) requests for accessing and using data. The API allows students and professors to interact with the small vehicle and the treadmill, sending commands to the system and receiving the feedback information. It was implemented by the computer science master's student.

The small remote-controlled vehicle is a Diddyborg robot kit designed and developed by Piborg, which is a company focused on Raspberry Pi robotic kit development. The small vehicle is composed of six main components: computer, sensors, power supply, controller, motors, and chassis. The computer, which consists of a Raspberry Pi 3b+

and a 32GB SD Card, controls the entire system, establishing the connection between the vehicle and the RESTful API. The sensors embedded in the car are a camera and a voltage sensor. Energy is supplied by 20 AA rechargeable batteries and regulated by a ThunderBorg board. The ThunderBorg board indicates the level of current using LED lights and regulates energy supplied to the motors. The chassis is the mechanical structure of the vehicle, which is formed by a top plate, a bottom plate, posts, motor brackets, nuts, screws, and bolts. Figure 6 shows the Diddyborg robot assembled.

The treadmill was designed and built by the mechanical engineering master’s student to emulate different terrain conditions. It consists of a structure of medium-density fiberboard (MDF) and gears made from polyoxymethylene (POM). The gears are acted and controlled by servo motors that are controlled by an Arduino UNO board.

Figure 6 - Structure of the Systems Life Cycle Remote Laboratory



Source: SysLCM Archives

4.1.2 Systems Life Cycle Remote Laboratory - Educational use

The prototype was used as a case of digital twin design for teaching how to conceptualize a digital twin using different approaches such as model based systems engineering (MBSE), theory of inventive problem solving (TRIZ), and product development process based on the lean philosophy.

The purpose of this platform is to provide an environment in which students can experience a digital twin, developing a conceptual understanding and constructing knowledge about design possibilities. The platform can support courses that aim to introduce concepts related to Industry 4.0, including digital technologies such as internet of things, digital thread, and cyber-physical systems.

The platform is considered to be the object of study of master's and bachelor's projects that can develop new functionalities and implement upgrades in order to create new educational uses and improve the user experience. In the same way, it is considered to hold hackathons that engage students in the development of specific solutions for the platform such as the design of a virtual environment in which students could simulate its use.

4.1.3 Systems Life Cycle Remote Laboratory - Analysis

The prototype can support the development of two fundamental objectives of engineering instructional laboratories listed by ABET, which were detailed in Section 2.1 Laboratories in engineering education: models and experiment. Students can conduct activities using the prototype to explore modelling approaches and grasp the main features of digital products such as digital twin and digital thread. The adoption of a collaborative learning approach in association with the prototype can facilitate the development of soft skills related to communication, leadership, and teamwork.

In terms of industry 4.0, the prototype is a potential educational tool for teaching technical concepts and design methodologies. It can support the construction of conceptual frameworks about smart products and digital technologies. Table 13 describes the competencies for industry 4.0 that can be developed by the use of the platform.

Table 13 - Competencies for industry 4.0 addressed in the Systems Life Cycle Remote Laboratory

Category	Competency	Related learning objectives of engineering instructional laboratories	Domain of learning	How can this competency be addressed?
Domain specific and generic technical competencies	To design IT processes in the context of production and to use IT components for human-machine interaction.	Design, experiment, and models.	Cognitive	Students can understand the concepts of internet of things, cyber-physical systems, human-machine interaction, and digital twin through experimentation.
	To establish a connection between a digital twin and its physical reality.	Design, models, instrumentation, experiment, sensory awareness, and psychomotor.	Cognitive and psychomotor	Students can grasp the complexity of digital twins through experimentation. Analysing the operation of the platform, students can develop models that describe the structure and behavior of digital twins.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Design, teamwork, and communication.	Cognitive and affective	The adoption of project-based learning strategy in association with the platform can enhance communication skills.
	To act confidently and effectively in social (including intercultural) contexts.	Ethics in laboratory, sensory awareness, and communication.	Cognitive, psychomotor and affective	The adoption of project-based learning strategy in association with the platform can enhance interpersonal skills.
Self-competencies	To act self-determined and self-organized.	Psychomotor, sensory awareness, learn from failure, safety, and ethics in the laboratory.	Cognitive, psychomotor and affective	The adoption of project-based learning strategy in association with the platform can enhance organizational skills.
	To act on the basis of one's own open mindedness and creativity.	Creativity, models, and design.	Cognitive and affective	Students can learn how to develop models and solutions for industry 4.0.

The prototype can support the development of a comprehensive conceptual understanding of cyber-physical systems. This is one of the learning objectives in cyber-physical systems, and embedded systems courses. The experience provided by the prototype can help students to grasp the evolution of embedded systems into cyber-physical systems. Table 14 describes the competencies for cyber-physical systems that can be developed by students using the educational platform.

Table 14 - Competencies for cyber-physical systems engineering addressed in the Systems Life Cycle Remote Laboratory

Category	Subcategory	Description	Related learning objectives of engineering instructional laboratories	Domain of learning	How can this competency be addressed?
Technical knowledge and skills	General	Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Design, instrumentation, experiment, models, data analysis, creativity, and learn from failure.	Cognitive and affective	Students can learn how to model and design products in the context of industry 4.0. The platform can be used as a case study.
	Cyber-physical systems basis	Computing for the physical world: sensors, actuators, embedded systems.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective	Students can experience a remote system, sending commands and collecting data. They can understand the aspects involved in the design of cyber-physical systems.
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective	Students can grasp the complexity of cyber-physical systems life cycle by using the platform.
	Systems engineering	System-level approach,	Design, creativity and models.	Cognitive and affective	The platform can be used as

		systems integration across domains, and systems of systems.			a case study for the development of models based on the model based systems engineering approach.
	Engineering	Physics	Data analysis, instrumentation, experiment, models, and design.	Cognitive	Students can develop physical models for the dynamics of the platform.
Social knowledge and skills		Presentation	Communication	Cognitive and affective	The adoption of project-based learning strategy in association with the platform can enhance presentation skills.
		Technical writing	Communication	Cognitive and affective	The adoption of project-based learning strategy in association with the platform can enhance writing skills.

4.2 eXplore Cyber-Physical Systems platform - Contextualization

The eXplore Cyber-Physical Systems (xCPS) is a platform designed and implemented at the Eindhoven University of Technology for research and education in cyber-physical systems. Although the platform was designed as an on-site educational resource for hands-on activities, it can be used as a basis for the development of a remote lab dedicated to teaching cyber-physical systems. The platform consists of a small scale machine that emulates the operation of a production line in which cylindrical objects of different shapes and colors can be assembled and disassembled (ADYANTHAYA *et al.*, 2017). It is located at the Embedded Systems Laboratory.

The platform was conceptualized as a solution to the unavailability of industrial machines for hands-on activities in the university (ADYANTHAYA *et al.*, 2015). The use of industrial machines usually demands custom installation, high investment, frequent maintenance, strict safety rules, and dedicated staff. The development of platforms that emulate a realistic industrial environment for engineering education is a strategic solution to overcome these issues. Realistic environments can enable the development of techniques, measurements and analysis that are closer to practice (ADYANTHAYA *et al.*, 2015). In this context, the xCPS was developed to offer a real experience of cyber-physical systems for students and researchers. It can emulate the operation of industrial machines such as large-scale printers. Its development process was characterized by the integration of contributions from several bachelor's and master's projects, student assistants, and PhD. researchers.

The Electronic Systems group at the Eindhoven University of Technology comprises research and educational activities related to the design, analysis, validation and optimization of electronic systems for diverse engineering applications (EINDHOVEN UNIVERSITY OF TECHNOLOGY, 2021). It is an organizational unit that is part of the Department of Electrical Engineering.

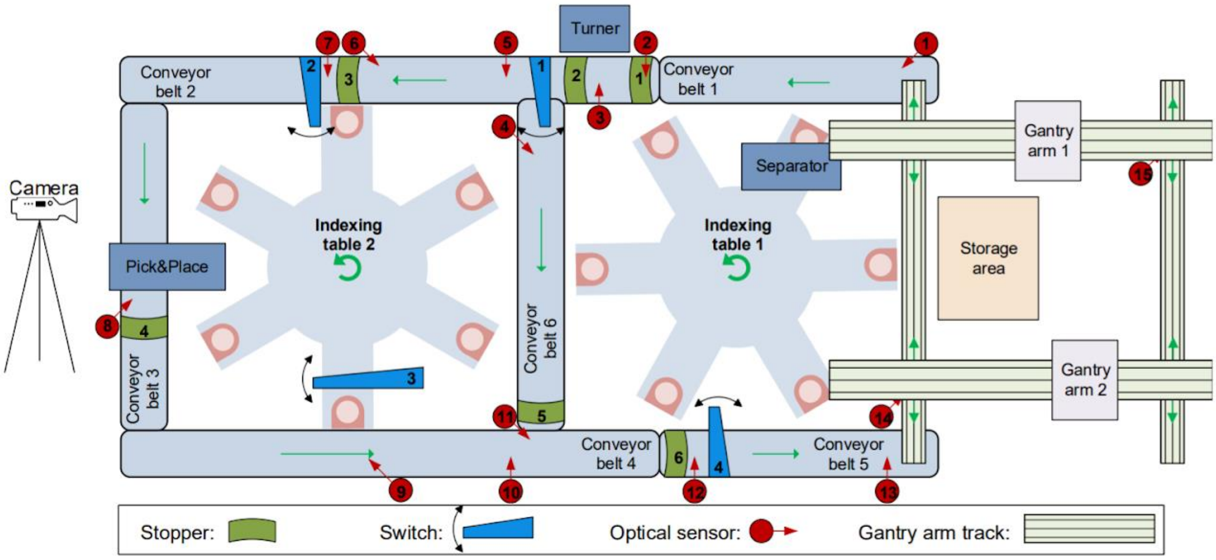
The Eindhoven University of Technology is a university of technology located in the city of Eindhoven (The Netherlands). It was founded in 1956 by collaboration between industry, local government and academia (EINDHOVEN UNIVERSITY OF TECHNOLOGY, 2021). The university is structured in nine departments: Biomedical Engineering, Built Environment, Electrical Engineering, Industrial Design, Industrial Engineering & Innovation Sciences, Chemical Engineering and Chemistry, Applied Physics, Mechanical Engineering, and Mathematics and Computer Science. It is the centre of the Brainport Eindhoven which is a technology hub focussed on the development of sustainable innovations for improving quality of life (EINDHOVEN UNIVERSITY OF TECHNOLOGY, 2021).

The educational approach adopted by the university is characterized by the combination of scientific curiosity with a hands-on mentality (EINDHOVEN UNIVERSITY OF TECHNOLOGY, 2021). Learning by doing is highlighted as the main educational strategy used in the university. Students are encouraged to design solutions for complex problems, applying theoretical knowledge and developing a wide range of skills and competencies.

4.2.1 eXplore Cyber-Physical Systems platform - Structure

xCPS platform is formed by one storage area, six conveyor belts, two indexing tables, two gantry arms, six actuators called “stoppers”, four switches, one turner, one camera, two actuators for assembly and disassembly of pieces, and 15 sensors (ADYANTHAYA *et al.*, 2015; ADYANTHAYA *et al.*, 2017). The mechanical components such as gantry arms and conveyor belts are actuated by electrical motors, servos, and pneumatic actuators. The system is controlled by signals from data acquisition and control input/output cards inside a general-purpose computer platform (ADYANTHAYA *et al.*, 2015). Figure 7 illustrates the overall structure of the platform.

Figure 7 - Schematic representation of the xCPS platform

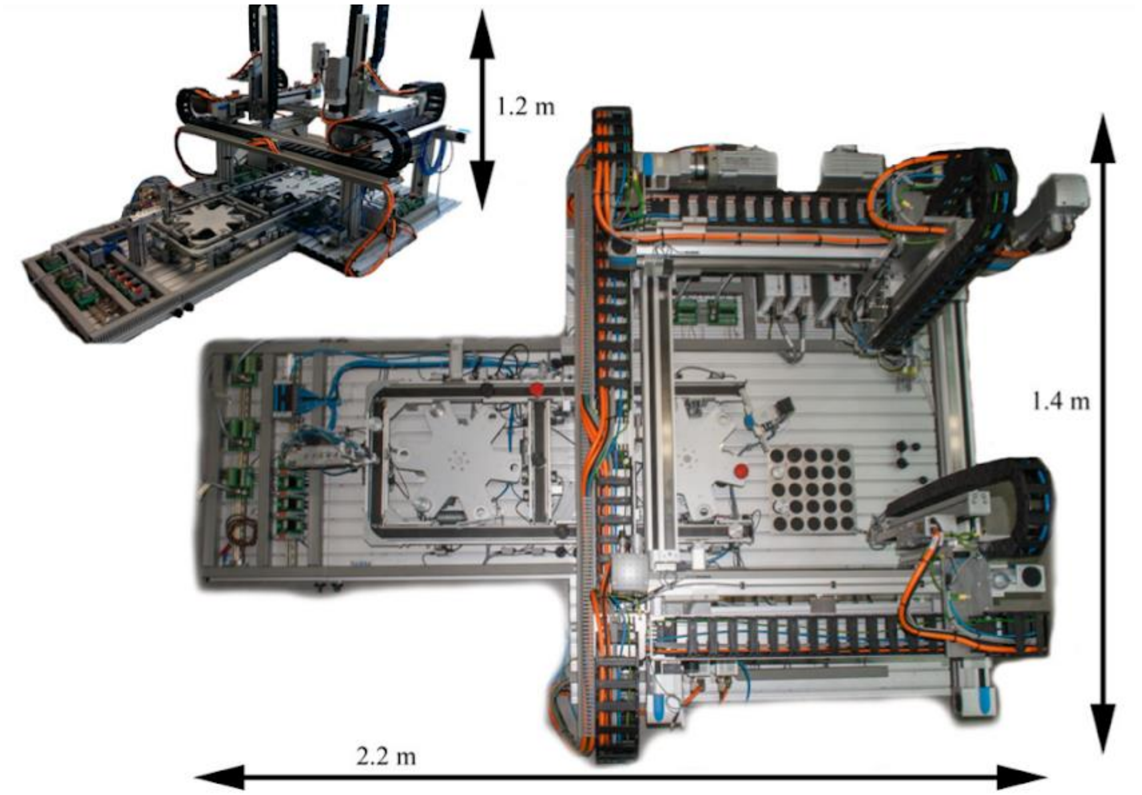


Source: Adyanthaya *et al.* (2015)

Stopper actuators were positioned at key points along the assembly system in order to block the movement of pieces and create buffers for the accumulation of pieces on the conveyor belts. The storage area is a grid where it is possible to store up to 25 components. Switches are used for changing the route of individual pieces. A turner is located in a strategic position to flip pieces. The separator is an actuator that can disassemble two combined pieces. The pick & place is another actuator that is able to clamp a part and combine it with a complementary part. A camera was added to the platform for the detection of shape, colour, and location of each piece. The sensors are used for the detection of presence of pieces in the surrounding area

(ADYANTHAYA *et al.*, 2015). Figure 8 shows two different views of the platform, highlighting its width, height and length.

Figure 8 - Schematic representation of the xCPS platform



Source: Adyanthaya *et al.* (2015)

The pieces used in the platform are cylindrical, coming in two complementary shapes to allow the execution of assembly and disassembly processes. The pieces are available in three different colors, which are black, red, and silver, to enable the creation of different use cases for the platform.

The hardware abstraction layer of the platform is a C++ based Application Programming Interface (API) that contains a set of functions that allow users to program the systems without deep understanding of the hardware layer (ADYANTHAYA *et al.*, 2017). The layer was implemented in two sublayers: the low-level layer is formed by functions that act as device drivers for actuators and sensors; the high-level layer increases the abstraction in order to improve the user experience in terms of usability and safety (ADYANTHAYA *et al.*, 2017).

xCPS platform also includes a virtual platform designed in the Blender 3D rendering software. The virtual platform was created to allow students to make simulations and visualizations of the physical platform. The essential elements of the machine, which are used for moving pieces along the emulation process, were rendered in the virtual model. The Blender physics simulation engine enables the conduction of simulations in which physical interactions between pieces and machine elements are modelled. Sensors are also emulated by checking collisions with invisible regions (ADYANTHAYA *et al.*, 2017). The API used in the simulation is the same as the one used in the physical platform.

4.2.2 eXplore Cyber-Physical Systems platform - Educational use

The main goal of the xCPS platform is to offer a small-scale cyber-physical industrial environment in which learning and research activities can be conducted for different purposes. ADYANTHAYA *et al.* (2017) and ADYANTHAYA *et al.* (2015) describe five examples of activities that can be conducted using the platform: supervisory control, combinatorial optimization, timing analysis, automatic verification and image-based sensing and control. Supervisory control activities analyse how to coordinate and orchestrate the operation of different elements of the system in order to achieve the production target. Combinatorial optimization focuses on the optimization of the actions to ensure that the system can achieve predefined performance targets. Timing analysis aims to develop performance analysis based on throughput and latency indicators. Automatic verification explores the use of abstraction techniques for infinite-state and hybrid automata for checking whether the parameters defined by the higher level models are followed during the physical realization. Image-based sensing control addresses the use of sensor data and image processing algorithms for the control of the system. These activities exemplify the multidisciplinarity of the platform that can be an important resource for collaboration between students from different engineering disciplines.

The platform is used as a research tool by bachelor and master students for the development of thesis projects and internships. Table 15 shows a list of projects that were developed using the platform. The variety of topics investigated in the listed projects evidences the multidisciplinary nature of the xCPS.

Table 15 - Projects developed using the xCPS platform

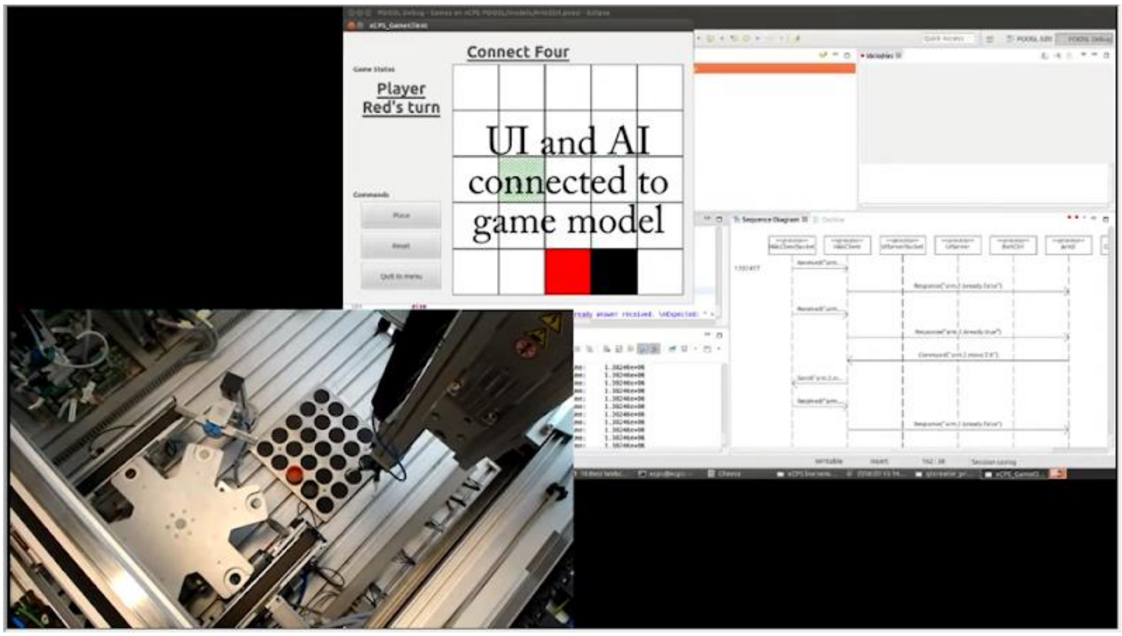
Project title	**Type**
Playing Connect Four with Robotic Arms	Bachelor's thesis
Playing games on xCPS using POOSL	Bachelor's thesis
Visualizing xCPS using Blender and POOSL	Bachelor's thesis
Visualizing xCPS using Blender and POOSL	Bachelor's thesis
Detecting the orientation of work pieces in an assembly line	Bachelor's thesis
Modeling the xCPS platform using SimEvents	Bachelor's thesis
Throughput analysis of xCPS using timed-automata	Bachelor's thesis
Detecting irregularities in execution traces	Bachelor's thesis
A fast and robust algorithm for the detection of circular pieces in a cyber physical system	Bachelor's thesis
Updating the PC, DAQ cards and marking cables	Research assistantship
Connecting the hardware to the DAQ and fixing the robot arms	Research assistantship
Enhancing and porting a Matlab circular pieces detection algorithm	Internship
Image-based throughput analysis and control for flexible manufacturing systems	Master graduation
Reliable WSN for xCPS	Master graduation
Scenario-based adaptive data-intensive controller for a cyber-physical system	Master graduation
Modeling and analysis of the xCPS platform using the Activity Specification Formalism	Master graduation

Source: xCPS (2021)

xCPS platform opened up the opportunity for the adoption of gamification as an educational strategy in engineering courses. Students can program the platform for playing interactive games such as connect four, which is a popular two-player board game. Figure 9 presents two students playing connect four on the platform. The gamification of the platform was a research topic investigated by students in a bachelor's thesis as shown in Table 13.

Game theory can provide mathematical models for performance optimization of production systems. Using the platform, students can experience the application of game theory in optimization problems. It enables students to explore the application of theories for solving real-world problems.

Figure 9 - xCPS platform and gamification



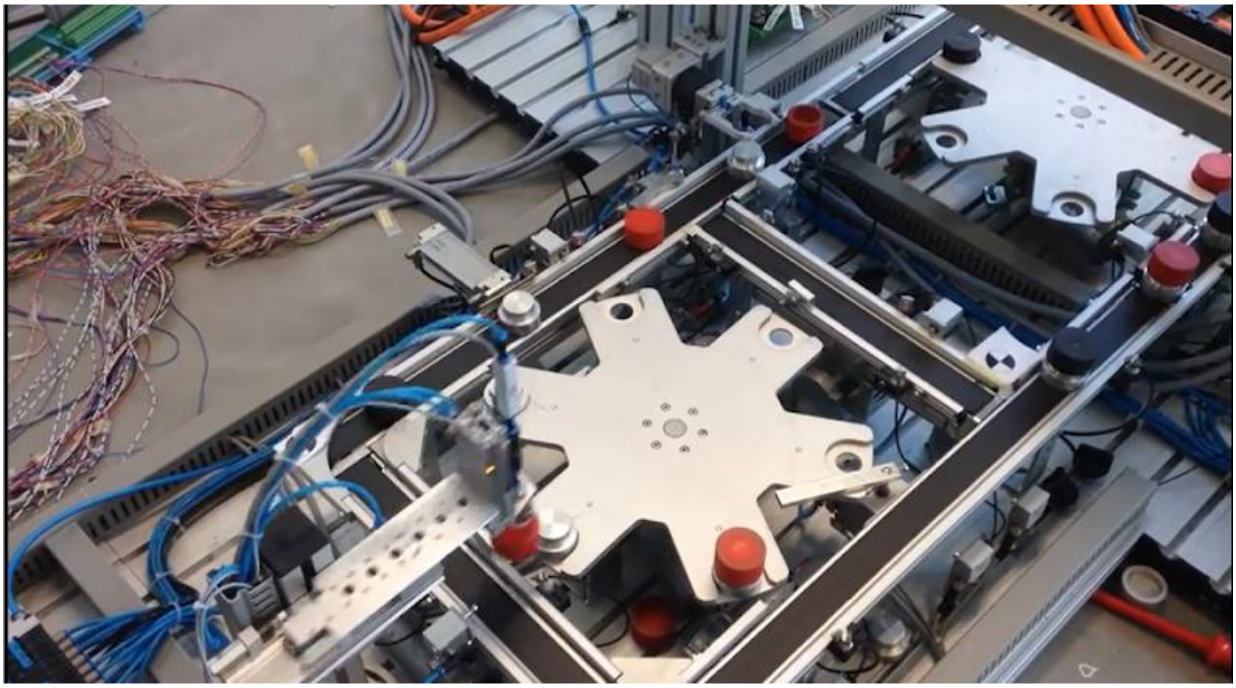
Source: xCPS (2021)

The platform provides a real-world experience that allows students to investigate and explore different aspects of industrial processes. Industrial processes such as chip manufacturing, assembly lines, and large-scale printing can be simulated successfully. Figure 10 presents the simulation of an assembly line. Exploring the functionalities available on the platform, students can grasp the complexity of cyber-physical systems, developing the understanding of the diverse characteristics involved in its design, implementation, operation, and maintenance.

The investigation of different models and approaches for optimization of production systems is facilitated by the xCPS platform. Researchers can perform small-scale experiments in order to analyse the performance of models and approaches. Although real-scale processes are more complex, the use of small-scale emulators permits to identify key parameters, relationship between them, and their influence on a process. It provides a test environment for the development of industrial solutions by adopting, for instance, the design science research methodology.,

The platform is also a tool for teaching the MBSE approach. This approach is a formalization of the use of models as the main basis in the development and management of engineering systems. The development of models has been the subject of numerous studies involving several knowledge areas. It allows systems to be developed and managed throughout their entire life cycle using an integrated and transdisciplinary approach.

Figure 10 - The simulation of an assembly line using the xCPS platform



Source: xCPS (2021)

4.2.3 eXplore Cyber-Physical Systems platform - Analysis

xCPS platform has been generating diverse opportunities for hands-on activities with engineering students from different disciplines and levels. The wide range of activities that can be performed using the platform enables the development of all the fundamental objectives of engineering instructional laboratories listed by ABET, which were detailed in Section 2.1 Laboratories in engineering education. The platform allows students to use instruments, create models, conduct experiments, analyse data, redesign processes, learn by exploring, be creative in the development of engineering solutions, work in groups, grasp the complexity of industrial processes and understand ethical issues. Communication skills are also developed by the construction of reports, papers, and oral presentations. The use of a small-scale industrial machine is important for the development of sensory and safety awareness.

Some learning objectives for teams can be strengthened by adopting the project-based learning strategy in courses. The engagement of students in the development of engineering projects can be a period of intense learning and growth of skills for them. The xCPS platform is a flexible environment in which students can develop and test different design solutions. Students can check their models and solutions using a virtual environment that simulates the operation of the physical platform.

In terms of competencies related to industry 4.0, the flexibility and multidisciplinarity of the platform permit to conduct activities that address domain specific competencies related to the use of digital technologies in an industrial context. It is a useful tool for the conduction of activities that enhance engineering and design skills related to industry 4.0. General competencies such as problem solving, soft skills, systems thinking, and technological literacy can be developed in accordance with the educational strategies adopted. The development of social competencies can be addressed by the adoption of strategies that stimulate the creation of a collaborative and interactive learning environment. Personal competencies are developed through performing different tasks for the required assignments. Table 16 describes the competencies for industry 4.0 that can be developed by the use of the platform.

Table 16 - Competencies for industry 4.0 addressed in the eXplore Cyber-Physical Systems platform

Category	**Competencies**	**Related learning objectives of engineering instructional laboratories**	**Domain of learning**	**How can this competency be addressed?**
Domain specific and generic technical competencies	To act and collaborate in interdisciplinary contexts.	Models, design, safety, teamwork, ethics in laboratory and experiment.	Cognitive and affective	The platform can be used for the development of interdisciplinary projects.
	To flexibly adapt business processes to changeable conditions to new technologies.	Learn from failure, models, and creativity.	Cognitive and affective	Through experimentation, students can understand the potential use of digital technologies that can be adopted in business and manufacturing processes.
	To design IT processes in the context of production and to use IT components for human-machine interaction.	Design, experiment, and models.	Cognitive	Students can design, test, and validate different IT processes for manufacturing purposes using the platform. The human-machine interaction can also be addressed in different contexts, such

				as playing board games.
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	Design, experiment, models, instrumentation, sensory awareness, learn from failure and psychomotor.	Cognitive, affective and psychomotor	Students can design and test different production processes using the platform. The platform can be used for teaching and researching topics related to automation and control, optimization, and computer vision.
	To establish a connection between a digital twin and its physical reality.	Design, models, instrumentation, experiment, sensory awareness, and psychomotor.	Cognitive and psychomotor	The platform can provide an experience about the design and development of digital twins for production processes.
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Data analysis, models, and experiment.	Cognitive	Students can collect and analyse large amounts of data through the conduction of different experiments. It is possible to use the platform for testing statistical models applied to production processes.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Models, data analysis, and design.	Cognitive	Students can model, design, and analyse systems using different approaches, methods, and techniques.
	To initiate and to implement innovation processes.	Creativity, models, and design.	Cognitive and affective	The platform can support the development of a wide range of processes.
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	Design, ethics in the laboratory, and safety.	Cognitive and affective	It is possible to reflect about the legal aspects involved in the production processes through design activities and safety/ethical analysis.
	To use the appropriate evaluation tools in	Data analysis, models, sensory awareness, instrumentation,	Cognitive, psychomotor and affective	The platform provides different production scenarios with complex issues that require the

	complex decision-making situations.	safety, psychomotor, and ethics in the laboratory.		use of tools and techniques for the decision making process.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Design, teamwork, and communication.	Cognitive and affective	The adoption of project-based learning strategy in association with the platform can enhance communication skills.
	To act confidently and effectively in social (including intercultural) contexts.	Ethics in laboratory, sensory awareness, and communication.	Cognitive, psychomotor and affective	The adoption of project-based learning strategy in association with the platform can enhance interpersonal skills.
	To lead production units and teams with goal orientation.	Teamwork and communication.	Cognitive and affective	By simulating industrial processes, students can work in groups and experience different work positions in production environments.
	To design digitally supported interaction and cooperation processes.	Design, creativity, instrumentation, and models.	Cognitive and affective	Students can develop digital solutions using the platform.
Self-competencies	To act self-determined and self-organized.	Psychomotor, sensory awareness, learn from failure, safety, and ethics in the laboratory.	Cognitive, psychomotor and affective	The adoption of project-based learning strategy in association with the platform can enhance organizational skills.
	To act on the basis of one's own open mindedness and creativity.	Creativity, models, and design.	Cognitive and affective	The platform is a flexible environment in which students are able to create and test different artifacts.
	To design and implement your own lifelong learning.	Creativity, models, design, and experiment.	Cognitive and affective	Through experimentation, students can assess their learning, construct knowledge, and understand what is still necessary to learn for the development of specific tasks.

Teaching cyber-physical systems using the platform offers students the opportunity to experience and explore industrial cyber-physical systems. One of the most common learning objectives related to cyber-physical systems is to understand the complexity and characteristics of these systems. It is the first step in a cyber-physical systems course and a topic in most embedded systems courses. This learning objective is supported by the platform successfully. After this step, cyber-physical systems courses usually go in different directions in accordance with their syllabus. The platform supports learning objectives related to design and use of the model-based systems engineering approach in cyber-physical systems. In terms of the competencies required by industry and academia for cyber-physical systems engineers, which were defined by MAKIO-MARUSIK (2017), the platform is a useful tool that allows the conduction of activities that integrates the development of technical knowledge and skills, social knowledge and skills, and attitudes. Table 17 describes the competencies for cyber-physical systems that can be developed by students using the educational platform.

Table 17 - Competencies for cyber-physical systems engineering addressed in the eXplore Cyber-Physical Systems platform

Category	**Subcategory**	**Description**	**Related learning objectives of engineering instructional laboratories**	**Domain of learning**	**How can this competency be addressed?**
Technical knowledge and skills	General	Solid foundations together with multidisciplinary awareness.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective	Through experimentation, students can construct knowledge and acquire practical experience in diverse engineering disciplines.
		Broad knowledge and skills of multiple areas of engineering expertise.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective	The multidisciplinarity of the platform enables the development of activities that involve multiple engineering disciplines.
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Design, instrumentation, experiment, models, data analysis, creativity, and learn from failure.	Cognitive and affective	Students can acquire practical experience in product development from the perspective of production processes.

	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective	Students can grasp the complexity of computing concepts and develop artifacts related to computer science and software engineering.
		Computing for the physical world: sensors, actuators, embedded systems.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective	The platform provides a flexible environment with sensors and actuators, which can be used for multiple activities.
		Discrete and continuous mathematics.	Models, experiment and data analysis.	Cognitive	Students can develop and test mathematical models using the platform.
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective	The platform allows the development of a wide range of hands-on activities that can explore the application of sensing, actuation, control, communication, and computing.
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Models and design.	Cognitive	Students can experience, develop and test models related to automation, control, and robotics.
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective	The platform provides an environment in which students can explore the complexity of cyber-physical systems life cycle through hands-on activities.
	Non-functional characteristics of cyber-	Security and privacy	Design, models, experiment, data analysis, and	Cognitive and affective	Security and privacy issues can be addressed in the scope of projects.

	physical systems		ethics in the laboratory.		
		Interoperability	Design, models, instrumentation, learn from failure and experiment.	Cognitive and affective	Students can study aspects of technical interoperability through experimentation.
		Reliability and dependability	Design, models, instrumentation, learn from failure and experiment.	Cognitive and affective	Students can analyse the reliability of production processes.
		Power and energy management	Design, models, instrumentation, and experimentat.	Cognitive	Students can develop projects and activities that aim to investigate energy aspects of production processes.
		Safety	Design, models, experimentation, safety, data analysis, and ethics in the laboratory.	Cognitive and affective	Safety issues related to production processes can be investigated using the platform.
		Stability and performance	Design, models, instrumentation, learn from failure and experimentation.	Cognitive and affective	Students can investigate the performance of production processes using the platform.
		Human factors and usability	Safety, ethics in the laboratory, experiment, design, models, instrumentation, sensory awareness, creativity, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective	The human-machine interaction and user experience can be addressed in different contexts, such as playing board games.
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Design, creativity and models.	Cognitive and affective	Students can adopt the model based system engineering approach in the development of their projects.
	Engineering	Engineering Process	Data analysis, models, design, experiment, instrumentation, sensory awareness, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective	The platform emulates an industrial environment in which students can experience industrial processes and issues.
		Industrial automation, plant modeling.	Data analysis, models, design, experiment,	Cognitive, psychomotor	Students can experience, develop and test

			instrumentation, sensory awareness, learn from failure, and psychomotor.	, and affective	models related to automation, control, and robotics.
		Statistical methods and mining techniques	Data analysis, models, and design.	Cognitive	The platform can support tests of statistical models applied to production processes.
		Physics	Data analysis, instrumentation, experiment, models, and design.	Cognitive	Students can explore physical models through experimentation.
	Business and humanities	Project management	Design, creativity, teamwork, communication, and models.	Cognitive and affective	By simulating industrial processes, students can work in groups and experience differen t work positions in production environments.
		Economics	Models, design, experiment, and data analysis.	Cognitive	Students can investigate economic indicators of production processes.
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Communication, teamwork, creativity, experiment, and design.	Cognitive and affective	Working in interdisciplinary teams can enhance collaboration skills.
		Collaboration with customers.	Communication, teamwork, experiment, and design.	Cognitive and affective	The development of artifacts for external stakeholders can enhance collaboration with customer skills.
		Communicatio n within heterogeneous interdisciplinary multicultural teams and with customers.	Communication, teamwork, creativity, experiment, and design.	Cognitive and affective	The adoption of project-based learning strategy in association with the platform can enhance communication skills.
		Presentation	Communication	Cognitive and affective	The adoption of project-based learning strategy in association with the platform can enhance presentation skills.
		Technical writing	Communication	Cognitive and affective	The adoption of project-based learning strategy in

				association with the platform can enhance writing skills.
Attitudes	Flexibility to manage rapidly evolving technologies.	Data analysis, design, models, experiment, instrumentation, and learn from failure.	Cognitive and affective	The platform provides different production scenarios with complex issues that require the use of tools and techniques for the decision making process.
	Definition as well as solving problems.	Creativity, design, instrumentation, and experiment.	Cognitive and affective	Students can design artifacts for solving production problems using the platform.
	Analytical skills	Design, models, experiment, creativity, data analysis, sensory awareness, learn from failure, psychomotor, and communication.	Cognitive, psychomotor, and affective	Students can model, design, and analyse artifacts using different approaches, methods, and techniques.
	Creativity	Creativity	Cognitive and affective	The platform offers a flexible environment in which students can create diverse engineering artifacts.
	Entrepreneurship	Design, models, experiment, creativity, communication, and teamwork.	Cognitive and affective	The flexibility of the platform can stimulate entrepreneurial thinking.
	Critical thinking and critical attitude towards technological developments.	Creativity, models, design, data analysis, learn from failure and experiment.	Cognitive and affective	Students can experience the development of technological solutions using the platform.
	Cross-disciplinary thinking	Design, models, creativity, and experiment.	Cognitive and affective	Through the development of multidisciplinary projects, students can think in a multidisciplinary way.
	Lifelong learning	Creativity, models, design, learn from failure and experiment.	Cognitive and affective	Through experimentation, students can assess their learning, construct knowledge, and understand what is

				still necessary to learn for the development of specific tasks.

The platform enables the adoption of different educational approaches and strategies that can lead to different learning outcomes and skills development. Thus, professors have more flexibility to select strategies and methods in accordance with the learning objectives of each course. As an educational tool for hands-on activities, the xCPS platform strengthens the learning experience stimulating the development of diverse skills and competencies. Students have been using the platform for learning activities in projects in the electrical engineering, automotive technology, and embedded systems programs and development of research projects. The Electronic Systems group plans to start using the platform for course projects as well, from the 2022 academic year.

4.3 Skyrats platform – Contextualization

Skyrats team is a student organization dedicated to the study, design and development of unmanned aerial vehicles (UAVs), which are also known as drones, at Escola Politécnica in Universidade de São Paulo (Brazil). The organization consists of a multidisciplinary group of students and two professors, who are responsible for the supervision of the team. Since 2017, its foundation year, the team has been attending diverse competitions, such as the International Micro Air Vehicle Conference and Competition and the Brazilian Robotics Competition. The workspace of the team is located at the Interdisciplinary Center in Interactive Technologies (CITI-USP) that is a research environment dedicated to the development of multidisciplinary scientific investigations focussed on the themes of human computer interaction and interactive electronic media.

As an extension initiative of the Escola Politécnica, Skyrats is an opportunity for students to experience the design, implementation, maintenance and upgrade of engineered systems. The preparation of an UAV for a competition requires the accomplishment of diverse activities related to different disciplines, such as project management, product development, and software development. The engagement of students in these activities stimulates the acquisition of a wide range of knowledge, skills and competencies associated with the practice of engineering.

The course “Embedded systems design” at the Department of Electronic Systems Engineering in Polytechnic School aims to instruct students how to plan, develop and validate embedded systems design (USP E-DISCIPLINAS, 2020). The course is part of the electrical engineering undergraduate program. It is based on the active learning approach in which students are stimulated to develop projects in a collaborative way. The classes are a combination of hands-on activities, theory sessions, and question & answer sessions. Hands-on activities are usually conducted in the CITI-USP, students can access the building in order to work on their projects and discuss issues with the course monitors. Table 18 details the course syllabus.

Drones of the Skyrats team are adopted as educational platforms for the understanding and development of embedded systems. The use of drones as development platforms allows the integration between an extension initiative and curricular courses. Team members act as monitors to support students in hands-on activities. Students use the spiral development approach to design and implement embedded systems, which consists of short cycles that include listening, design, coding, and testing.

Table 18 - Embedded systems design course syllabus

	Study topics
1	Introduction – embedded systems, microcontrollers, design of microcontroller based embedded systems
2	Requirements specification, conceptual design, detailed project, software-hardware partition, implementation and tests
3	Formal modelling techniques, specification and synthesis
4	Cyber-physical systems
5	Anatomy of a microcontroller based embedded system: types, hardware and software
6	Microcontrollers: taxonomy, ISA architecture, memory, I/O and external peripherals
7	Input-Output: Polling, Interrupt and DMA
8	Software development for Microcontroller based Embedded Systems

Source: USP E-DISCIPLINAS (2020)

he Escola Politécnica of the Universidade de São Paulo is one of the most traditional engineering schools in Brazil, which was established in 1893, located in the city of São Paulo. It is composed of 15 departments that offer 17 courses for undergraduate students besides 10 master and 9 doctorate tracks (POLI-USP, 2021). The courses, tracks, and research areas involve the following engineering disciplines: chemical, civil, computer, electrical - automation and control, electrical - power and automation, electrical - electronic and computer systems, electrical - telecommunications, environmental, materials, mechanical, mechatronics, metallurgical, mining, naval, nuclear, petroleum, and production (POLI-USP, 2021).

4.3.1 Skyrats platform – Structure

Drones are considered complex cases of embedded systems that have six degrees of freedom, advanced control algorithms, sophisticated architecture, limitation in the availability of energy, limited processing power, and weight restrictions. These embedded systems can be used in different economic sectors for a variety of purposes, performing complex tasks, such as inspection of power transmission lines, rescue of persons in distress, and environmental monitoring of soil, water, and forests. The adoption of drones as an educational platform takes advantage of the multidisciplinary environment of the CITI-USP in order to engage students in the development of complex embedded systems that cover most of the electrical engineering disciplines. Figure 11 indicates the workspace, drones, sensors and single board computers of the Skyrats Team.

Designing and developing drones include the application of advanced technologies from microelectronics, image processing, telemetry, data capturing, image capture, software, telecommunications, energy storage and supply, data structure, human machine interface, and control and automation. Besides that, it requires the analysis of legal, safety, ethical and societal issues that are related to the operation of these systems. In this perspective, this platform enables a rich and deep understanding about the application of embedded systems.

The drones adopted in the course are composed of battery, brushless motors, electronic-speed-controllers (ESC), propellers, camera, set of sensors (GPS, depth camera, and light detection and ranging - LIDAR), single board computer, and flight control unit (FCU). The utilization of two computers is an architectural strategy that ensures safety and reliability in the operation of the drones. FCU is dedicated to the operation and control of the drones, while SBC is devoted to the performance of tasks with a high level of abstraction, such as computer vision methods.

Figure 11 - Workspace of the Skyrats team

The open-source firmware PX4 autopilot is used for controlling the drones autonomously. Nuttx is the real time operating system adopted for the control. Pixhawk is the FCU adopted, which consists of a real time computer with Nuttx as the operating system and a set of on-board sensors (accelerometer, barometer, etc). Labrador is the single board computer, which is designed and manufactured by the Caninos Loucos technology development program at CITI-USP, and runs the Debian operating system. Mavlink is the communication protocol and Robot Operating System (ROS) is the middleware used, which allows the communication between computer clusters.

Gazebo simulator is an open-source 3D platform that allows testing and simulating robotic environments and systems. The simulation environment includes sensors and actuators, and simulation description format (SDF). The protobuf protocol can be used for running simulations on different servers. It is used in the course to test the embedded system design developed by the students.

4.3.2 Skyrats platform - Educational use

Embedded systems is a challenging area due to the constant evolution of digital technologies. It requires that embedded systems courses should be constantly adapted and updated in line with new technological, economic and social developments. The use of drones as educational platforms allows students to experience a complex and sophisticated embedded system that is constantly evolving. The embedded systems design course established a partnership with the Skyrats team in order to enable the use of their drones and software tools in hands-on activities.

Students initially learn mechanical and electrical characteristics of drones for understanding the limitations and possibilities of use. They can observe and interact with the system to grasp the basic aspects of each physical element. Then, they learn and practice how to use software tools for testing, operating and controlling drones. ROS and Gazebo Simulator are the main software tools used. The simulator offers an environment in which students can test and explore solutions for embedded and cyber-physical systems. It allows the verification of the project design in terms of safety and reliability.

Student's projects consist of the development of a solution of embedded systems for a problem defined by the professor. The problem usually involves technical and design aspects that were addressed during theoretical and practical classes. In this sense, students should apply the knowledge and experience acquired during the course to create a solution that is able to perform the tasks required by the problem. The solution is designed and implemented using the software tools.

Currently, the limitation of resources is a barrier to the implementation of the final solutions in drones. The amount of available drones, sensors, and tools is not enough for all the groups of students. Thus, the projects are mainly focused on cyber aspects of embedded systems, such as control solutions. Although the solution is implemented using virtual environments, students should take into account all the limitations and complexities of drones in a real environment.

4.3.3 Skyrats platform – Analysis

The use of drones as an educational platform allows students to experience the development of complex and sophisticated embedded systems that integrate advanced technologies from multiple engineering disciplines. Students learn how to design, test, and validate embedded systems, developing skills and competencies related to the construction of engineering solutions using digital technologies. The platform enables the development of five fundamental objectives of engineering instructional laboratories listed by ABET: creativity, design, experiment, models, and teamwork.

As students have to work in groups for the development of a solution of embedded systems, communication and collaboration skills are enhanced through the course. Through practical classes students can explore concepts and theories related to embedded systems, constructing knowledge and acquiring practical experience about the use of these systems as an engineering solution for different purposes. The adoption of project-based learning as the main educational strategy enhances the development of social and self-competencies. The use of sensors in the project can address skills related to computing for the physical world. In this sense, students have the opportunity to develop several competencies related to industry 4.0, as shown in Table 19.

Table 19 - Competencies for industry 4.0 addressed in the Skyrats platform

Category	**Competency**	**Related learning objectives of engineering instructional laboratories**	**Domain of learning**	**How can this competency be addressed?**
Domain specific and generic technical competencies	To design IT processes in the context of production and to use IT components for human-machine interaction.	Design, experiment, and models.	Cognitive	Students learn how to design and implement IT systems for different purposes.
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate	Design, experiment, models, instrumentation, sensory awareness, learn	Cognitive, affective and psychomotor	Students have the opportunity to design and test projects related to control and automation of systems.

	interfaces (including the implementation of problem-solving and optimization processes).	from failure and psychomotor.		
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Data analysis, models, and experiment.	Cognitive	Students can use computer vision methods in their projects to deal with data collected by sensors.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Models, data analysis, and design.	Cognitive	Students learn how to design and implement a complex system with multiple elements and functionalities.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Design, teamwork, and communication.	Cognitive and affective	The project-based learning strategy adopted in the course enables the development of this competency.
	To act confidently and effectively in social (including intercultural) contexts.	Ethics in laboratory, sensory awareness, and communication.	Cognitive, psychomotor and affective	The use of project-based learning as the main educational strategy enhances interpersonal skills.
	To design digitally supported interaction and cooperation processes.	Design, creativity, instrumentation, and models.	Cognitive and affective	Students can design different systems using virtual environments.
Self-competencies	To act self-determined and self-organized.	Psychomotor, sensory awareness, learn from failure, safety, and ethics in the laboratory.	Cognitive, psychomotor and affective	The adoption of project-based learning strategy in association with the platform can enhance organizational skills.
	To act on the basis of one's own open mindedness and creativity.	Creativity, models, and design.	Cognitive and affective	Students learn how to create complex embedded systems.
	To design and implement your own lifelong learning.	Creativity, models, design, and experiment.	Cognitive and affective	Students can grasp the importance of self-study for their career.

Through theoretical lessons and hands-on activities students can understand the elements that form cyber-physical systems, and the complexity and potentialities of these systems in engineering. The use of the spiral development approach allows students to learn how to design cyber-physical systems in a fast and effective way. They can also acquire experience in the development of cyber-physical systems, modeling and testing solutions using software tools that enable the analysis and assessment of multiple aspects of the proposed solution. Table 20 presents the competencies related to cyber-physical systems addressed in the adoption of the Skyrats platform.

Table 20 - Competencies for cyber-physical systems engineering addressed in the Skyrats platform

Category	**Subcategory**	**Description**	**Related learning objectives of engineering instructional laboratories**	**Domain of learning**	**How can this competency be addressed?**
Technical knowledge and skills	General	Broad knowledge and skills of multiple areas of engineering expertise.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective	The development of embedded systems involves advanced technologies from multiple areas of engineering expertise. Students learn how to integrate these technologies in the development of complex engineered systems.
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Design, instrumentation, experiment, models, data analysis, creativity, and learn from failure.	Cognitive and affective	Students can acquire practical experience in the development of engineered systems using advanced technologies.
	Cyber-	Computing concepts, computer	Design, models, learn from failure, data analysis,	Cognitive and affective	Students use concepts and technologies

	physical systems basis	science, software engineering.	experiment, creativity, and instrumentation.		from computer science and software engineering in the development of their projects.
		Computing for the physical world: sensors, actuators, embedded systems.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective	Students learn how to design, implement, test and validate embedded systems.
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective	Students explore the application of sensing, actuation, control, communication, and computing in the context of embedded systems.
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Models and design.	Cognitive	Students experience, develop and test models related to automation, control, and robotics.
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective	Students can grasp the complexity of cyber-physical systems life cycle and learn how to design and implement these systems.
	Non-functional characteristics of cyber-physical systems	Security and privacy	Design, models, experiment, data analysis, and ethics in the laboratory.	Cognitive and affective	Security and privacy issues can be addressed in the scope of projects.
		Power and energy management	Design, models, instrumentation, and experimentat.	Cognitive	Students should deal with power and energy

					limitations in the scope of their projects.
		Safety	Design, models, experimentation, safety, data analysis, and ethics in the laboratory.	Cognitive and affective	Safety issues related to operation of drones are addressed in the projects.
		Stability and performance	Design, models, instrumentation, learn from failure and experimentation.	Cognitive and affective	Students can investigate the performance and stability of the embedded systems.
		Human factors and usability	Safety, ethics in the laboratory, experiment, design, models, instrumentation, sensory awareness, creativity, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective	The human-machine interaction and usability can be addressed in the scope of projects.
	Engineering	Industrial automation, plant modeling.	Data analysis, models, design, experiment, instrumentation, sensory awareness, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective	Students can experience, develop and test models related to automation, control, and robotics.
		Physics	Data analysis, instrumentation, experiment, models, and design.	Cognitive	Students learn the dynamics of unmanned aerial vehicles.
Social knowledge and skills		Presentation	Communication	Cognitive and affective	Students should present their projects at the end of the course.
		Technical writing	Communication	Cognitive and affective	Students should write a report that details how their projects were developed.
Attitudes		Definition as well as solving problems.	Creativity, design, instrumentation, and experiment.	Cognitive and affective	Students should solve a problem using the platform and experience acquired during the course.
		Analytical skills	Design, models, experiment, creativity, data	Cognitive, psychomotor, and affective	Students can model, design, and analyse a

		analysis, sensory awareness, learn from failure, psychomotor, and communication.		complex embedded system.
	Creativity	Creativity	Cognitive and affective	Students should be creative in the development of their projects.
	Critical thinking and critical attitude towards technological developments.	Creativity, models, design, data analysis, learn from failure and experiment.	Cognitive and affective	Students can experience the development of technological solutions.
	Lifelong learning	Creativity, models, design, learn from failure and experiment.	Cognitive and affective	Students can assess their learning and understand what is still necessary to learn for the development of specific tasks.

4.4 Synthesis of the key findings

The platforms analysed in these three case studies can support the development of multiple competencies related to industry 4.0 and cyber-physical systems. The previous sections detailed how each platform can address different competencies and which fundamental learning objectives of engineering educational platforms are developed in each one. The adoption of active learning strategies, such as project-based learning, problem-based learning, and cooperative learning, for the use of the platforms can enhance the development of social and self-competencies related to industry 4.0 and cyber-physical systems.

The use of educational platforms for hands-on activities in engineering education can support the development of essential technical competencies for industry 4.0 and cyber-physical systems engineering. Students have the opportunity to work in teams in the development of projects that can involve advanced technologies from different engineering disciplines. They can grasp how to design and implement cyber-physical systems for different purposes. In this sense, it provides an environment in which they can practice the application of design, creativity, science and technology to the development of engineering solutions in different contexts.

Table 21 presents which competencies for industry 4.0 can be addressed in each platform. The flexibility and multidisciplinarity of the xCPS platform enable the realization of a wide range of hands-on activities that can support the development of multiple competencies for industry 4.0. SysLCM and Skyrats platforms are more limited in this sense. The xCPS provides an environment in which students can investigate different problems and develop diverse engineering solutions from scratch. It enhances skills related to creativity, problem solving, and product design, which are essential for engineers in the context of industry 4.0. On the other hand, SysLCM and Skyrats platforms focus on providing an environment in which students can explore concepts and technologies related to industry 4.0 and cyber-physical systems. Exploring learning environments enable the use of inquiry-based learning approach, which is characterized by the engagement of students in the learning process through the investigation of concepts, technologies and phenomena. Students can learn the potentialities of industry 4.0 technologies and reflect about the integration of these technologies in the development of engineered systems.

Table 21 - Competencies for industry 4.0 addressed in each platform

Category	**Competencies**	**SysLCM**	**xCPS**	**Skyrats**
Domain specific and generic technical competencies	To act and collaborate in interdisciplinary contexts.		✓	
	To flexibly adapt business processes to changeable conditions to new technologies.		✓	
	To design IT processes in the context of production and to use IT components for human-machine interaction.	✓	✓	✓
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).		✓	✓
	To establish a connection between a digital twin and its physical reality.	✓	✓	
	To deal with large amounts of data and to use appropriate statistical skills (including		✓	✓

	recognizing the importance of algorithms and the management of sensitive data).			
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.		✓	✓
	To initiate and to implement innovation processes.		✓	
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.		✓	
	To use the appropriate evaluation tools in complex decision-making situations.		✓	
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	✓	✓	✓
	To act confidently and effectively in social (including intercultural) contexts.	✓	✓	✓
	To lead production units and teams with goal orientation.		✓	
	To design digitally supported interaction and cooperation processes.		✓	✓
Self-competencies	To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action.		✓	
	To act self-determined and self-organized.	✓	✓	✓
	To act on the basis of one's own open mindedness and creativity.	✓	✓	✓
	To design and implement your own lifelong learning.		✓	✓

The xCPS platform offers the possibility to create cyber-physical systems from scratch for different purposes. Students can analyse specific features of a cyber-physical system, investigating its performance and capabilities. The platform supports activities that enable the analysis of the whole cyber-physical systems life cycle. SysLCM and Skyrats platforms support mostly the development of exploring activities in which students can grasp the complexity of cyber-physical systems and learn how to design these systems. Table 22 details which competencies related to cyber-physical systems can be addressed in each platform.

Table 22 - Competencies for cyber-physical systems engineering addressed in each platform

Category	Subcategory	Description	SysLCM	xCPS	Skyrats
Technical knowledge and skills	General	Solid foundations together with multidisciplinary awareness.		✓	
		Broad knowledge and skills of multiple areas of engineering expertise.		✓	✓
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	✓	✓	✓
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.		✓	✓
		Computing for the physical world: sensors, actuators, embedded systems.	✓	✓	✓
		Discrete and continuous mathematics.		✓	
		Cross-cutting application of sensing, actuation, control, communication, and computing.		✓	✓
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.		✓	✓
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	✓	✓	✓
	Non-functional characteristics of cyber-physical systems	Security and privacy		✓	✓
		Interoperability		✓	
		Reliability and dependability		✓	
		Power and energy management		✓	✓
		Safety		✓	✓
		Stability and performance		✓	✓

		Human factors and usability		✓	✓
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	✓	✓	
	Engineering	Engineering Process		✓	
		Industrial automation, plant modeling.		✓	✓
		Statistical methods and mining techniques		✓	
		Physics	✓	✓	✓
	Business and humanities	Project management		✓	
		Antropoly, sociology			
		Economics		✓	
		Legislation			
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.		✓	
		Collaboration with customers.		✓	
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.		✓	
		Presentation	✓	✓	✓
		Technical writing	✓	✓	✓
Attitudes		Flexibility to manage rapidly evolving technologies.		✓	
		Definition as well as solving problems.		✓	✓
		Analytical skills		✓	✓
		Creativity		✓	✓
		Entrepreneurship		✓	

	Critical thinking and critical attitude towards technological developments.		✓	
	Cross-disciplinary thinking		✓	
	Lifelong learning		✓	✓

The platforms can support remote activities in different ways. The SysLCM platform was developed as a remote educational platform for the development of hands-on activities 24/7 through the RESTful API implemented.

The Skyrats platform can not support the development of physical projects remotely. During the pandemic, students had to design and test their projects of embedded systems using virtual environments, such as development tools and simulation software. Despite this, the interdisciplinary center in which the platform is located has infrastructure, such as sensors, robust server, high-speed network, safe cage for testing drones, and physical space, that can facilitate the design and implementation of a remote lab project for teaching and learning of embedded systems design.

The xCPS platform was developed for on-site activities. It can also be used in its virtual environment on any computer with sufficient processing power. Although the platform has sensors, control software, simulation environment, remote communication and actuators that could enable its remote use, there are concerns about the occurrence of unsafe situations. Technically, it would be possible to control it remotely through the existing API.

4.5 Concluding remarks

The case studies examined the design and development of educational platforms that focussed on addressing digital technologies in engineering. The analysis showed that small size platforms can be adopted in courses for the development of hands-on activities, which enable students to acquire multiple competencies related to industry 4.0 and cyber-physical.

5 GUIDELINES FOR THE DESIGN OF CYBER-PHYSICAL SYSTEMS REMOTE LABS

This chapter presents guidelines for the design of remote labs that aim to support the development of practical activities related to teaching and learning of cyber-physical systems in engineering courses. The guidelines are based on the literature review and analysis about teaching industry 4.0 and cyber-physical systems in engineering education, which are presented in Chapter 2, and the conduction of case studies of educational platforms developed for teaching concepts and technologies related to these topics, which are detailed in Chapter 4.

Cyber-physical systems is a broad knowledge field that involves multiple engineering disciplines, humanities and social sciences, and business and project management. These systems can be implemented as an engineered solution in a wide variety of contexts, such as medicine, agriculture, ecology, aviation, smart city, defense, and manufacturing. In this sense, engineers should learn how to design cyber-physical systems for different purposes taking into account an extensive collection of requirements that includes physical and computational limitations, users' demands, costs, and legal and ethical issues.

Remote educational platforms are essential tools for engineering education in face of industry 4.0 and the uncertainties of the current pandemic. The use of remote platforms allows students to conduct hands-on activities safely, avoiding the spread of disease during critical periods. Learning how to make and control processes remotely is a fundamental experience for engineering students to develop competencies related to the industry 4.0. Besides that, the implementation of a network of remote educational platforms enables the sharing of resources among institutions, democratizing the access to advanced tools and best learning practices. It is fundamental for countries such as Brazil which has continental dimensions and difficulties to provide advanced resources to all Brazilian universities. Time flexibility is another important characteristic of these tools that permit students to meet each other for performing experiments at different points in time.

The first step of the cyber-physical systems learning path consists in the construction of the conceptual understanding. Students should grasp the complexity of these systems and reflect about the potential application of this technological concept in different contexts as an engineered solution. A learning environment in which students can explore cyber-physical systems and industry 4.0 technologies enhances the successful completion of this step. The environment should include a real case of a cyber-physical system and allow students to interact with it. Thus, it is possible to stimulate the curiosity and develop interest in investigating cyber-physical systems from different perspectives: the structure of a cyber-physical system; its general behavior; how its elements are integrated; how it reacts to changes in its external environment; which advanced technologies can be used; how to control it remotely; how to collect, process and interpret data.

After understanding the concept through inquiry-based learning activities, students should learn how to design an engineered solution based on cyber-physical systems. In this step of the learning path, the most important point is to learn methods and techniques that can be used for designing a technological solution from scratch. At this point, students should be able to analyse the context of a problem, identify stakeholders, define requirements, create solutions, and select a final design solution. Different approaches can be used for this purpose, one of the most adopted in cyber-physical systems courses is the MBSE. This step is strongly linked to the development of competencies related to the systems lifecycle management and product design and development process. Exploring a case of a cyber-physical system can support the understanding of the steps involved in the design and development process. It is important to have a virtual library in which students can investigate archives, models, decisions, reports, sketches, and blueprints that show the whole lifecycle of the system.

The implementation of the final solution may require technical background in multiple engineering disciplines, such as automation and control, computing, sensors, software, communication, and dynamic systems. Hence, the formation of multidisciplinary groups is strongly recommended for the design and implementation of cyber-physical systems that require broad knowledge and skills of multiple areas of expertise. This strategy is also important for the development of technical, social and self-competencies related to the industry 4.0 and cyber-physical systems. Engineers should be able to work, communicate and collaborate in multidisciplinary contexts.

Cyber-physical systems have two main dimensions: physical and cyber. It is possible to model, design and test a solution based on cyber-physical systems using virtual environments, such as development tools and simulation software. However, the complete implementation and validation of a solution requires the use of physical elements. Thus, a physical platform in which students can construct cyber-physical systems for different purposes is essential. This platform should be flexible in order to permit the exploration and development of a wide range of solutions involving multidisciplinary groups. The flexibility consists in allowing the implementation of different configurations of systems. The xCPS case at Eindhoven University is an example of a flexible platform for the performance of learning and research activities in cyber-physical systems. The platform emulates an industrial environment in which it is possible to investigate and propose a wide range of solutions and problems related to industry 4.0 and cyber-physical systems. This characteristic provides professors the freedom to select different problems and industrial cases for the development of course projects.

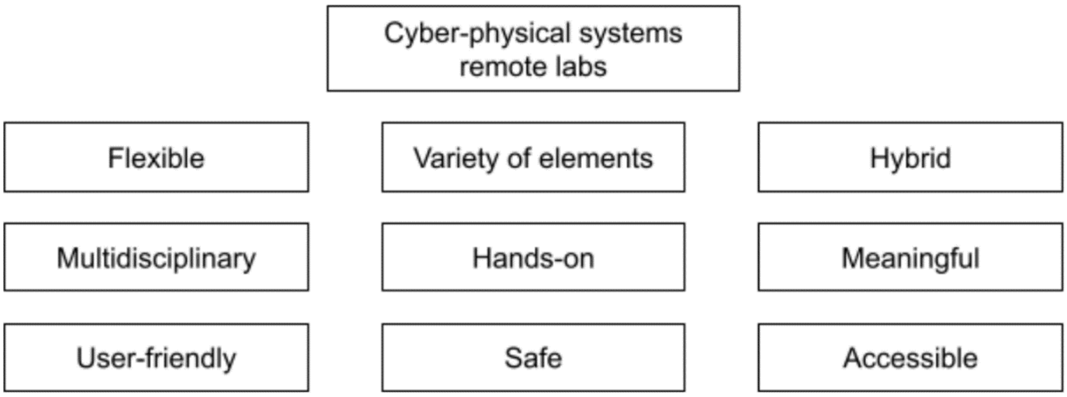
The platform should be an environment in which students can implement, test and validate cyber-physical systems. In this way they have the opportunity to acquire knowledge, skills and competencies in all the steps of the cyber-physical systems development cycle. Through experiencing the whole development cycle it is possible to achieve the most common learning objectives related to cyber-physical systems in engineering education, which are listed in Section 2.6.1. Furthermore, this approach is also strategic for the development of the key competencies for cyber-physical systems engineering.

The integration of the physical and cyber dimensions of a cyber-physical system demands hands-on activities that are difficult to perform in a remote environment. The construction of the physical subsystem, which can consist of single board computers, sensors, actuators, control boards, communication devices, and power supply, requires face-to-face activities. However, these activities can be carried out by robots or lab technical assistants. The use of robotics to overcome this limitation increases the implementation and maintenance costs of the lab structure, but it ensures high availability. Some students can act as lab technical assistants. In this task they should implement the physical subsystem designed by other students who can not access the lab resources on-site. It is fundamental in cases of sharing of labs, allowing students from other regions or universities to use all lab resources.

These solutions allow students and professors from other institutions or regions to use the platform for the development of complete cyber-physical systems. In the case of the host institution, the complete implementation and validation of cyber-physical systems can be addressed by the adoption of a hybrid learning approach. The implementation of remote platforms in engineering education is also an important strategy to ensure full accessibility for students with disabilities.

Figure 12 depicts the main features that the design of cyber-physical systems remote labs should follow in order to provide an effective and usable learning environment for engineering students.

Figure 12 - Main features for cyber-physical systems remote labs



5.1 Concluding remarks

The guidelines explained in this chapter form the basis of the design of remote educational platforms for cyber-physical systems in engineering courses. These indicate the main features that should be included as requirements in the design of the platform.

6 CYBER-PHYSICAL SYSTEMS REMOTE LAB PROOF OF CONCEPT

This chapter presents the development process of a proof of concept of a cyber-physical systems remote lab. It was conducted in accordance with the methodology described in Section 3.3 Proof of concept study. In this sense, this chapter was divided into four sections, each one dedicated to a specific phase of the study. Section 6.1 details the design concept. Section 6.2 describes the prototyping process. Section 6.3 indicates the tests that were carried out to assess the design concept. Section 6.4 analyses the design concept.

6.1 Design requirements

The design conceptualization was based on the guidelines for the development of cyber-physical systems remote labs presented in Chapter 5. The use of open-source platforms was one of the most important requirements adopted in the selection of design elements in order to create a solution concept that can be replicated and further developed by other researchers, developers, professors and designers.

One of the main guidelines for cyber-physical systems educational platforms is flexibility. It means that platforms should offer a learning environment in which students can design cyber-physical systems for multiple purposes. Thus, the platform should be formed by components that can be assembled and disassembled in different configurations easily. In this case, the use of elements designed for educational purposes, such as robotic and maker kits, can be a feasible solution.

The cost of implementation and maintenance is another important design parameter. A remote lab concept based on open-source and low cost platforms eases its use and replication by other institutions. It also allows the implementation of multiple educational platforms in a single lab that can reach enough amount for providing one to each project team in cyber-physical systems courses.

As cyber-physical systems are characterized by a deep integration of computational and physical components, the design concept should include computational, mechanical, electrical and electronic elements. It means that cyber-physical systems remote labs are an integration of microcontrollers, computers, sensors, actuators, mechanical structure, assembling components, electronic components, communication protocols, software, database, cloud, and communication modules.

The lab should offer an environment in which students can construct engineered solutions for real-world problems. Real-world situations based on the concept of meaningful learning can be associated with project-based learning strategies for teaching the concept and design of cyber-physical systems. Through the development of projects, students have the opportunity to use and experience advanced technologies related to industry 4.0 and cyber-physical systems, learning how to integrate multiple technologies in a single solution. These features can be achieved whether the combination of design elements allows the representation and simulation of productive activities such as manufacturing processes, materials transportation, warehouse systems, or logistic flow. These are also fundamental features for the development of inquiry-based learning activities.

In terms of access, the design concept adopted a hybrid approach in which some activities are conducted remotely through web interfaces and others on-site. The system can be controlled, reprogrammed, and tested remotely. A web interface should provide views of the system operation. However, the implementation of new configurations can be carried out just on-site by project members, teaching assistants or authorized students.

The design of the proof of concept was defined from a list of qualitative requirements, as shown in Figure 13, that ensures its potential applicability as an educational platform for teaching and learning cyber-physical systems. The design elements are presented in the following subsection. Figure 14 presents a block definition diagram of the design concept created in the SysML language.

Figure 13 - Design requirements diagram.

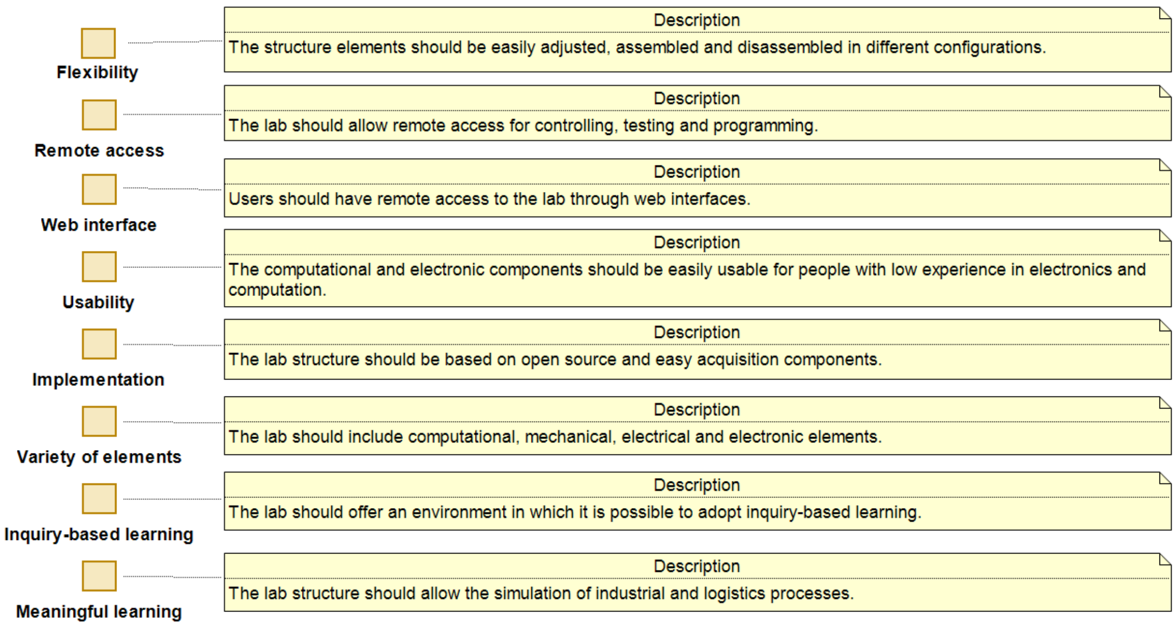
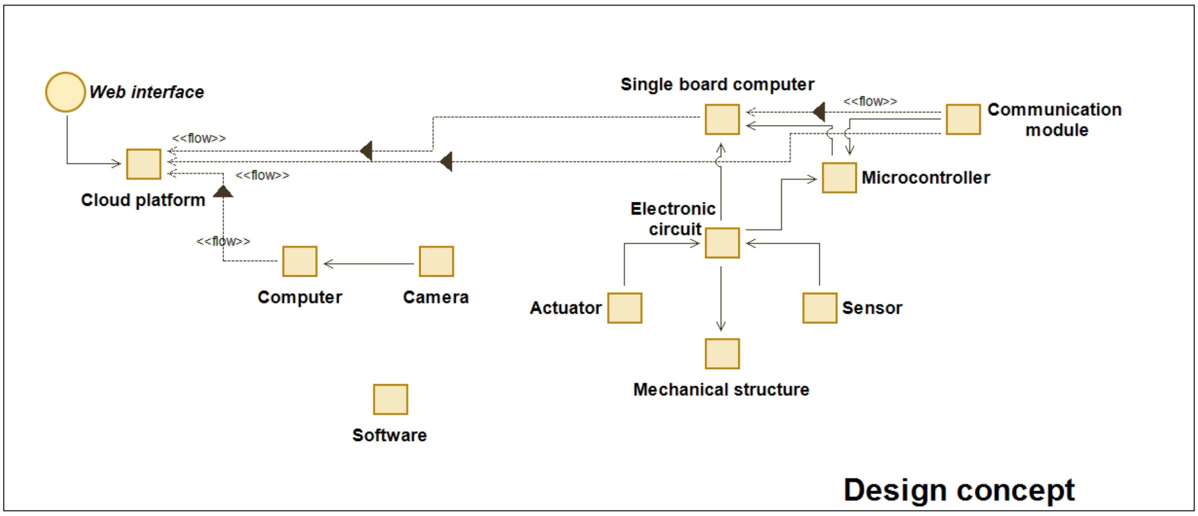


Figure 14 - Block definition diagram of the design concept based on SysML language.



6.1.1 Design requirements

The design elements used in this proof of concept were defined based on the design requirements and the analysis of available single board computers, microcontrollers, sensors and actuators at CITI-USP, research laboratory in which this master research was conducted. The present subsection describes the selection of design elements, presenting technical features of the main components. Table 26 summarizes the list with all components adopted.

CITI-USP is recognized as a research and development center of open platforms for internet of things applications. It hosts the Caninos Loucos Program that develops and manufactures open single board computers and microcontrollers aiming to create a community of developers for the application of technologies based on internet of things in the Brazilian industry, promote learning by doing process for teaching programming and digital technologies in basic education, and disseminate electronic learning embedded in universities and vocational schools (CANINOS LOUCOS, 2022). Single board computers developed and manufactured by the program were adopted in the INSPIRE pulmonary ventilator, which was created in an emergency context to supply the Brazilian health system demand due to the COVID-19 pandemic. The design concept incorporated the Labrador 32 bits board and the Pulga core V2.0 microcontroller, both designed and manufactured by the program.

The Labrador 32 bits is an open single board computer (SBC) that is formed by a combination of two boards, the core board, a small size board that contains the central processing unit (CPU), graphic central unit (GPU), power management unit (PMU), and memory, and the base board, a board in which the core board is placed and provides a set of communication interfaces (CANINOS LOUCOS, 2022). The SBC runs Debian 10, a Linux operating system. Figure 15 shows the base and figure 16 presents the core board. Table 23 describes the technical specification of the Labrador.

Table 23 - Specification of the Labrador 32 bits single board computer

Core board V2.0	
CPU	32-bit quad-core ARM® Cortex™ 1,3GHz A9R4 CPU (ARM v7 instruction set)
GPU	Imagination PowerVR SGX544. Supports: OpenGL-ES 1.1 and 2.0, OpenGL 1.2.1, OpenCL 1.1
Memory	2 GB DDR3 SDRAM 16GB eMMC
Operating system	Debian 10 Linux Kernel 4.14.13 32-bits
PMU	ATC2306C – Power management and audio subsystem
Video	1080p@60fps supports video encoding (including H264, H263, MPEG-4)
Expansion	204 pins DDR3 SODIMM connector (male)
Button	Alternate Dual-Frequency Ultrasound (ADFU)
Base board M V1.0	
Storage	MicroSD Card Slot SD/SDHC/SDXC

Ethernet	10/100Mbps (RJ45)
Wireless	Wi-Fi 802.11 b/g/n 2.4GHz Bluetooth 4.0 1 x infrared receptor (38kHz)
USB	1 x HDMI 1.4 (type A), up to 1920×1080@60Hz 1 x LVDS-DSI para LCDs, up to 1920×1080@60Hz 1 x CVBS PAL/NTSC (PJ342 3,5mm)
Display	HDMI output Analog stereo output (PJ342 3,5mm) I2S input/output Embedded microphone
Audio	HDMI output Analog stereo output (PJ342 3,5mm) I2S input/output Embedded microphone
Camera	1 x 8 bits parallel interface
LED	1 x 8 bits parallel interface
Buttons	1 x on/off 1 x reboot 1 x programmable
Power	5~12V @ 3W
Expansion	204-pins SODIMM connector (female) 40-pin header: 28 GPIOs (compatible with Raspberry Pi / supports UART, I2C, SPI, PWM and I2S) ADC input
Debug	UART

Source: CANINOS LOUCOS (2020)

Figure 15 - Inquiry-based learning framework.

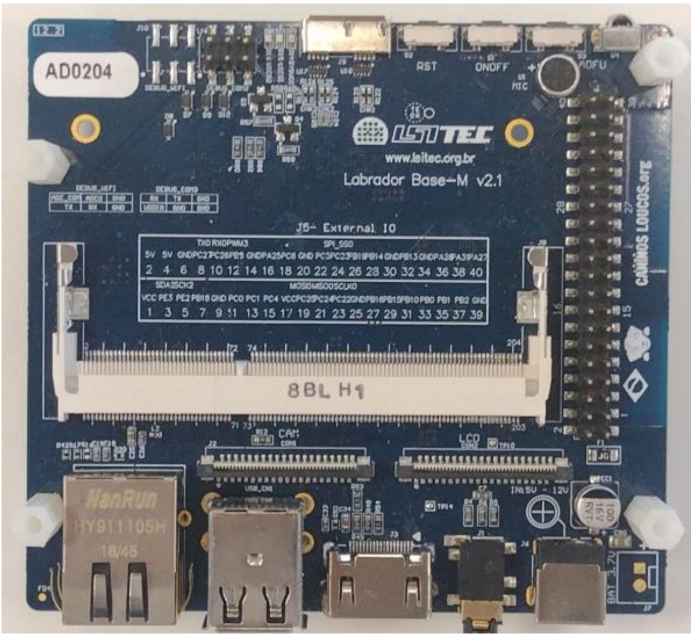


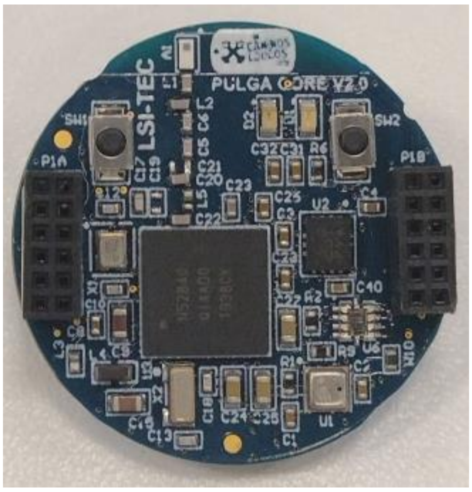
Figure 16 - Core board of the Labrador single board computer

The Pulga core is a microcontroller with sensors that allows measuring temperature, light/ultraviolet, humidity, pressure, acceleration, rate of rotation, and strength of magnetic fields. Due to its small dimensions, approximately the size of a quarter dollar coin, the board is classified as low power (CANINOS LOUCOS, 2022). It supports Bluetooth 5.0, enabling connection between multiple Pulgas. The operating system is compatible with Mbed. Figure 17 presents the Pulga and table 24 details its technical specification.

Table 24 -Specification of the Pulga core

Core board V2.0	
CPU	ARM Cortex-M4F
Disk	1024 kB
RAM	256 kB
Wireless	Bluetooth 5.0 / Bluetooth Mesh
Security	Crypto Acceleration (ECC, AES, SHA)
Peripherals	I2C, I2S, SPI, UART, USART, GPIO Light/UV sensor, 9-axis sensor (Gyroscope, Accelerometer, Magnetometer) and Environmental sensor (Temperature, Humidity, Pressure)
LED	2 x programmable (Reg/Orange)
Buttons	2 x programmable
Energy	1~6V with harvesting capability
Expansion	24 I/O pins (Coreboard) 58 I/O pins (Module)
Debug	SWD
Operating System	Mbed compatible

Figure 17 - Pulga core microcontroller



In terms of mechanical elements, the design included a Tank Mechanical Kit designed and manufactured by Open-Source Electronics Prototyping Platform (OSEPP), which is a Canadian company specialized in Arduino compatible products such as robotic kits, mechanical parts, sensors, shields, and other components. The company also developed an Integrated Development Environment (IDE) using a graphical block system to ease the creation of projects with Arduino. The kit consists of a small platform for the creation of robotic projects using Arduino. Its design was inspired by tank vehicles used in the exploration of regions with different terrain conditions. It is composed of 9V DC motors, wheels, chassis, rubber belt, and assembling components.

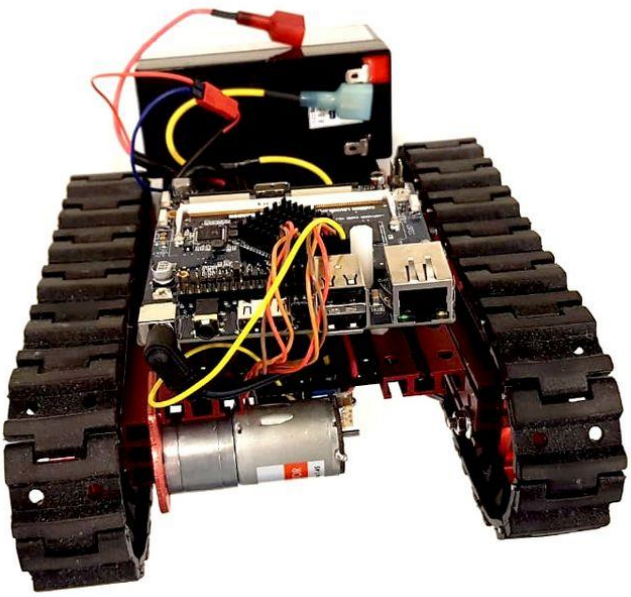
A Labrador board is used as a central control unit in the tank vehicle. A dual H-bridge motor driver based on the L298N chip, which accepts standard transistor-transistor logic (TTL) levels and drives DC motors, is the motor driver module. A lead-acid battery is the power supply of the system. Jumpers and connectors are used for connecting the system components. Figure 18 shows the system assembled. Appendix E includes instructions for assembling the vehicle.

LEDs, buzzers and micro servo motors were included as actuators in the lab concept due to the ease of acquisition and use. Light dependent resistor (LDR), HC-SR04 ultrasonic distance sensor, USB camera, and DHT11 temperature and humidity sensor are also added to the design concept for increasing the availability of sensor components.

Arduino Uno was added as an alternative microcontroller board, which is based on the ATmega328P and has 14 digital input/output pins. Table 25 summarizes the main features of Arduino UNO.

The open-source single-board microcontroller NodeMCU ESP8266 was adopted for connecting different objects using Wi-fi protocol, while the HC-05 Bluetooth module was used to provide Bluetooth connection to the Arduino UNO. These components can be used as elements for the development of multiple projects based on cyber-physical systems concept, adding flexibility to the lab concept. This also enables the analysis of interoperability and communication protocols between different platforms.

Figure 18 - Tank vehicle controlled by Labrador board



Source: CANINOS LOUCOS (2020)

Table 25 - Technical features of the Arduino UNO

Arduino UNO based on ATmega328P microcontroller	
Operating voltage	5V
Digital I/O pins	14 (of which 6 provide PWM output)
DC current per I/O pin	20 mA
Flash memory	32 KB of which 0.5 KB used by bootloader
Clock speed	16 MHz

Source: ARDUINO (2022)

The ThingSpeak platform was used for the remote communication between users and lab devices. It is an open-source platform that establishes the connection among multiple devices through the internet, also allowing the aggregation, visualization and analysis of data in the cloud (THINGSPEAK, 2022). It was used in association with the Heroku Cloud Platform that can be used for implementing and operating applications entirely in the cloud. Heroku was the platform selected for the implementation of the remote lab web interface.

A camera is used for the visualization of the lab devices in real time through the Youtube streaming platform that was incorporated in the web interface developed.

Table 26 - Design elements of the cyber-physical systems remote lab proof of concept

Class	**Design element**
Microcontroller	Arduino UNO
	Dual H-bridge motor driver based on L298N
	Caninos Loucos Pulga core V2.0
Single board computer	Caninos Loucos Labrador 32 bits
Communication module	NodeMCU ESP8266
	Webcam
	Computer
	HC-05 Bluetooth module
Web interface	Heroku cloud platform
	Youtube broadcast platform
Cloud	ThingSpeak platform
Sensor	DHT 11 temperature and humidity sensor
	Light dependent resistor
	Caninos Loucos Pulga core V2.0
	HC-SR04 ultrasonic distance sensor
	USB Camera
Actuator	DC motor
	LED
	Buzzer

	Servo motor
Mechanical structure	OSEPP tank mechanical kit
Power system	Lead-acid battery (12 V and 4,5 Ah)

6.1.2 Prototype design

Based on the intended requirements, the prototype design was created by the integration of available design elements, listed on Table 25, aiming to implement a flexible platform that can emulate an industrial environment. In this sense, the prototype design sought to represent an industrial warehouse in which a smart vehicle can perform multiple tasks. The smart vehicle can be controlled and reprogrammed remotely, allowing users to redesign its software. In addition to the smart vehicle, the system can have other devices, such as controllers, sensing and actuator modules, that can interact with each other in the performance of different tasks. Users can observe and analyse the behaviour of the whole system remotely, accessing data collected by sensors. As the smart vehicle is the unique component that allows remote reprogramming, other devices included in the system should be reprogrammed by professors, teaching assistants, authorized student or laboratory technicians, as well as the physical reconfiguration of the system. In this sense, the proof of concept adopted a hybrid approach in which some activities related to the operation of the platform involve direct action of people. These features ensure the achievement of requirements listed on Figure 13 (design requirements diagram).

6.2 Prototyping

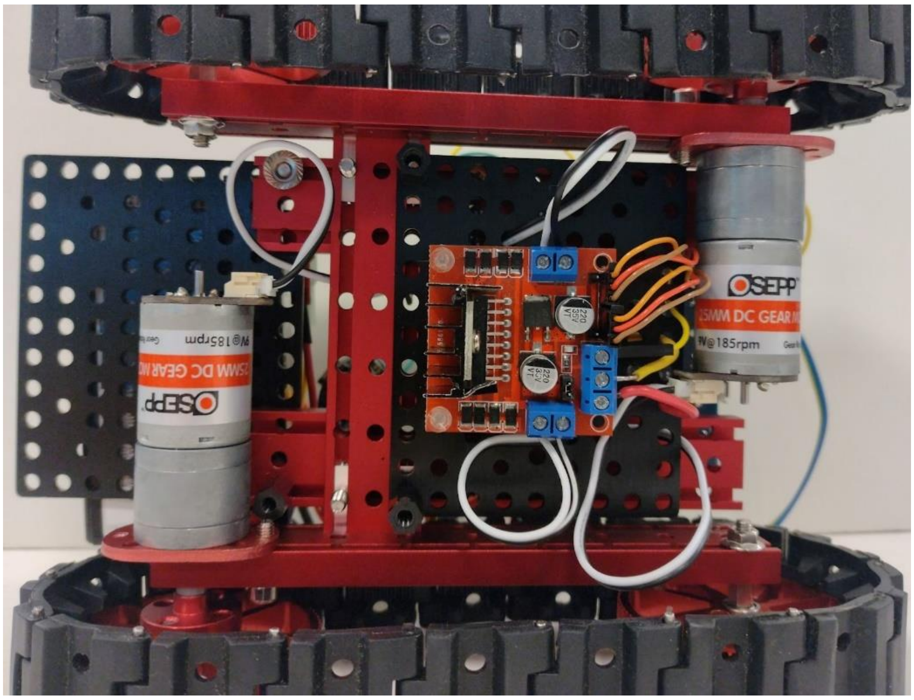
This phase sought to implement a functional prototype that could demonstrate and validate the concept of a flexible educational platform used in a hybrid way (remotely and on-site) for developing competencies related to cyber-physical systems.

The first step consisted in assembling electrical and mechanical components of the smart vehicle. The chassis was assembled with two DC motors, a battery module, a dual H-bridge motor driver based on L298N, a Labrador 32 bits and a Pulga core.

Jumpers, connectors and fixing screws were used in the assembling process. The battery module consists of a rechargeable lead-acid battery.

The DC motors were directly connected to the dual H-bridge motor driver which in turn was connected to the Labrador and battery module, which is shown in Figure 19. The dual H-bridge gets voltage reference and control signals from Labrador. Control signals are used for controlling each DC motor and its rotational speed. The control of rotational speed can be carried out through the pulse width modulation (PWM) technique.

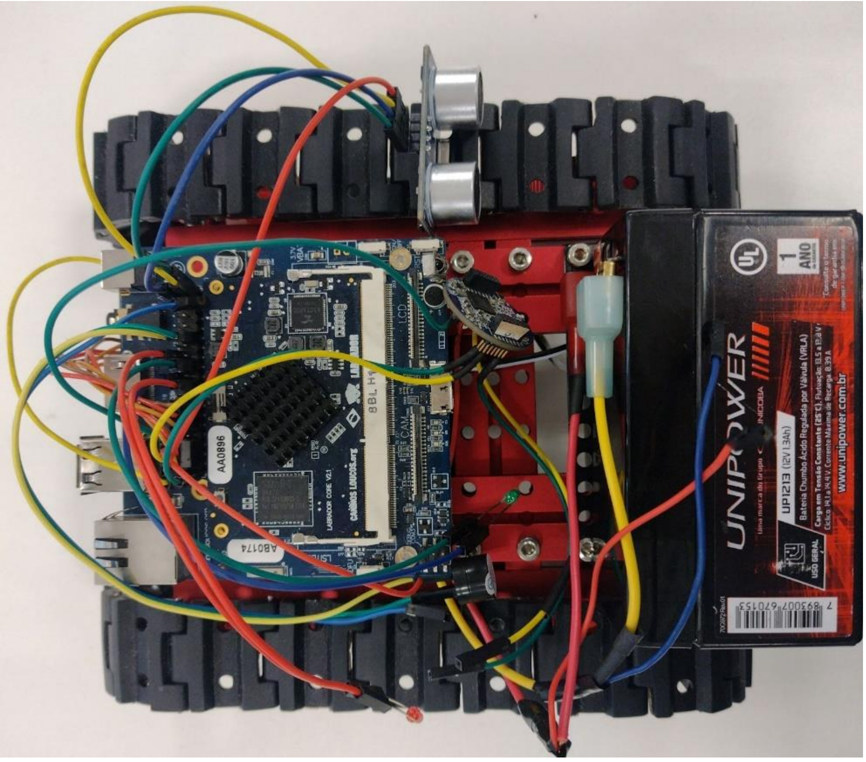
Figure 19 - DC motors and the dual H-bridge motor driver assembled in the smart vehicle



PWM technique is a digital modulation that operates two signal levels (*on* - which is 1 in binary code - and *off* - 0). It consists in controlling how long the digital signal is "*on*" in each period, a fixed length of time. Using this technique in electrical circuits, it is possible to control the average voltage in each period. As the rotational speed of a DC motor is directly proportional to the supply voltage, PWM can be applied to control the rotational speed of DC motors, which are actuators widely used in industrial systems.

The Labrador board is the control center of the vehicle. All the sensors and actuators inserted in the vehicle were connected to the Labrador, most of these plugged into the general purpose input/output (GPIO) pins of the board. It contains the core software of the vehicle and establishes the communication between the vehicle and external devices. Users can control and reprogram the vehicle remotely using the secure shell protocol (SSH) to connect with the Labrador. Figure 20 presents the connections on the Labrador.

Figure 20 - Connections on the Labrador board in the smart vehicle



SSH is a network protocol that offers users a safe way to access a device in an open network. It uses the model client-server and encrypts the data using both private and public keys. The protocol uses a system of three-layers (BARRET; SILVERMAN; BYRNES, 2005):

- transport layer which establishes a safe and protected communication between server and client, during and after the authentication;
- authentication layer which communicates the authentication methods supported to clients. It also performs the authentication process of users;
- connection layer which manages the communication between devices after the conclusion of the authentication process.

Users can access the SSH using specialized tools such as Putty, which is a free and open-source software that emulates command terminals in Windows and Unix platforms and supports the communication of devices as SSH clients. Another way of accessing is to run a script in the operating system command-line for establishing the communication.

The HC-SR04 ultrasonic distance sensor was added to the vehicle in order to avoid collisions and measure the distance between the vehicle and other devices. The pulga core was included in the vehicle as a sensing module which is capable of measuring temperature, pressure and humidity of the environment. Controlling these parameters can be an essential activity for the management of some products in industrial warehouse systems.

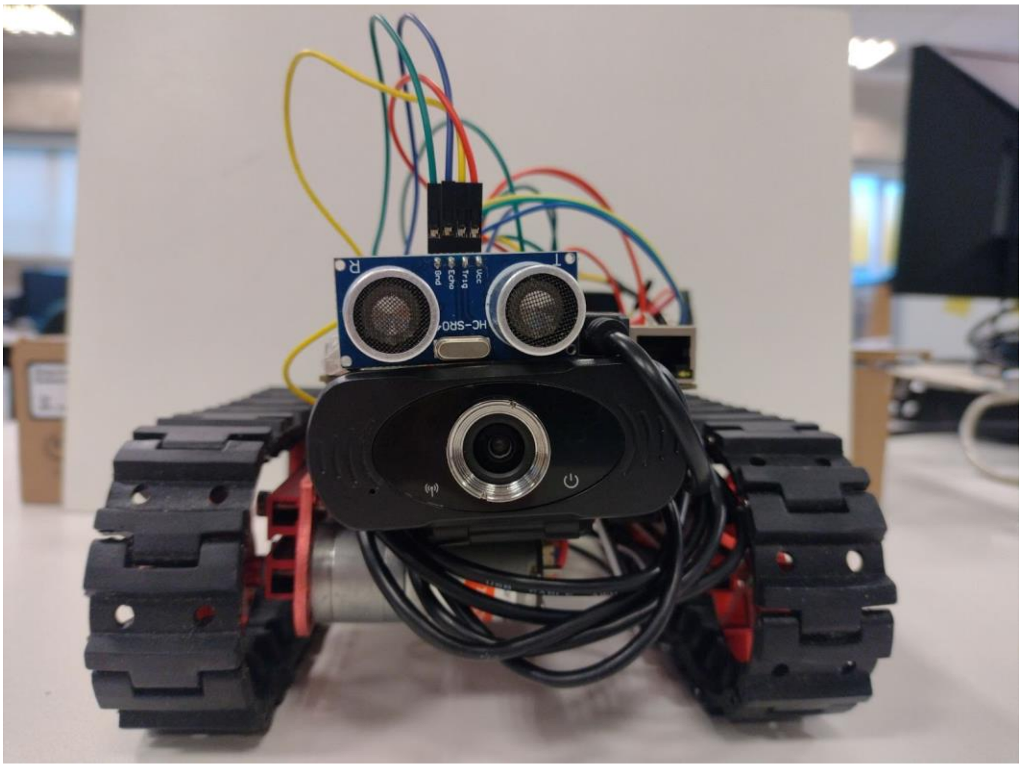
A USB camera was inserted in the vehicle as a sensor that enables the use and implementation of techniques related to artificial intelligence and computer vision. Using this sensor, the smart vehicle is able to scan quick response (QR) codes, recognize elements in the environment and allow users to observe the execution of tasks from a shop floor perspective. It was plugged into a USB port of the Labrador.

Two LEDs and a buzzer were included in the vehicle as actuators that enables the control system to show the vehicle operational status to the environment. These actuators are widely used in vehicles as signalling devices.

The connection between Pulga core and Labrador 32 bits was effectuated using the universal asynchronous receiver-transmitter (UART) protocol and GPIO pins. UART is a protocol used for the transmission and reception of serial data. It is based on a physical circuit that uses only two wires to transmit data without the use of clock signals, allowing the connection between two devices that should be configured for transmitting and receiving the same data packet structure. The Pulga was configured and programmed using the Mbed platform, which is an open-source development environment and operating system used for internet-connected devices based on ARM microcontrollers. New C libraries were built for the integration of these devices and then added to the vehicle control program.

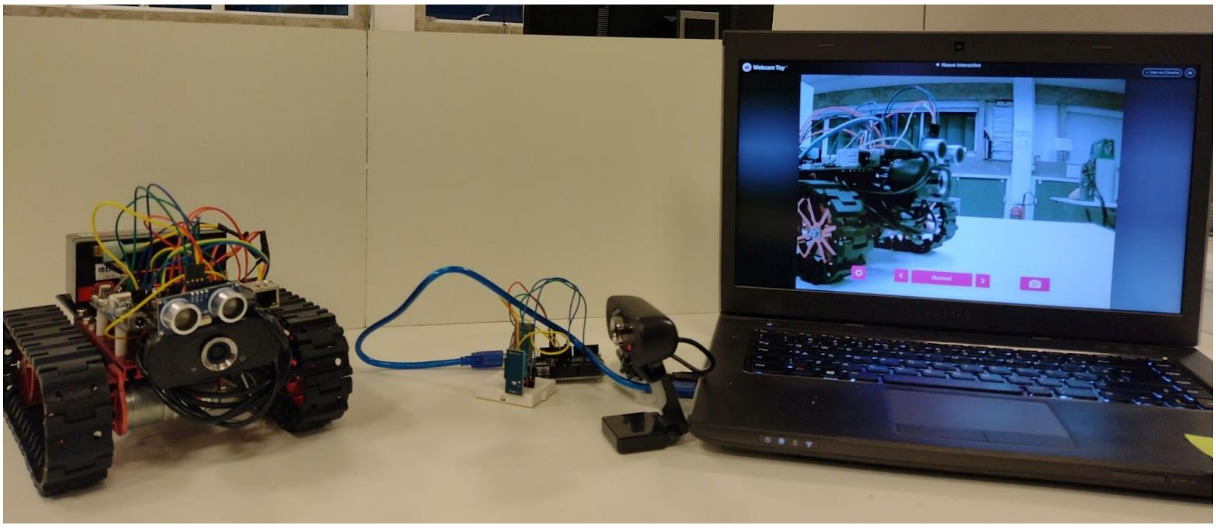
The configuration and programming of the operating system of the smart vehicle were carried out connecting the Labrador to a monitor, a mouse and a keyboard to facilitate the development process. The operating system adopted in the Labrador is Debian 10, which is free and open-source, supporting the development of a wide range of internet of things applications. The programming language adopted was C, which is a general purpose, procedural and compiled computer programming language. It is widely used in the development of systems applications for embedded systems. Appendix D includes the programs embedded in the Pulga Core and Labrador board. Figure 21 exposes the frontal view of the smart vehicle.

Figure 21 - Frontal view of the smart vehicle



The microcontroller adopted as an external device in the configuration of the prototype was the Arduino UNO board. A protoboard was used for the construction of an electronic circuit that included the DHT 11 temperature and humidity sensor and the HC-05 Bluetooth module. The idea behind the inclusion of this device was to simulate the communication between the smart vehicle and other machines in the warehouse system. The bluetooth module was used for wireless communication between Labrador and Arduino. The configuration of the Arduino was carried out using a computer and the Arduino IDE, which adopts C++ as the programming language. Figure 22 presents the components of the prototype assembled and working.

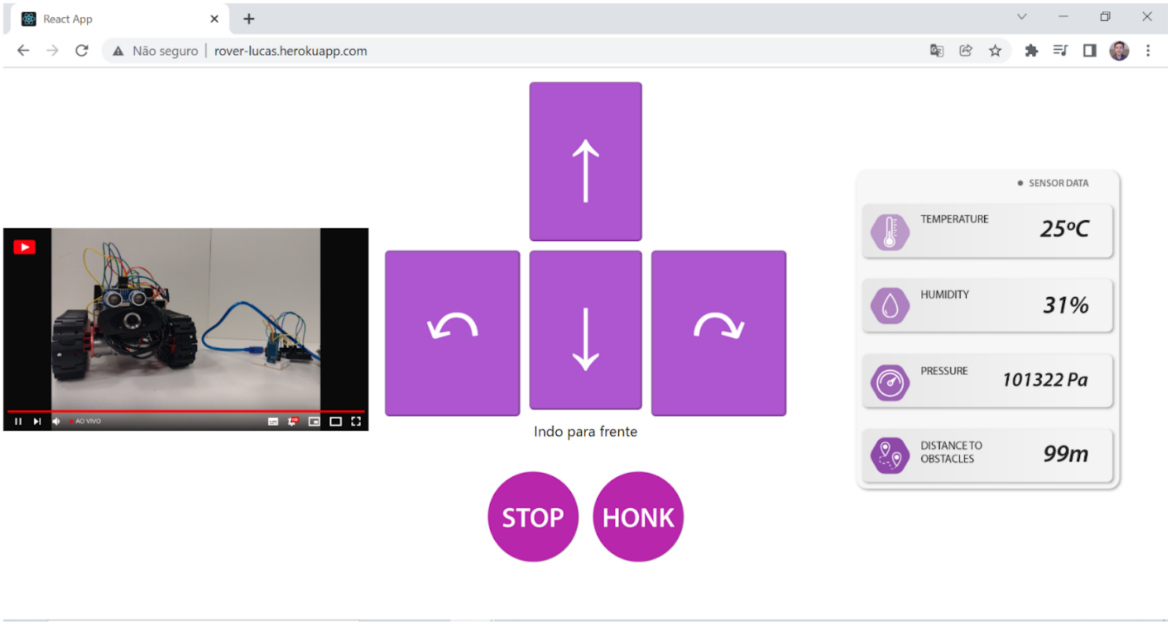
Figure 22 - Prototype of the cyber-physical systems remote lab



The web interface of the remote lab was developed in the Heroku platform using React, which is an open-source framework based on Javascript created for the construction of user interfaces, as presented in Figure 23. The ThingSpeak platform was configured as a gateway that receives data from the smart vehicle and transmits user commands to it. The web interface was integrated to the ThingSpeak and Youtube Broadcast platform to present the operational status of the experimental setup to remote users. A webcam was plugged into a computer connected to the internet for broadcasting the lab setup on Youtube. Users can send commands, such as “move forward”, “move backward”, “turn left”, “turn right”, “stop”, and “honk”, to the vehicle and read the data collected by the sensors on the interface. These platforms can be reconfigured easily for new configurations of the lab.

The account created in the ThingSpeak was for free users. In this mode, the platform limits the amount of data transmitted or received per unit time, establishing an interval of 15 seconds between two requests (get or post data). Thus, remote requests on the web interface had a delay of at least 15 seconds.

Figure 23 - Web interface of the cyber-physical systems remote lab



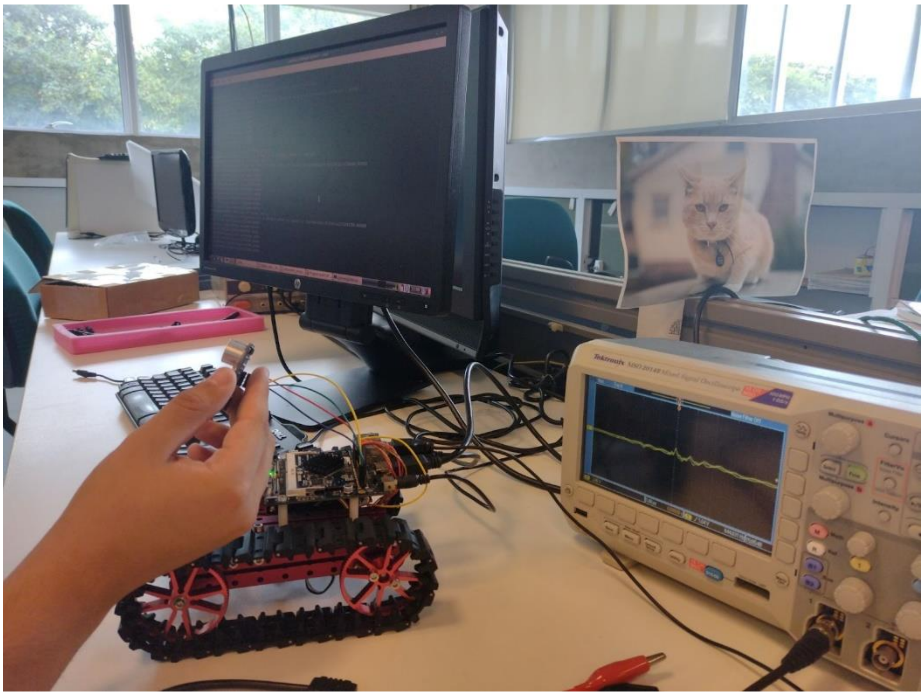
6.3 Prototype testing

The analysis of the prototype was based on functional tests and professor assessments. Functional tests were carried out during the prototyping phase. The functionalities included in the configuration of the prototype were implemented in several sequential steps. After the implementation of each step, a functional test was carried out to check whether the new function was running properly in the prototype. The prototype was adjusted frequently after each functional test to ensure the achievement of the intended functionalities.

Figure 24 shows a functional test performed after the integration of the HC-SR04 ultrasonic distance sensor in the vehicle. The test sought to check the precision level of the sensor operation before including its function to the main program of the vehicle.

The purpose of the assessment carried out by engineering professors was to identify which competencies related to industry 4.0 and cyber-physical systems could be addressed using the prototype as an educational platform and collect suggestions based on teaching experience for the further development of remote labs devoted to cyber-physical systems.

Figure 24 - Functional test performed during the implementation of the prototype



Five professors who teach courses related to digital technologies were invited to participate in this assessment. The size of the sample of respondents was decided based on books of usability testing written by researchers (NIELSEN, 1993) (PREECE; ROGERS; SHARP, 2002) (RUBIN; CHISNELL, 2008). These authors stated that this number of people is enough to observe problems and analyse the prototype in terms of the aims of its intended use. Selecting professors who have experience in teaching digital technologies was a refinement strategy for collecting specialized assessments. The participants are described in Table 27.

The presentation and demonstration session were performed individually, using Google Meet, between January 21th and 31st of 2022. The sessions were undertaken by this master’s student, as the researcher of this study, following the script described in Appendix A. Before the demonstration of the prototype, the researcher discussed with participants the panorama of cyber-physical systems in the industry and engineering education, describing the purpose of this research. The participants were free to ask questions and make comments during the presentation. Participants were instructed to critically analyse the prototype using the assessment form (Appendix B). They could fill the form during the presentation or after that, sending the filled form to the researcher on the same day of the presentation and demonstration session. The prototype analysis was based just on information included in this form by participants. This fact was mentioned by the researcher in the beginning of the session.

Table 27 - Description of the research participants

ID	Institution	City	Subjects	Engineering Courses	Years of experience as a teacher in engineering
P1	INSPER	São Paulo	Microcontrollers & Internet of Things, Programming Techniques, Software Lab, Software Lab, Nature of Design, and Co-Design Apps	Computer, Mechanical, and Mechatronics	8
P2	Universidade Federal do Amapá	Macapá	Distributed Systems, Graph Theory, Automata and Formal Languages, Compilers, and Scientific Research Methodology	Electrical	3
P3	Instituto Federal de São Paulo	Campinas	Electronics, Integrative Projects, and Final Project	Electrical and Electronics	19
P4	Instituto Federal de São Paulo	Bragança Paulista	Microcontrollers, Programmable Logical Devices, and Microcontrolled Systems	Control and automation	3
P5	Universidade Federal de São Paulo	São Paulo	Educational Design, Games, Virtual Reality, Research and Innovation, and Immersive Technologies	Environmental and Sanitary, and Production	5

The assessment form presented in Appendix B includes three sections: participant profile, prototype analysis, and general feedback. Participant profile collected information about the teaching experience of the professors. Prototype analysis was based on the competency framework, which was also used in the analysis of the case studies. General feedback was an open space to collect suggestions, criticisms and other comments.

During the presentation and demonstration session, the researcher kept an impartial and neutral attitude to avoid influencing the assessment process. The focus of the sessions was to present and demonstrate the prototype implemented as a proof of concept of a cyber-physical systems remote lab. The analysis and interpretation of the assessment tests were performed afterwards based on the procedures proposed by BARDIN (1977).

BARDIN (1977) proposed a set of communication analysis procedures that can be used for the processing of qualitative data obtained from interviews, lectures, documents or forms. This analysis allows the acquiring of knowledge related to the conditions of production or reception of messages based on inference. It consists of three steps: pre-analysis, data exploration and processing, and inference and interpretation. Based on this content analysis, the treatment of the forms sought to categorize the data in terms of competencies, educational approaches, and recommendations for further development. These recommendations were included in Section 7.1 Suggestions, which brings up directions for further development and research of remote labs dedicated to cyber-physical systems. The Forms filled by participants were fully included in Appendix C.

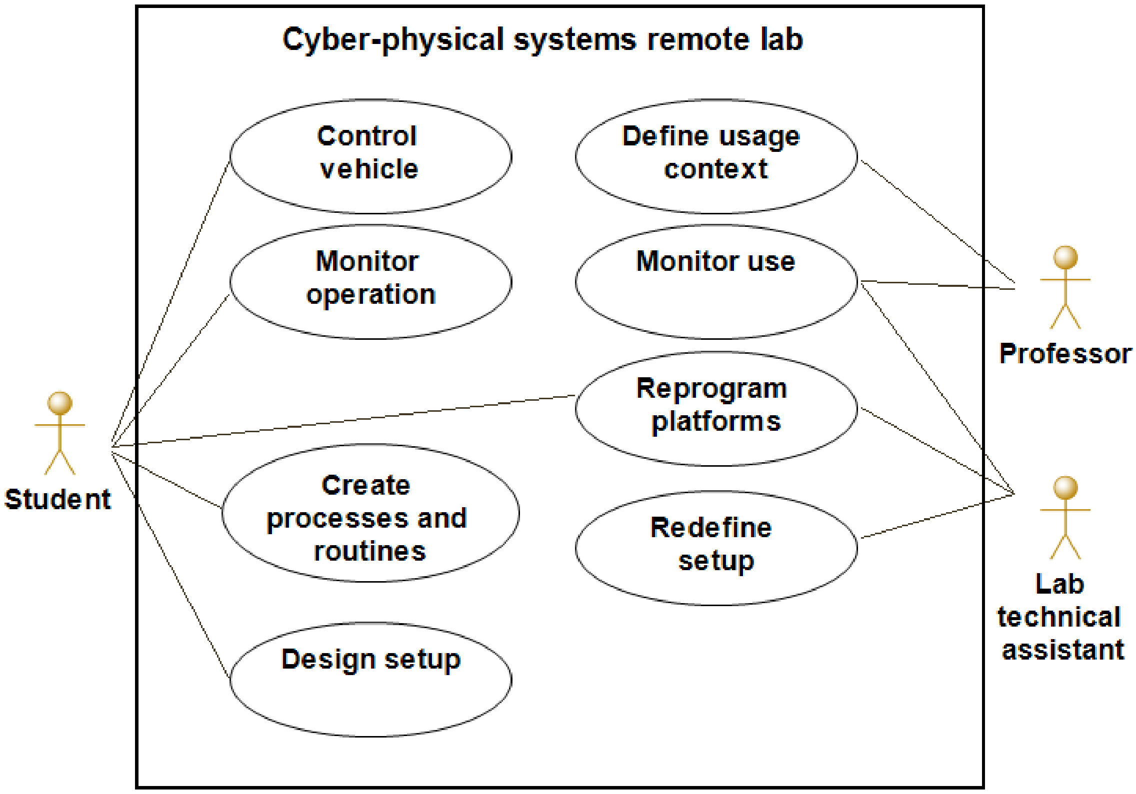
6.4 Prototype analysis

Functional tests demonstrated that the smart vehicle can be reprogrammed remotely using the SSH protocol. The integrated operation of the Pulga core and Labrador board was well succeeded, as well as the Bluetooth communication between Labrador and Arduino Uno. The Labrador was able to send requests and gather data from Pulga core and Arduino Uno. It was possible to control the smart vehicle, watch its operation in real time, and read the information provided by the sensors through the web interface. All design elements added to the experimental setup worked properly, which could emulate the operation of an industrial warehouse system.

Figure 25 depicts the use case diagram of the prototype using SysML language and based on the hybrid approach. The inclusion of a lab technical assistant, which can be a student with a background in embedded systems or cyber-physical systems, lets students redefine the setup and reprogram platforms that are not directly accessed via remote connection. Professors can monitor its use and define usage context.

Although the proposed experimental setup has not included all the design elements listed in Table 25, the inclusion of these components is essential to ensure flexibility and variety of elements, which open up different possibilities for the educational application of the platform. Users can find a wide range of reports about the use of these components on the internet, which ease up their application in different design configurations. The components obtained from the Caninos Loucos Program still require further information about their use in order to be more usable for people without a strong background in computer science. Most of the design elements are open-source, however the platforms adopted for remote communication between users and experimental setup are proprietary and have limitations in the free mode of use.

Figure 25 - Use case diagram of the prototype



Based on the content analysis, Tables 28 and 29 summarize the information gathered from the assessment forms filled by five engineering professors. Most of the professors indicated that the prototype can be used for the development of multiple competencies related to industry 4.0 and cyber-physical systems. They also have described different approaches for educational application of the prototype considering the competencies classified as applicable (“yes”).

The main educational approach indicated was the adoption of multidisciplinary project-based learning in specific contexts that seek to address technologies, models and concepts considered as fundamental for a course, such as digital twin, internet of things, software development, life cycle management, control, artificial intelligence, statistical models, and physical theories. Exploring the platform was also highlighted as an important strategy to stimulate students to construct knowledge and acquire experience in the combination of science, design, and creativity, which can be considered the core of engineering. Developing and managing project teams give the opportunity to address social competencies and attitudes. Furthermore, students can learn from each other specially in multidisciplinary teams.

Table 28 - Assessment of the prototype in terms of industry 4.0

PROTOTYPE ASSESSMENT			
COMPETENCIES RELATED TO INDUSTRY 4.0			
Category	**Competencies**	**Number of "yes" answers**	**Approaches that can be used with engineering students**
Technical competencies	To act and collaborate in interdisciplinary contexts.	5	Problem solving in interdisciplinary contexts. Development of projects with concepts of internet of things and artificial intelligence for multiple purposes. Modelling and designing setups. Exploring the prototype in different subjects. Integrative projects.
	To flexibly adapt business processes to changeable conditions to new technologies.	4	Using feedback in real time. Experimentation. Addressing innovative technologies. Projects related to entrepreneurship.
	To design IT processes in the context of production and to use IT components for human-machine interaction.	5	Interacting with indicators. Development of solutions including usability tests. Modelling processes. Development of projects. Stimulating the creation of innovative solutions based on digital technologies.
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	2	Performing experiments with different difficulty levels. Combination of problem based learning and contextualized learning.
	To establish a connection between a digital twin and its physical reality.	4	Development of solutions based on the concept of digital twin. Experimenting and implementing the concept of digital twin.
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the	4	Exploring the collected data.

	importance of algorithms and the management of sensitive data).		Developing studies on data treatment. Addressing the collection and treatment of data.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	4	Experimenting and observing different setups. Development of solutions from scratch, including functional and non-functional tests. Using programming and simulations. Analysis of functional requirements and system behavior.
	To initiate and to implement innovation processes.	5	Proposing interdisciplinary goals. Design of new features for the setup. Challenge based learning. Project-based learning. Development of new setups.
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	2	Solvings problems that involve entrepreneurial and security aspects. Addressing ethical issues in the work.
	To use the appropriate evaluation tools in complex decision-making situations.	3	Exploring tools and interacting with indicators. Assessing collected data and making decisions.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	2	Team work. Adopting a way of working similar to business environments.
	To act confidently and effectively in social (including intercultural) contexts.	3	Team work. Addressing ethical and social guidelines.
	To lead production units and teams with goal orientation.	2	Training teams in tasks of production. Project-based learning.
	To design digitally supported interaction and cooperation processes.	5	Experimenting and designing different setups. Development of projects by multidisciplinary teams using digital platforms. Exploring design concepts remotely.
Self-competencies	To realistically assess the value of one’s own subjective knowledge of experience and incorporate it accordingly into one’s own action.	4	Tasks including debugging and real-time feedback. Programming and testing new routines and procedures. Problem based learning. Brainstorming sessions. Validation of concepts.
	To act self-determined and self-organized.	4	Problem based learning, flipped classroom, and project-based learning. Addressing the PDCA cycle. Using guidelines for work, schedules, and work breakdown structure.
	To act on the basis of one’s own open mindedness and creativity.	4	Stimulating the design of new setups. Development of projects from scratch. Problem based learning. Exploring and testing concepts.

	To design and implement your own lifelong learning.	4	Experimentation and development of projects. Development of projects from scratch. Problem based learning. Experience sharing.

Table 29 - Assessment of the prototype in terms of cyber-physical systems

PROTOTYPE ASSESSMENT				
COMPETENCIES RELATED TO CYBER-PHYSICAL SYSTEMS				
Category	**Subcategory**	**Description**	**Number of “yes” answers**	**Approaches that can be used with engineering students**
Technical knowledge and skills	General	General Solid foundations together with multidisciplinary awareness.	4	Challenge based learning. Collecting data and exploring how the system converts “information” in “bits”. Integration of hardware and software components. Multidisciplinary project-based learning.
		Broad knowledge and skills of multiple areas of engineering expertise.	5	Exploring the environment and reflecting about its influence on the processes. Development of solutions involving multiple engineering disciplines. Integration of hardware and software components. Project-based learning.
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	5	Using ISO/NBR. Combination of product development process and challenge based learning. Project-based learning. Integration of hardware and software components.
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	4	Debugging tasks with different layer-levels. Developing solutions based on the concepts of internet of things and artificial intelligence. Addressing practices related to computer science and software engineering. Modelling and designing setups. Working with back-end and front-end applications.
		Computing for the physical world: sensors, actuators, embedded systems.	5	Challenge based learning. Collecting data and exploring how the system converts “information” in “bits”. Development of solutions from scratch. Modelling and designing setups. Working with sensors and actuators.

		Discrete and continuous mathematics.	4	Working with sensors that need an analog-digital converter. Modelling and designing setups. Addressing topics related to signal processing. Use of mathematical logic.
		Cross-cutting application of sensing, actuation, control, communication, and computing.	5	Working with sensors, actuators, microcontrollers, and single board computers. Developing multidisciplinary projects. Integration of hardware and software components. Understanding inputs and outputs for remote control.
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	5	Generating a priority-queue system as a task for students. Development of integrative solutions that include different technologies. Project-based learning. Integration of hardware and software components. Working with sensors, actuators, microcontrollers, and single board computers. Use of different programming platforms.
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	4	Free tasks in which half-part of the students have to “create a scenario” and half-part to solve it. Project-based learning in the context of product/service life cycle management. Integration of software and hardware components. Adopting life cycle management as the framework for the development of projects.
	Non-functional characteristics of cyber-physical systems	Security and privacy	3	Addressing tasks related to privacy and security aspects. Use of protocols.
		Interoperability	4	Using multiple platforms. Project-based learning. Learning community. Integration of software and hardware components.
		Reliability and dependability	3	Assessing these aspects in tasks. Using evaluation models in projects.
		Power and energy management	4	Assessing the life cycle and studying different types of supply energy systems. Addressing aspects of energy efficiency. Working with sensors and indicators for managing the energy supply.
		Safety	2	Addressing industrial and labor safety.

		Stability and performance	4	Assessing these aspects in tasks. Using evaluation models in projects. Use of sensors and indicators.
		Human factors and usability	4	Conducting usability tests. Using evaluation models in projects. Meetings for discussing and assessing these aspects in projects and solutions.
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	4	Using systems modelling languages for the description of the design. Training the use of tools for systems engineering. Adopting the systems engineering approach in the development of projects.
	Engineering	Engineering Process	5	Developing user interface XML for data collection and visualization. Project-based learning in the context of engineering processes. Exploring engineering tools. Design thinking.
		Industrial automation, plant modeling.	5	Addressing statistical control process tasks. Development of automation and industrial solutions. Exploring engineering tools.
		Statistical methods and mining techniques	4	Collecting and treating data. Exploring statistical techniques. Using tools for statistical analysis.
		Physics	4	Developing physical models for processes. Using software for physical analysis.
	Business and humanities	Project management	5	Evaluating costs, resources and time to complete tasks. Project-based learning. Use of work breakdown structure Team work.
		Anthropology, sociology	0	
		Economics	3	Evaluating costs, resources and time to complete tasks. Project-based learning. Development of business plans.
		Legislation	1	Analysis of requirements related to regulatory agencies and labor rights.
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	4	Multidisciplinary team work. Challenge based learning. Project-based learning. Collaboration with different labs located in other universities and regions.
		Collaboration with customers.	3	Team work. Challenge based learning.

			Defining different roles for the formation of teams. Usability and validation tests.
	Communication within heterogeneous interdisciplinary multicultural teams and with customers.	3	Multidisciplinary team work. Use of web platforms for follow up projects and feedback.
	Presentation	5	Classroom symposium with external teachers. Requiring presentations.
	Technical writing	5	Classroom symposium with external teachers. Requiring reports.
Attitudes	Flexibility to manage rapidly evolving technologies.	4	Project-based learning. Problem based learning. Integration of software and hardware components. Use of agile methodologies.
	Definition as well as solving problems.	5	Team work. Challenge based learning. Project-based learning. Problem based learning Integration of software and hardware components.
	Analytical skills	4	Problem based learning. Project-based learning. Integration of software and hardware components. Ideation sessions.
	Creativity	4	Team work. Challenge based learning. Project-based learning. Problem based learning. Development of solutions for different problems. Integration of software and hardware components. Prototyping.
	Entrepreneurship	4	Challenge based learning. Project-based learning. Problem based learning. Integration of software and hardware components. Development of business plans.
	Critical thinking and critical attitude towards technological developments.	4	Challenge based learning. Project-based learning. Problem based learning. Integration of software and hardware components. Brainstorming sessions.
	Cross-disciplinary thinking	4	Development of solutions in multidisciplinary contexts. Project-based learning. Problem based learning. Integration of software and hardware components. Mentoring program.
	Lifelong learning	4	Project-based learning. Problem based learning. Integration of software and hardware components. Learning community.

The findings of the tests highlight that the cyber-physical systems remote lab proof of concept could meet all the intended requirements. The design concept was able to include most of the competencies related to industry 4.0 and cyber-physical systems, which validates the proof of concept in terms of its potential as an educational platform for instructing engineering students in courses dedicated to the introduction and design of cyber-physical systems. It also indicates that further development of this concept can contribute to the creation of a flexible laboratory that can be easily replicated and shared among institutions.

6.5 Concluding remarks

The proof of concept study examined the design and development of a remote laboratory that seeks to provide a learning environment in which engineering students can explore, experiment and design cyber-physical systems. Engineering professors have assessed the prototype in terms of competencies that can be addressed by adopting it in engineering courses. The findings highlight the potentiality and feasibility of the concept, which can be further developed considering different contexts and focusing on specific technologies related to industry 4.0.

7 CONCLUSIONS

Cyber-physical systems is an inherently multidisciplinary field that requires the integration of theories, concepts, models, techniques, and technologies from different science and engineering disciplines for the development of advanced systems, which are characterized by the combination between cyber (computing, communication, and storage) and physical (sensor and actuator) elements. In this sense, the use of learning environments in which students can explore concepts, experience technologies, and design systems is fundamental for enabling them to construct knowledge and acquire competencies in cyber-physical systems. The competency framework proposed in this work indicates that industry 4.0 and cyber-physical systems demand the development of multiple laboratory activities. The adoption of a set of educational strategies and approaches was pointed as fundamental for addressing multiple competencies.

Although the technologies involved in cyber-physical systems are mainly concentrated in electrical, electronic and computer engineering, understanding what is and how to design this new generation of systems is essential for all engineering disciplines. The development of engineered solutions is a common task for all engineers and the application of digital technologies is widespread in almost all areas. This research sought to develop an educational platform that can be used for this purpose. The design elements are open-source and easy to use, which improve the usability of the platform. As the platform includes elements that can be used for exploring different concepts, models, and technologies, it offers multiple application possibilities for other courses that address technologies and concepts related to industry 4.0, such as internet of things, artificial intelligence, programming, product development process, robotics, automation and control, and big data. These possibilities were pointed out by the engineering professors who have assessed the developed platform.

Flexibility is one of the most important guidelines for the conception of cyber-physical systems remote laboratories in order to allow the development of multidisciplinary projects and create a learning environment in which it is possible to address multiple concepts and technologies. Despite the focus on cyber-physical systems, laboratories with this feature can be classified as a multi purpose educational platform.

The adoption of a hybrid approach (remote and on-site) opens opportunities for the creation of a wide range of setups, which lets students deal with physical elements. The remote operation without the possibility of redesigning setups restricts the application of platforms in terms of competencies and learning objectives that can be addressed by hands-on activities.

The literature review investigated the role of laboratories in engineering education, which could be summarized into fundamental learning objectives of engineering laboratories. The use of remote and virtual labs in education was analysed and studies that focused on the use of remote labs for teaching concepts related to industry 4.0 were reviewed. Core competencies required for industry 4.0 and cyber-physical systems were identified and associated with the fundamental learning objectives of engineering laboratories in order to create the competency framework. The review about cyber-physical systems in engineering education analysed courses and modules focused on cyber-physical systems in different universities, identifying educational strategies and learning objectives related to cyber-physical systems in engineering courses.

Through three case studies, different platforms developed for exploring technologies and concepts in the field of industry 4.0 were analysed. This analysis was fundamental to understand the applicability and identify the main features of educational platforms for engineering courses. The cases showed the possibility of creating platforms based on varied meaningful contexts.

The guidelines proposed in this work indicate the main features that should be included as requirements in the design of cyber-physical systems remote laboratories for engineering courses.

The proof of concept demonstrated that cyber-physical systems remote laboratories can be developed based on open-source and ease of acquisition components and platforms, which facilitate further development and replication by other institutions and researchers. It also eases the implementation of multiple platforms in just one lab, which allows professors to allocate one platform per group of students.

The prototype of a cyber-physical systems remote lab developed in the proof of concept study was assessed by engineering professors in terms of which competencies related to industry 4.0 and cyber-physical systems could be addressed by using it. The assessments indicated that the prototype can be associated with different educational strategies for allowing students to develop multiple competencies and explore different concepts and technologies related to industry 4.0 and cyber-physical systems. It demonstrated that a platform based on a simple design can be a strategic educational tool for engineering courses in the perspective of competency-based education.

7.1 Future work

The use of remote labs for instructing engineering students from different disciplines is still a topic that requires further research to assess educational effectiveness and usage characteristics, which would allow to identify potential applicabilities in different courses based on solid evidence. Although there are a wide range of studies that validated and reported the use of virtual and remote labs for instructing students, they have focused mainly on elementary and secondary education. One important aspect that should be further investigated and evaluated is the use of remote platforms for the development of team projects.

Despite the concept of cyber-physical systems remote lab developed in this work has not included security and privacy aspects, these are fundamental requirements for virtual learning environments that should be considered and investigated to ensure compliance with applicable legislation and regulations. Particularly in Brazil, the General Personal Data Protection Law must be accomplished.

Further development of the implemented proof-of-concept of cyber-physical systems remote lab should include technical improvements and new features, such as:

- new web interface in which students can check, reproduce, and access samples and/or data, with evaluation tools to allow addressing decision making processes and statistical techniques;
- new design elements that can open possibilities for creating a wide range of setups;

- laboratory management system that allows technical assistants and professors to monitor the use of the lab;
- safety mechanisms that ensure the safe operation of all devices in the lab;
- data warehouse for storing data gathered from experiments;
- virtual learning community in which documents, codes, and design configurations can be shared, commented and discussed by users;
- simulation environment in which students can assess and test their design solution before the physical implementation (this is also important for ensuring the safe use of the lab);
- new remote access platform that eases tasks such as control and programming and minimizes the time delay.

During the implementation of these improvements, it is recommended to assess the usability of the laboratory with experts, students, lab technical assistants, and professors to maximize and optimize the user experience, which is fundamental for learning environments. The safety and security should be tested as well for ensuring the fulfilment of these critical requirements.

Implementation, maintenance and operation costs should be taken into account for assessing the economic feasibility of a cyber-physical system remote lab. This assessment could include the possibility of sharing among institutions, which allow investigating operational models in terms of use and costs..

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APPENDIX A - DESCRIPTION OF DEMONSTRATION SESSIONS

This appendix details the script created for presentation and demonstration sessions of the prototype. It also includes the activities that should be completed by research participants.

Tasks carried out by the researcher in the session

1) Discuss the current panorama of cyber-physical systems in the industry and engineering education based on the literature review.
2) Describe the purpose of the prototype as an educational platform for teaching cyber-physical systems in engineering courses.
3) Demonstrate the functionalities of the prototype.
4) Details how the prototype works in terms of its design elements.
5) Present the assessment form.
6) Collect the filled assessment forms.

Tasks performed by research participants in the session and assessment test

1) Take part in the discussion about cyber-physical systems.
2) Observe the demonstration of the prototype.
3) Ask questions or make comments about the purpose of the research and the construction of the prototype.
4) Fill the assessment form.
5) Send the filled form to the researcher.

APPENDIX B - ASSESSMENT FORM

This appendix presents the assessment form applied for the analysis of the prototype by engineering professors.

PROTOTYPE ASSESSMENT FORM

[1] PARTICIPANT PROFILE

Name: ____
Educational formation:____
How long have you been teaching in engineering courses?______________________
Which courses have you been teaching in engineering courses?__________________
Which educational platforms have you been using in these courses?_______________

[2] PROTOTYPE ANALYSIS

A.Which competencies related to industry 4.0 can be developed using the prototype?
B.How do you think that these competencies can be addressed?

Category	Competencies	Related learning objectives of engineering laboratories	Domain of learning	Question A	Question B
Technical competencies	To act and collaborate in interdisciplinary contexts.	Models, design, safety, teamwork, ethics in laboratory and experiment.	Cognitive and affective		
	To flexibly adapt business processes to changeable conditions to new technologies.	Learn from failure, models, and creativity.	Cognitive and affective		
	To design IT processes in the context of production and to use IT components for human-machine interaction.	Design, experiment, and models.	Cognitive		
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	Design, experiment, models, instrumentation, sensory awareness, learn from failure and psychomotor.	Cognitive, affective and psychomotor		
	To establish a connection between a digital twin and its physical reality.	Design, models, instrumentation, experiment, sensory awareness, and psychomotor.	Cognitive and psychomotor		

	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Data analysis, models, and experiment.	Cognitive		
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Models, data analysis, and design.	Cognitive		
	To initiate and to implement innovation processes.	Creativity, models, and design.	Cognitive and affective		
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	Design, ethics in the laboratory and safety.	Cognitive and affective		
	To use the appropriate evaluation tools in complex decision-making situations.	Data analysis, models, sensory awareness, instrumentation, safety, psychomotor, and ethics in the laboratory.	Cognitive, psychomotor and affective		
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Design, teamwork, and communication.	Cognitive and affective		
	To act confidently and effectively in social (including intercultural) contexts.	Ethics in laboratory, sensory awareness, and communication.	Cognitive, psychomotor and affective		
	To lead production units and teams with goal orientation.	Teamwork and communication.	Cognitive and affective		
	To design digitally supported interaction and cooperation processes.	Design, creativity, instrumentation, and models.	Cognitive and affective		
Self-competencies	To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action.	Design, models, and creativity.	Cognitive and affective		
	To act self-determined and self-organized.	Psychomotor, sensory awareness, learn from failure, safety, and ethics in the laboratory.	Cognitive, psychomotor and affective		
	To act on the basis of one's own open mindedness and creativity.	Creativity, models, and design.	Cognitive and affective		
	To design and implement your own lifelong learning.	Creativity, models, design, and experiment.	Cognitive and affective		

C.Which competencies related to cyber-physical systems can be developed using the prototype?
D.How do you think that these competencies can be addressed?

Category	**Subcategory**	**Description**	**Related learning objectives of engineering instructional laboratories**	**Domain of learning**	**Question C**	**Question D**
Technical knowledge and skills	General	Solid foundations together with multidisciplinary awareness.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective		
		Broad knowledge and skills of multiple areas of engineering expertise.	Design, instrumentation, experiment, models, data analysis, psychomotor, sensory awareness, creativity, and learn from failure.	Cognitive, psychomotor, and affective		
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Design, instrumentation, experiment, models, data analysis, creativity, and learn from failure.	Cognitive and affective		
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective		
		Computing for the physical world: sensors, actuators, embedded systems.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective		
		Discrete and continuous mathematics.	Models, experiment and data analysis.	Cognitive		
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Experiment, psychomotor, sensory awareness, creativity, instrumentation, design, and models.	Cognitive, psychomotor, and affective		

		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Models and design.	Cognitive		
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Design, models, learn from failure, data analysis, experiment, creativity, and instrumentation.	Cognitive and affective		
	Non-functional characteristics of cyber-physical systems	Security and privacy	Design, models, experiment, data analysis, and ethics in the laboratory.	Cognitive and affective		
		Interoperability	Design, models, instrumentation, learn from failure and experiment.	Cognitive and affective		
		Reliability and dependability	Design, models, instrumentation, learn from failure and experiment.	Cognitive and affective		
		Power and energy management	Design, models, instrumentation, and experimentat.	Cognitive		
		Safety	Design, models, experimentation, safety, data analysis, and ethics in the laboratory.	Cognitive and affective		
		Stability and performance	Design, models, instrumentation, learn from failure and experimentation.	Cognitive and affective		
		Human factors and usability	Safety, ethics in the laboratory, experiment, design, models, instrumentation, sensory awareness, creativity, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective		
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Design, creativity and models.	Cognitive and affective		

	Engineering	Engineering Process	Data analysis, models, design, experiment, instrumentation, sensory awareness, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective		
		Industrial automation, plant modeling.	Data analysis, models, design, experiment, instrumentation, sensory awareness, learn from failure, and psychomotor.	Cognitive, psychomotor, and affective		
		Statistical methods and mining techniques	Data analysis, models, and design.	Cognitive		
		Physics	Data analysis, instrumentation, experiment, models, and design.	Cognitive		
	Business and humanities	Project management	Design, creativity, teamwork, communication, and models.	Cognitive and affective		
		Antropoly, sociology	Models, teamwork and design.	Cognitive and affective		
		Economics	Models, design, experiment, and data analysis.	Cognitive		
		Legislation	Models, design, experiment, safety, ethics in the laboratory.	Cognitive and affective		
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Communication, teamwork, creativity, experiment, and design.	Cognitive and affective		
		Collaboration with customers.	Communication, teamwork, experiment, and design.	Cognitive and affective		
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.	Communication, teamwork, creativity, experiment, and design.	Cognitive and affective		
		Presentation	Communication	Cognitive and affective		
		Technical writing	Communication	Cognitive and affective		

Attitudes	Flexibility to manage rapidly evolving technologies.	Data analysis, design, models, experiment, instrumentation, and learn from failure.	Cognitive and affective		
	Definition as well as solving problems.	Creativity, design, instrumentation, and experiment.	Cognitive and affective		
	Analytical skills	Design, models, experiment, creativity, data analysis, sensory awareness, learn from failure, psychomotor, and communication.	Cognitive, psychomotor, and affective		
	Creativity	Creativity	Cognitive and affective		
	Entrepreneurship	Design, models, experiment, creativity, communication, and teamwork.	Cognitive and affective		
	Critical thinking and critical attitude towards technological developments.	Creativity, models, design, data analysis, learn from failure and experiment.	Cognitive and affective		
	Cross-disciplinary thinking	Design, models, creativity, and experiment.	Cognitive and affective		
	Lifelong learning	Creativity, models, design, learn from failure and experiment.	Cognitive and affective		

[3] GENERAL FEEDBACK

A. Do you have any suggestions, compliments or criticisms? Please comment.

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APPENDIX C - DATA COLLECTED FROM PARTICIPANTS

This appendix brings together the assessment forms filled by the research participants in the prototype testing. The five participants were identified as P1, P2, P3, P4, and P5.

C.1. Data collected from participant 1

Participant ID	P1
Institution	INSPER
Education formation	Bachelor of Mechanical & Industrial Engineering (Universidade do Vale do Itajaí) Master's in Computer Science (Universidade do Vale do Itajaí) PhD Candidate in Electrical Engineering (Escola Politécnica da Universidade de São Paulo)
How long have you been teaching in engineering courses?	8 years
Which subjects have you been teaching in engineering courses?	Microcontrollers & Internet of Things (Computer Science and Computer Engineering) Programming Techniques (Computer Science and Computer Engineering) Software Lab (Computer Science and Computer Engineering) Co-Design Apps (Computer Engineering/Mechanical Engineering and Mechatronic Engineering) Nature of Design (Computer Engineering/Mechanical Engineering and Mechatronic Engineering)
Which educational platforms have you been using in these courses?	Miro & Mural: where students can share their main ideas and define & ideate their projects. Google Docs: where students can share results filling some frameworks. Fusion 360: where students prototype physical results TinkerCad: a second option for Fusion (Physical prototype) and to test digital prototypes (with arduino and ESP8266). FabLab: a real environment to test and create their prototypes. Figma and Adobe XD: where students design digital prototypes.

COMPETENCIES RELATED TO INDUSTRY 4.0			
Participant ID		P1	
Category	**Competencies**	**Question A**	**Question B**
Technical competencies	To act and collaborate in interdisciplinary contexts.	Yes	when students have a purpose and try to solve a problem using the prototype. For example: if you have a scenario that could be impacted by field variations (roughness) or to try to solve some stock problem, that could be interdisciplinary.
	To flexibly adapt business processes to changeable conditions to new technologies.	Yes	when students get in touch with feedback in real time

	To design IT processes in the context of production and to use IT components for human-machine interaction.	Yes	if challenged to look at the interfaces and with clear indicators of what and where they are interacting, I believe so.
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	No, but …	I think it's possible, but just on the first level. Where students are challenged to solve a problem but it's not clear if they could "hack" or change some things.
	To establish a connection between a digital twin and its physical reality.	Yes	It is one of the main features of the prototype.
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Yes, but …	I think it's possible, but it's necessary to have an interface to help students to check, reproduce and access samples and/or data. Thinspeak is the first level for that.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Yes	Exploring different elements included in the system.
	To initiate and to implement innovation processes.	Yes	I think of a proposal and interdisciplinary goals here. Maybe if students check the process to try to design a new feature or skill, that could help them a lot here.
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	No	A possibility here could be identified as something related to work security and remote testing.
	To use the appropriate evaluation tools in complex decision-making situations.	Yes	Students can explore different tools to make decisions.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Yes, but …	a lesson plan could help with team task suggestions
	To act confidently and effectively in social (including intercultural) contexts.	Yes	It can be included in the definition of problems for projects.
	To lead production units and teams with goal orientation.	Yes, but …	a lesson plan, with a couple of tasks, could help, such as a pre-training.
	To design digitally supported interaction and cooperation processes.	Yes	It is part of the experience of using a remote platform.
Self-competencies	To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action.	Yes	debugging and real-time feedback help here
	To act self-determined and self-organized.	Yes	using techniques such as problem based learning, flipped classroom, and project-based learning.
	To act on the basis of one's own open mindedness and creativity.	Yes	Stimulating students to create different system configurations.

	To design and implement your own lifelong learning.	Yes	Stimulating students to create different system configurations.

COMPETENCIES RELATED TO CYBER-PHYSICAL SYSTEMS

Participant ID		P1		
Category	**Subcategory**	**Description**	**Question C**	**Question D**
Technical knowledge and skills	General	General Solid foundations together with multidisciplinary awareness.	Yes	Mini-challenges that encourage students to collect data and hacking a system to understand how digital/analog sensors convert “information” in “bits”
		Broad knowledge and skills of multiple areas of engineering expertise.	Yes	Exploring environment and encourage students to describe how the differences can affect collecting process
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Yes	Using ISO/NBR and maybe a mini-challenge in which each student solves a part and the final result is combined to generate a new product.
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Yes	Debugging some simple tasks and with three different layer-levels: Easy-tasks to move the car, medium-tasks to solve a closed problem, free-tasks when half-part of students have to “create a scenario” and half-part try to solve it.
		Computing for the physical world: sensors, actuators, embedded systems.	Yes	Mini-challenges that encourage students to collect data and hacking a system to understand how digital/analog sensors convert “information” in “bits”
		Discrete and continuous mathematics.	Yes	Working with sensors that need Analog-Digital Converter and that have to work with events or capture a lot of data to generate one “best” sample.
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Yes	Working with different components such as sensors, actuators, and control boards.
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Yes	Generating a priority-queue system as a task for students, that have to create priority users that could program an action.
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing,	Yes	free-tasks when half-part of students have to “create a scenario” and half-part try to solve it.

		deployment and sustainment.		
	Non- functional characteristics of cyber-physical systems	Security and privacy	Yes	Task that more multiple hits and the problem of unauthorized people accessing the command
		Interoperability	Yes	Connecting multiple control boards and cloud platforms.
		Reliability and dependability	Yes	Including tasks related to these topics in the scope of the course.
		Power and energy management	Yes	Measuring the life-cycle and trying to compare how different types of supply energy systems could affect the capture process and life-cycle of the application. Or a redundancy system for when the power goes out developed by students.
		Safety	No	
		Stability and performance	Yes	Including tasks related to these topics in the scope of the course.
		Human factors and usability	Yes	Students can assess the usability and human factors related to different systems configurations.
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Yes	This methodology can be required in the description of systems.
	Engineering	Engineering Process	Yes	Developing an UIX to interface data collection and data visualization, developed by students.
		Industrial automation, plant modeling.	Yes	Maybe including statistical control process tasks, for example: measuring and counting failures in a process and reporting it for a data visualization system.
		Statistical methods and mining techniques	Yes	Improving data visualization systems with statistical techniques. If they have a real world problem that needs data collection, such as a temperature in a steel-cut process, that could impact, for example, in how the cut-tools could be affected.
		Physics	Yes	Exploring physical models.
	Business and humanities	Project management	Yes	Evaluating costs, resources and time spent to complete the challenges.
		Anthropology, sociology	No	

		Economics	Yes	Evaluating costs, resources and time spent to complete the challenges.
		Legislation	No	It’s not clear for me if that is addressed with current experiments.
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Yes	with team-work challenge: free-tasks when half-part of students have to “create a scenario” and half-part try to solve it.
		Collaboration with customers.	Yes	with team-work challenge: free-tasks when half-part of students have to “create a scenario” and half-part try to solve it.
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.	Yes	working with multidisciplinary groups.
		Presentation	Yes	create a classroom symposium to demonstrate real experiments by students, perhaps in the scenario activity, and create an assessment roadmap with external teachers.
		Technical writing	Yes	create a classroom symposium to demonstrate real experiments by students, perhaps in the scenario activity, and create an assessment roadmap with external teachers.
Attitudes		Flexibility to manage rapidly evolving technologies.	Yes	with project-based learning.
		Definition as well as solving problems.	Yes	with team-work challenge: free-tasks when half-part of students have to “create a scenario” and half-part try to solve it.
		Analytical skills	Yes	with problem based learning.
		Creativity	Yes	with team-work challenge: free-tasks when half-part of students have to “create a scenario” and half-part try to solve it.
		Entrepreneurship	Yes	Proposing problems and stimulating the development of creative solutions.
		Critical thinking and critical attitude towards technological developments.	Yes	Proposing technological challenges and stimulating the creation of solutions.
		Cross-disciplinary thinking	Yes	Proposing problems and stimulating the development of creative solutions.

	Lifelong learning	Yes	Stimulating students to create different system configurations.
Participant ID	P1		
Suggestions			

C.2. Data collected from participant 2

Participant ID	P2
Institution	Universidade Federal do Amapá
Education formation	Bachelor's and Master's degrees in Computer Science, and PhD Candidate in Computer Science.
How long have you been teaching in engineering courses?	3 years
Which subjects have you been teaching in engineering courses?	Distributed Systems, Graph Theory, Automata and Formal Languages, Compilers, and Scientific Research Methodology
Which educational platforms have you been using in these courses?	Google Workspace for Education and Microsoft Teams.

COMPETENCIES RELATED TO INDUSTRY 4.0			
Participant ID		P2	
Category	**Competencies**	**Question A**	**Question B**
Technical competencies	To act and collaborate in interdisciplinary contexts.	yes	Elaboração de projetos que utilizem conceito de IoT e IA com aplicação na área da saúde, por exemplo.
	To flexibly adapt business processes to changeable conditions to new technologies.	No	
	To design IT processes in the context of production and to use IT components for human-machine interaction.	yes	Realização de atividades práticas de desenvolvimento de soluções com elaboração de testes experimentais com usuários finais.
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	No	
	To establish a connection between a digital twin and its physical reality.	No	
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	No	
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	yes	Utilização em práticas de projetos considerando o acompanhamento passo a passo, desde a sua concepção, passando pela construção da solução até a

			realização de testes funcionais e não-funcionais.
	To initiate and to implement innovation processes.	yes	Incentivar os(as) alunos(as) a construírem projetos a partir de um modelo inicial, considerando este protótipo.
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	No	
	To use the appropriate evaluation tools in complex decision-making situations.	No	
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	No	
	To act confidently and effectively in social (including intercultural) contexts.	No	
	To lead production units and teams with goal orientation.	No	
	To design digitally supported interaction and cooperation processes.	yes	Elaboração de projetos com equipes multidisciplinares, que possam ser desenvolvidos considerando diferentes “expertises”.
Self-competencies	To realistically assess the value of one’s own subjective knowledge of experience and incorporate it accordingly into one’s own action.	No	
	To act self-determined and self-organized.	yes	Na realização de práticas de projeto.
	To act on the basis of one’s own open mindedness and creativity.	yes	Esta característica pode ser explorada na elaboração de projetos do “zero” considerando um modelo inicial, que seria o protótipo.
	To design and implement your own lifelong learning.	yes	Esta característica também pode ser explorada na elaboração de projetos do “zero” considerando um modelo inicial, que seria o protótipo.

COMPETENCIES RELATED TO CYBER-PHYSICAL SYSTEMS				
Participant ID		P2		
Category	**Subcategory**	**Description**	**Question C**	**Question D**
Technical knowledge and skills	General	General Solid foundations together with multidisciplinary awareness.	no	
		Broad knowledge and skills of multiple areas of engineering expertise.	yes	Considerando os diferentes componentes utilizados no protótipo, essa habilidade pode ser facilmente explorada na construção de diferentes soluções de engenharia.
		Practical experience in product development process including state-of-	yes	Utilizando o protótipo em práticas de projeto

		the-art technologies, tools and best practices.		
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	yes	Na própria construção de uma solução partindo deste protótipo se pode utilizar diversos conceitos da computação, como, por exemplo, IA e IoT. Além de práticas da Engenharia de Software que podem ser abordadas na elaboração de projetos.
		Computing for the physical world: sensors, actuators, embedded systems.	yes	Utilizando os próprios componentes do protótipo na construção de soluções do “zero”.
		Discrete and continuous mathematics.	no	
		Cross-cutting application of sensing, actuation, control, communication, and computing.	yes	Na construção de projetos interdisciplinares.
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	yes	Na construção de soluções integradas e utilizando diferentes tecnologias
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	yes	Essas habilidades podem ser exploradas utilizando o protótipo em práticas de projetos, considerando o ciclo de vida do desenvolvimento de soluções.
	Non-functional characteristics of cyber-physical systems	Security and privacy	no	
		Interoperability	no	
		Reliability and dependability	no	
		Power and energy management	no	
		Safety	no	
		Stability and performance	no	
		Human factors and usability	no	
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	no	
	Engineering	Engineering Process	yes	Essas habilidades podem ser exploradas utilizando o protótipo em práticas de projetos, considerando os processos de engenharia.
		Industrial automation, plant modeling.	yes	O protótipo pode ser facilmente utilizado em soluções de automação industrial
		Statistical methods and mining techniques	no	

		Physics	no	
	Business and humanities	Project management	yes	Na utilização em práticas de projeto
		Anthropology, sociology	no	
		Economics	no	
		Legislation	no	
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	yes	Desenvolvimento de projetos interdisciplinares e em equipe
		Collaboration with customers.	no	
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.	no	
		Presentation	yes	Apresentação dos projetos desenvolvidos
		Technical writing	yes	Elaboração da documentação da solução
Attitudes		Flexibility to manage rapidly evolving technologies.	no	
		Definition as well as solving problems.	yes	Práticas de projeto
		Analytical skills	no	
		Creativity	yes	Desenvolvimento de diferentes soluções a partir do protótipo
		Entrepreneurship	no	
		Critical thinking and critical attitude towards technological developments.	no	
		Cross-disciplinary thinking	no	
		Lifelong learning	no	

Participant ID	P2
Suggestions	Integração com outras ferramentas, como, por exemplo, uma ferramenta de modelagem.

C.3. Data collected from participant 3

Participant ID	P3
Institution	Instituto Federal de São Paulo - Campinas
Education formation	Doutor em Engenharia Mecânica (Controle e Automação), Graduação e mestrado em engenharia elétrica.

How long have you been teaching in engineering courses?	Desde 2002 (19 anos).
Which subjects have you been teaching in engineering courses?	Eletrônica, Orientação de TCC, Projetos Integradores.
Which educational platforms have you been using in these courses?	Moodle, Protheus, Matlab, simuladores de CLPS

COMPETENCIES RELATED TO INDUSTRY 4.0			
Participant ID		P3	
Category	**Competencies**	**Question A**	**Question B**
Technical competencies	To act and collaborate in interdisciplinary contexts.	parcial	Modelos e design - sim Segurança - parcial Trabalho em grupo - não
	To flexibly adapt business processes to changeable conditions to new technologies.	parcial	Na parte experimental sim. Na montagem de hardware - não
	To design IT processes in the context of production and to use IT components for human-machine interaction.	sim	Sim, é válido o modelo e ganha-se tempo na simulação
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	Sim	Para ser operacional deve ter um estudo dirigido para que os alunos não se percam no meio do processo. É possível realizar diversos experimentos com vários graus de dificuldade.
	To establish a connection between a digital twin and its physical reality.	sim	É capaz de passar o conteúdo de aprendizagem para os alunos.
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Sim	É possível, porém deve-se ter um estudo dirigido e exemplos que mostrem ao aluno o tratamento dos dados.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	sim	O conjunto de simulação e programação é factível utilizando este sistema
	To initiate and to implement innovation processes.	Sim	Deve dar os desafios aos alunos para que possam implementar as soluções e alavancar a criatividade.
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	Sim	Com a estratégia de identificar um problema de segurança, os alunos podem propor e absorver conhecimentos utilizando o sistema. Por ser remoto o sistema é mais seguro.
	To use the appropriate evaluation tools in complex decision-making situations.	Parcial	É um assunto mais complexo e creio que exija mais maturidade dos alunos para chegar a este nível.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Não	É uma atividade muito individual, assim a habilidade de trabalho em grupo, resolução de conflitos fica prejudicada.

	To act confidently and effectively in social (including intercultural) contexts.	Não	Difícil avaliar remotamente.
	To lead production units and teams with goal orientation.	parcial	Verificar se o aluno possui liderança via remoto é muito difícil de notar uma vez que é necessário verificar como é o relacionamento entre os pares.
	To design digitally supported interaction and cooperation processes.	sim	É possível avaliar e desenvolver esta habilidade.
Self-competencies	To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action.	sim	Através das simulações é possível verificar a validação dos códigos e propostas aplicadas.
	To act self-determined and self-organized.	parcial	Consegue-se avaliar se o aluno segue o planejamento.
	To act on the basis of one's own open mindedness and creativity.	sim	
	To design and implement your own lifelong learning.	sim	

COMPETENCIES RELATED TO CYBER-PHYSICAL SYSTEMS

Participant ID		P3		
Category	**Subcategory**	**Description**	**Question C**	**Question D**
Technical knowledge and skills	General	General Solid foundations together with multidisciplinary awareness.	Sim	Trabalho com projetos para integração do hardware e software
		Broad knowledge and skills of multiple areas of engineering expertise.	Sim	Trabalho com projetos para integração do hardware e software
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Sim	Trabalho com projetos para integração do hardware e software
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Sim	Prática nos simuladores
		Computing for the physical world: sensors, actuators, embedded systems.	Sim	Prática nos simuladores
		Discrete and continuous mathematics.	Sim	Prática nos simuladores
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Sim	Trabalho com projetos para integração do hardware e software
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Sim	Trabalho com projetos para integração do hardware e software

		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Sim	Trabalho com projetos para integração do hardware e software
	Non-functional characteristics of cyber-physical systems	Security and privacy	Sim	Apresentação de modelos sobre segurança industrial.
		Interoperability	Sim	Trabalho com projetos para integração do hardware e software
		Reliability and dependability	Sim	Apresentação de modelos sobre as metas.
		Power and energy management	Sim.	Apresentação de modelos sobre eficiência energética..
		Safety	Sim	Apresentação de modelos sobre segurança industrial.
		Stability and performance	Sim	Apresentação das metas a serem atingidas e das ferramentas disponíveis para alcançá-las.
		Human factors and usability	Sim.	Apresentação das metas a serem atingidas e das ferramentas disponíveis para alcançá-las.
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Sim	Treinamento sobre as ferramentas de engenharia disponíveis.
	Engineering	Engineering Process	Sim.	Treinamento sobre as ferramentas de engenharia disponíveis.
		Industrial automation, plant modeling.	Sim	Treinamento sobre as ferramentas de engenharia disponíveis.
		Statistical methods and mining techniques	Sim	Treinamento sobre as ferramentas de engenharia disponíveis.
		Physics	Sim	Treinamento sobre as ferramentas de engenharia disponíveis.
	Business and humanities	Project management	Sim	Desenvolvimento de projetos
		Anthropology, sociology	Não	
		Economics	Sim	Avaliação de custos em projetos
		Legislation	Não	
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Não	
		Collaboration with customers.	Não	

	Communication within heterogeneous interdisciplinary multicultural teams and with customers.	Não	
	Presentation	Sim	Elaboração de apresentações
	Technical writing	Sim	Elaboração de relatórios.
Attitudes	Flexibility to manage rapidly evolving technologies.	Sim	Trabalho com projetos para integração do hardware e software
	Definition as well as solving problems.	Sim	Trabalho com projetos para integração do hardware e software
	Analytical skills	Sim	Trabalho com projetos para integração do hardware e software
	Creativity	Sim	Trabalho com projetos para integração do hardware e software
	Entrepreneurship	Sim	Trabalho com projetos para integração do hardware e software
	Critical thinking and critical attitude towards technological developments.	Sim	Trabalho com projetos para integração do hardware e software
	Cross-disciplinary thinking	Sim	Trabalho com projetos para integração do hardware e software
	Lifelong learning	Sim	Trabalho com projetos para integração do hardware e software

Participant ID	P3
Suggestions	Apresentar os custos do laboratório remoto vs laboratório físico Como é a proposta do compartilhamento das expertises entre os participantes. Como trabalhar em grupo com uma atividade que é em boa parte individual e remota? Espero ter ajudado, muito bom o seu trabalho Lucas!!!

C.4. Data collected from participant 4

Participant ID	P4
Institution	Instituto Federal de São Paulo - Bragança Paulista
Education formation	Engenharia de Controle e Automação - UNIFEI; Mestre em Engenharia Mecânica - Unicamp; Doutor em Engenharia Mecânica - Unicamp.
How long have you been teaching in engineering courses?	3 years
Which subjects have you been teaching in engineering courses?	Dispositivos Lógicos Programáveis; Microcontroladores; Sistemas Microcontrolados.
Which educational platforms have you been using in these courses?	Moodle; Microsoft Teams.

COMPETENCIES RELATED TO INDUSTRY 4.0			
Participant ID		P4	
Category	**Competencies**	**Question A**	**Question B**
Technical competencies	To act and collaborate in interdisciplinary contexts.	Sim	O protótipo atua em diferentes componentes curriculares.
	To flexibly adapt business processes to changeable conditions to new technologies.	Sim	Abordando no protótipo tecnologias inovadores, como a IoT.
	To design IT processes in the context of production and to use IT components for human-machine interaction.	Sim	Utilizando o protótipo como ferramenta para o desenvolvimento de projetos.
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	Não	Utilizando o protótipo como ferramenta para o desenvolvimento de projetos.
	To establish a connection between a digital twin and its physical reality.	Sim	O protótipo pode ser usado
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Sim	Coletando dados de diferentes variáveis (exemplo temperatura, umidade, pressão) e trabalhando com os mesmos.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Não	
	To initiate and to implement innovation processes.	Sim	Utilizando o protótipo como ferramenta para o desenvolvimento de projetos.
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	Não	
	To use the appropriate evaluation tools in complex decision-making situations.	Sim	Passando opções de ferramentas aos alunos, tendo opções boas e não tão boas. O aluno analisa e escolhe a melhor opção para a solução do problema.
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Não	
	To act confidently and effectively in social (including intercultural) contexts.	Sim	Utilizando o protótipo com trabalho em grupo.
	To lead production units and teams with goal orientation.	Não	
	To design digitally supported interaction and cooperation processes.	Sim	O uso remoto do protótipo propicia o desenvolvimento desta competência.

Self-competencies	To realistically assess the value of one's own subjective knowledge of experience and incorporate it accordingly into one's own action.	Sim	Propondo a criação de soluções para problemas.
	To act self-determined and self-organized.	Sim	Utilizando a abordagem de projetos.
	To act on the basis of one's own open mindedness and creativity.	Sim	Com os alunos realizando experimentos, criando soluções para problemas.
	To design and implement your own lifelong learning.	Sim	Com os alunos realizando experimentos, criando soluções para problemas.

COMPETENCIES RELATED TO CYBER-PHYSICAL SYSTEMS				
Participant ID		P4		
Category	**Subcategory**	**Description**	**Question C**	**Question D**
Technical knowledge and skills	General	General Solid foundations together with multidisciplinary awareness.	Sim	O protótipo atua em diferentes componentes curriculares.
		Broad knowledge and skills of multiple areas of engineering expertise.	Sim	O protótipo atua em diferentes componentes curriculares.
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Não	
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Sim	O protótipo permite trabalhar diferentes conceitos da computação.
		Computing for the physical world: sensors, actuators, embedded systems.	Sim	
		Discrete and continuous mathematics.	Sim	Abordagem usando processamento de sinais, por exemplo.
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Sim	Abordagem de problemas que envolvam atuadores, sensores e controle.
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Sim	Abordagem de problemas que envolvam atuadores, sensores e controle.
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Não	
	Non-functional characteristics of cyber-physical systems	Security and privacy	Não	
		Interoperability	Sim	O protótipo permite trabalhar a questão da interoperabilidade entre diferentes plataformas.

		Reliability and dependability	Não	
		Power and energy management	Sim	Trabalhando o gerenciamento do consumo energético do protótipo.
		Safety	Não	
		Stability and performance	Sim	Alunos podem testar a estabilidade e analisar a performance do protótipo em diferentes casos.
		Human factors and usability	Sim	A questão da usabilidade pode ser abordada nos projetos.
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Sim	Alunos podem utilizar essa abordagem nos projetos.
	Engineering	Engineering Process	Sim	
		Industrial automation, plant modeling.	Sim	
		Statistical methods and mining techniques	Sim	No uso e criação de algoritmos para coleta e tratamento de dados dos sensores.
		Physics	Sim	Alunos podem entender e aplicar conceitos da física nos experimentos.
	Business and humanities	Project management	Sim	Utilizando a abordagem de projetos em grupo.
		Anthropology, sociology	Não	
		Economics	Não	
		Legislation	Não	
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Sim	Utilizando a abordagem de trabalhos em grupo.
		Collaboration with customers.	Sim	Ao inserir diferentes papéis nos trabalhos em grupo.
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.	Sim	Utilizando a abordagem de trabalhos em grupo.
		Presentation	Sim	Solicitando apresentações sobre projetos.
		Technical writing	Sim	Solicitando relatórios sobre projetos.
Attitudes		Flexibility to manage rapidly evolving technologies.	Sim	Utilizando diferentes técnicas e tecnologias nos experimentos.

	Definition as well as solving problems.	Sim	Utilizando projetos e problemas no uso do protótipo.
	Analytical skills	Sim	Na abordagem baseada em problemas e projetos.
	Creativity	Sim	Na abordagem baseada em problemas e projetos.
	Entrepreneurship	Sim	Na abordagem baseada em problemas e projetos.
	Critical thinking and critical attitude towards technological developments.	Sim	Na abordagem baseada em problemas e projetos.
	Cross-disciplinary thinking	Sim	Com os alunos realizando experimentos, criando soluções para problemas.
	Lifelong learning	Sim	Com os alunos realizando experimentos, criando soluções para problemas.

Participant ID	P4
Suggestions	Excelente trabalho. Conforme comentado em reunião, fica como sugestão a abordagem e indicação de ferramentas open-source a serem usadas como sistemas de gerenciamento de laboratório remoto.

C.5. Data collected from participant 5

Participant ID	P5
Institution	Universidade Federal de São Paulo
Education formation	Graduação em Arquitetura e Urbanismo, Mestrado em Ciência da Comunicação e Doutorado em Sistemas Eletrônicos,
How long have you been teaching in engineering courses?	Hoje atuo exclusivamente no curso de tecnologias educacionais, mas dei aula no curso de engenharia de 2012 a 2017.
Which subjects have you been teaching in engineering courses?	Realidade virtual, tecnologias imersivas, design educacional, games e pesquisa e inovação.
Which educational platforms have you been using in these courses?	Além do sistema institucional próprio de gestão, Moodle, Blackboard.

COMPETENCIES RELATED TO INDUSTRY 4.0			
Participant ID		P5	
Category	**Competencies**	**Question A**	**Question B**
Technical competencies	To act and collaborate in interdisciplinary contexts.	Sim	Projetos integradores em que diversas disciplinas contribuem para o desenvolvimento de uma ação do semestre.
	To flexibly adapt business processes to changeable conditions to new technologies.	Sim	Sempre propor que os projetos estejam atrelados a questões de empreendedorismo

	To design IT processes in the context of production and to use IT components for human-machine interaction.	Sim	Incentivar a inovação tecnológica, perpassando as tecnologias digitais
	To design and to control holistic and complex production processes and networked production structures as well as to manage appropriate interfaces (including the implementation of problem-solving and optimization processes).	Sim	Por mais que se desenvolva protótipos específicos em laboratórios, cada um deve estar atrelado a uma solução mais ampla. É importante que se apresente este contexto mais amplo de desenvolvimento.
	To establish a connection between a digital twin and its physical reality.	Sim	É importante (bem menos custoso e mais ágil) ter essa interface entre protótipos simulados e físicos
	To deal with large amounts of data and to use appropriate statistical skills (including recognizing the importance of algorithms and the management of sensitive data).	Sim	O protótipo permite ter a coleta de diversos tipos de dados em grande quantidade com armazenamento na nuvem. Os dados podem ser tratados e disponibilizados em visualizações e dashboards operacionais.
	To demonstrate system competency by recognizing functional elements, identifying system boundaries and making predictions about system behavior.	Sim	Fazer o estudo de requisitos funcionais e de eficiência de entrega é fundamental para avaliar possíveis implementações e melhorias
	To initiate and to implement innovation processes.	Sim	A flexibilidade do protótipo justamente permite inovações de uso e desenvolvimento
	To control the legal context of the entrepreneurial act to act strategically in a company-specific way.	Sim	Construindo um framework de checklist de ética de trabalho
	To use the appropriate evaluation tools in complex decision-making situations.	Sim	Dados podem ser coletados pelo protótipo como indicadores de avaliação
Social competencies	To communicate business fluently and to cooperate, both internally (in terms of process flows) and externally (in terms of customers and supplier relations).	Sim	É preciso implementar uma dinâmica de trabalho similar a ambientes corporativos para promover a comunicação profissional no laboratório
	To act confidently and effectively in social (including intercultural) contexts.	Sim	Todo local de trabalho precisa de diretrizes de conduta, incluindo termos de confidencialidade
	To lead production units and teams with goal orientation.	Sim	PBL justamente tem esse foco de promover o desenvolvimento de projetos em grupos.
	To design digitally supported interaction and cooperation processes.	Sim	É muito importante desenvolver a competência de desenvolvimento de projetos em plataformas digitais. Uma competência necessária para a inovação tecnológica.
Self-competencies	To realistically assess the value of one’s own subjective knowledge of experience and incorporate it accordingly into one’s own action.	Sim	Sessões de brainstorming e validações de conceito em grupo podem facilitar esse processo individual
	To act self-determined and self-organized.	Sim	Com diretrizes de trabalho, criação de cronograma de

			desenvolvimento e implementação da Estrutura Analítica de Projetos (Work Breakdown Structure)
	To act on the basis of one's own open mindedness and creativity.	Sim	O espaço de laboratório deve permitir a experimentação e testes
	To design and implement your own lifelong learning.	Sim	Incentivar a troca de experiências e espaço para indicar cursos correlatos

COMPETENCIES RELATED TO CYBER-PHYSICAL SYSTEMS				
Participant ID		P5		
Category	**Subcategory**	**Description**	**Question C**	**Question D**
Technical knowledge and skills	General	General Solid foundations together with multidisciplinary awareness.	Sim	Projetos podem (e devem) ter um desenvolvimento multidisciplinar para ser relevante
		Broad knowledge and skills of multiple areas of engineering expertise.	Sim	Um projeto pode incentivar de forma transversal competências de mecânica, eletrônica, computação, produção etc.
		Practical experience in product development process including state-of-the-art technologies, tools and best practices.	Sim	Sempre incentivar fazer o benchmarking no começo de qualquer projeto
	Cyber-physical systems basis	Computing concepts, computer science, software engineering.	Sim	Sempre será necessário ter a interação com sistemas computacionais, tanto no frontend quanto no backend
		Computing for the physical world: sensors, actuators, embedded systems.	Sim	É essencial ter habilidades de eletrônica tanto para receber informações quanto para acionar atuadores de forma remota
		Discrete and continuous mathematics.	Sim	Se houver tratamento de dados, sempre será necessário ter a lógica matemática sendo aplicada
		Cross-cutting application of sensing, actuation, control, communication, and computing.	Sim	Entendimento sobre inputs e outputs para permitir o controle remoto
		Modeling of heterogeneous and dynamic systems integrating control, computing, and communication.	Sim	Por ter vários subsistemas, é muito importante que se desenvolva a experimentação de diferentes plataformas de programação
		Cyber-physical systems life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment.	Sim	O ciclo apresentado é essencial para qualquer desenvolvimento de projeto e deve ser o framework primário

	Non-functional characteristics of cyber-physical systems	Security and privacy	Sim	Criação de protocolos
		Interoperability	Sim	Comunidade virtual de aprendizagem com indicação de cursos, boas práticas, exemplos
		Reliability and dependability	Sim	É importante que o usuário tenha essa percepção do potencial e limitação do espaço
		Power and energy management	Sim	Criação de sensores e indicadores
		Safety	Sim	Curso de segurança do trabalho
		Stability and performance	Sim	Criação de sensores e indicadores
		Human factors and usability	Sim	Reuniões constantes para apresentar os dados e abrir para conversas e dinâmicas para aprimoramento das ações
	Systems engineering	System-level approach, systems integration across domains, and systems of systems.	Sim	Dar a visão macro do projeto e os subprojetos atrelando aos sistemas e subsistemas de integração
	Engineering	Engineering Process	Sim	Conceitos de design thinking no projeto
		Industrial automation, plant modeling.	Sim	Correlação entre o que é desenvolvido no laboratório ciberfísico e a implementação industrial
		Statistical methods and mining techniques	Sim	Tratamento de dados gerados
		Physics	Sim	Conhecimento dos sensores e instrumentos de trabalho
	Business and humanities	Project management	Sim	WBS
		Anthropology, sociology		
		Economics	Sim	Plano de negócio
		Legislation	Sim	Direitos trabalhistas, agências de vigilância
Social knowledge and skills		Collaboration in heterogeneous interdisciplinary multicultural teams.	Sim	Conexão com laboratórios ciberfísicos em diversas localidades e contextos
		Collaboration with customers.	Sim	Rodadas de testes e validação
		Communication within heterogeneous interdisciplinary multicultural teams and with customers.	Sim	Plataformas web com diferentes níveis de acesso para permitir o acompanhamento e interação (feedback)
		Presentation	Sim	Datas-marco com entregas (apresentações) de fases de desenvolvimento
		Technical writing	Sim	Relatórios técnicos

Attitudes	Flexibility to manage rapidly evolving technologies.	Sim	SCRUM, projetos ágeis
	Definition as well as solving problems.	Sim	Netnografia, entrevistas, grupos focais
	Analytical skills	Sim	Ideação a partir de situações-problemas
	Creativity	Sim	Protótipo do azarão
	Entrepreneurship	Sim	Blueprint de serviço
	Critical thinking and critical attitude towards technological developments.	Sim	Roda de conversas e brainstorming
	Cross-disciplinary thinking	Sim	Rodadas de mentoria
	Lifelong learning	Sim	Repositório de conhecimento

Participant ID	P5
Suggestions	Parabéns pelo projeto e pelo protótipo. A relação entre as competências da Indústria 4.0, laboratórios ciberfísicos e educação de engenharia é essencial para formar profissionais capazes de aproveitar as potencialidades tecnológicas para a inovação.

APPENDIX D - EMBEDDED PROGRAMMING

This appendix includes the programs that are embedded in Pulga Core (Section 1) and Labrador board (Section 2). C is the programming language used in the development of the experimental setup.

D.1. PULGA CORE

```
#include <stdio.h>
#include "mbed.h"
#include "trace_helper.h"
#include "serial.h"
#include "lora_radio.h"
#include "lora.h"
#include "l86.hpp"
#include "BME280.h"

/*
 * Sets up an application dependent transmission timer in ms. Used only when
Duty Cycling is off for testing
 */
#define TX_TIMER                        10000

/**
 * Maximum number of events for the event queue.
 * 10 is the safe number for the stack events, however, if application
 * also uses the queue for whatever purposes, this number should be increased.
 */
#define MAX_NUMBER_OF_EVENTS            10

#define CONFIRMED_MSG_RETRY_COUNTER     3

void serial_post_to_queue(void);

static EventQueue ev_queue(MAX_NUMBER_OF_EVENTS *EVENTS_EVENT_SIZE);

static lorawan_app_callbacks_t callbacks;

RawSerial uart_gps(P0_5, P0_7, 9600);
mbed::DigitalOut force_on(P0_27);
mbed::DigitalOut _alive_led(P1_13, 0);
mbed::DigitalOut _actuated_led(P1_14,1);
InterruptIn dio0(P0_12);
extern DigitalOut SX1272_RESET(P1_15);

uint32_t sens0x = 0;
uint32_t sens0y = 0;
uint32_t sens0z = 0;
uint32_t sens00 = 0;
uint32_t sens01 = 0;
uint32_t sens02 = 0;

//int cont=0;
int read_sens=0;

int comm=1; // Selecionar: 0 para nenhum, 1 para BLE, 2 para Lorawan ou 3 para
Lora
int sensors=0;

void test_lora();
extern void init_Lorawan();
extern double flipBaseGPS(char *gMin);
```

```
void serial_gps_post_to_queue(void);
mbed::DigitalOut wkUp_L86(P1_2,PullUp); //COLOCAR ELE EM ALTO PARA ACORDAR O GPS

void init_L86(){

    force_on = 1;
    wait_ms(50);

    wkUp_L86 = 0;
    wait_ms(12);
    wkUp_L86 = 1;
    wait_ms(1);
}

void resetSX1272(){
    SX1272_RESET.write(1);
    wait_us(100);
    SX1272_RESET.write(0);
    wait_ms(6);
}

void serial_rx(){
    if(pc.readable()){
        pc.printf("rx: %c\n", pc.getc());
    }
    pc.attach(&serial_post_to_queue, RawSerial::RxIrq);
    return;
}

void serial_post_to_queue(void){
    //disable serial rx interrupt
    pc.attach(NULL, RawSerial::RxIrq);
    //enqueue the serial rx reception as a normal task
    ev_queue.call(SerialRx);
    return;
}

extern void init_P2P();

void le_temperatura();

extern int gpsCheck =0;
BME280 sensor_amb(P0_13, P0_15, 0x77 << 1);

// DigitalIn  OnePPS(ONEPPS_PIN);

RMC_data RMC;
GPS_data GPS_parse;
volatile int Char_index = 0;                    // index for char array
char Rx_data[MAX_NMEA_LENGTH] = "0";            // char array to store received bytes
char tx_line[82];
uint8_t valid = 0;
volatile uint8_t GPS_data_ready = 0;
volatile uint8_t sending = 0;
void serial_post_to_queue3();
char response[256];

double quectelLat = 0;
double quectelLon = 0;

extern void le_sensores(){
    uint8_t response_len;

    response_len = sprintf(response, "%f,%f,%f",
(float)sensor_amb.getTemperature(),
```

```
                                                    (float)sensor_amb.getPressure(),
                                                    (float)sensor_amb.getHumidity());

    pc.printf("<s");
    pc.putc(response_len);
    pc.printf("%s>\n\r", response);
    //pc.printf("response_len: %d\n", response_len);

    pc.attach(&serial_post_to_queue3, Serial::RxIrq);
}


void serial_post_to_queue3(void){
    //disable serial rx interrupt
    pc.attach(NULL, RawSerial::RxIrq);
    //enqueue the serial rx reception as a normal task
    ev_queue.call(le_sensores);
    return;
}

#include "BMX160.txt"
int main(void)
{   wait_ms(1000);

    pc.baud(9600);
    pc.printf("pc_config9600\n\r");

    sensor_amb.initialize();
    wait_ms(100);

    pc.attach(&serial_post_to_queue3, Serial::RxIrq);
    ev_queue.dispatch_forever();
    return 0;
}
```

D.2. LABRADOR BOARD

Program that controls the smart vehicle.

```
#include <ncurses.h>
#include <wiringPi.h>
#include <string.h>
#include <curl/curl.h>
#include <json-c/json.h>
#include <unistd.h>
#include <time.h>
#include <unistd.h>
#include <time.h>
#include <stdio.h>
#include <stdlib.h>
#include <termios.h>
#include <fcntl.h>
#include <sys/select.h>
#include <sys/types.h>
#include <sys/ioctl.h>
#define ESC 27
#define TAB 5
#define P1 5
#define P2 3
```

```
#define P3 15
#define P4 13
#define P5 7
#define P6 11
#define STATUS_LINE 12
#define BTN_UP_DELAY 200

#define PIN_TRIGGER 37
#define PIN_ECHO 38

#define PIN_BUZZ 29


struct string {
  char *ptr;
  size_t len;
};

void init_string(struct string *s) {
  s->len = 0;
  s->ptr = malloc(s->len+1);
  if (s->ptr == NULL) {
    fprintf(stderr, "malloc() failed\n");
    exit(EXIT_FAILURE);
  }
  s->ptr[0] = '\0';
}

size_t writefunc(void *ptr, size_t size, size_t nmemb, struct string *s)
{
  size_t new_len = s->len + size*nmemb;
  s->ptr = realloc(s->ptr, new_len+1);
  if (s->ptr == NULL) {
    fprintf(stderr, "realloc() failed\n");
    exit(EXIT_FAILURE);
  }
  memcpy(s->ptr+s->len, ptr, size*nmemb);
  s->ptr[new_len] = '\0';
  s->len = new_len;

  return size*nmemb;
}

//coisas do sensor ultrasonico

long getMicrotime(){
  struct timeval currentTime;
  gettimeofday(&currentTime, NULL);

  return currentTime.tv_sec * (int)1e6 + currentTime.tv_usec;
}

float readDistanceInMilimeters() {
    pinMode(PIN_TRIGGER, OUTPUT);
    digitalWrite(PIN_TRIGGER, LOW);

    pinMode(PIN_ECHO, INPUT);

    digitalWrite(PIN_TRIGGER, HIGH);
    usleep(10);
    digitalWrite(PIN_TRIGGER, LOW);

    int echo, previousEcho, lowHigh, highLow;
    long startTime, stopTime, difference;
    float rangeCm;
    lowHigh = highLow = echo = previousEcho = 0;
    while(0 == lowHigh || highLow == 0) {
        previousEcho = echo;
```

```
        echo = digitalRead(PIN_ECHO);
        if(0 == lowHigh && 0 == previousEcho && 1 == echo) {
            lowHigh = 1;
            startTime = getMicrotime();
        }
        if(1 == lowHigh && 1 == previousEcho && 0 == echo) {
            highLow = 1;
            stopTime = getMicrotime();
            }
        }
    difference = stopTime - startTime;
    rangeCm = difference / 58;
    return rangeCm*10;
}



void printLineCentered(int lineNumber, char msg[]) {
    int remaining;
    remaining = strlen(msg);
    if (remaining>COLS) {
        mvaddstr(lineNumber, 0, msg);
    } else {
        remaining = COLS - remaining;
        remaining = remaining/2;
        mvaddstr(lineNumber, remaining, msg);
    }
}

void printBreak(int lineNumber, char separator) {
    int x;
    for (x=0;x<COLS;x++) {
        mvaddch(lineNumber,x,separator);
    }
}

void drawWelcomeScreen () {
    printBreak(0,'-');
    printBreak(1,'-');
    printBreak(2,'-');
    printLineCentered(1," ROVER CONTROL ");
    mvaddstr(5, TAB, "Use the directional Keys (or the keys a,s,d,w) to control the Rover");
    mvaddstr(6, TAB, "Press q to quit");
    printBreak(8,'-');
    printBreak(9,'-');
    printBreak(10,'-');
    printLineCentered(9," CURRENT STATUS ");

}

void printStatus(char c[]) {
    printBreak(STATUS_LINE,' ');
    mvaddstr(STATUS_LINE, TAB, c);
}


void goForward() {
    printStatus("Going Forward");
    digitalWrite (P1, HIGH);
    digitalWrite (P2, LOW);
    digitalWrite (P3, HIGH);
    digitalWrite (P4, LOW);
}

void goBackward() {
    printStatus("Going Backward");
    digitalWrite (P1, LOW);
```

```
    digitalWrite (P2, HIGH);
    digitalWrite (P3, LOW);
    digitalWrite (P4, HIGH);
}

void goLeft() {
    printStatus("Turning Left");
    digitalWrite (P1, LOW);
    digitalWrite (P2, HIGH);
    digitalWrite (P3, HIGH);
    digitalWrite (P4, LOW);
}

void goRight() {
    printStatus("Turning Right");
    digitalWrite (P1, HIGH);
    digitalWrite (P2, LOW);
    digitalWrite (P3, LOW);
    digitalWrite (P4, HIGH);
}

void stopRover() {
    printStatus("Stopped");
    digitalWrite (P1, HIGH);
    digitalWrite (P2, HIGH);
    digitalWrite (P3, HIGH);
    digitalWrite (P4, HIGH);

}

void horn() {
    digitalWrite (PIN_BUZZ, HIGH);

}

void initBoard () {
    //Wiring
    wiringPiSetupPhys () ;

    //define pins to control the left side
    pinMode (P1, OUTPUT);
    pinMode (P2, OUTPUT);

    //define pins to control the right side
    pinMode (P3, OUTPUT);
    pinMode (P4, OUTPUT);

    pinMode (P5, OUTPUT);
    pinMode (P6, OUTPUT);

    digitalWrite (P5, HIGH);
    digitalWrite (P6, HIGH);

    pinMode (PIN_ECHO, INPUT);
    pinMode (PIN_TRIGGER, OUTPUT);

    pinMode (PIN_BUZZ, OUTPUT);

}


void initEnvironment() {
    //init the UI
    initscr();
    cbreak();
    noecho();
    keypad(stdscr,TRUE);
}
```

```c

int main (void)
{
    CURL *curl, *curl_post;
    CURLcode res;
    char p;
    char url[150];
    struct string s;
    struct json_object *parsed_json;
    struct json_object *parsed_feeds;
    struct json_object *feeds;
    struct json_object *feed;
    struct json_object *field1;
    struct json_object *entry_id;


    size_t n_feeds;
    size_t i;

    //Temporary variable for storage thingspeak command
    int c;
    int entry;
    int old_entry = 0;

    initBoard();
    initEnvironment();

    drawWelcomeScreen();
    //send a stop command


    // 1 = esquerda
    // 2 = direita
    // 3 = pra frente
    // 4 = pra traz
    // 5 = parar
    float distancia = 0;

    while(1) {
        distancia = readDistanceInMilimeters();
        sprintf(url,"https://api.thingspeak.com/update?api_key=OVT9OAHUSB3L5YSJ&field1=%f", distancia);
        //postando a distancia no thinkspeak
        curl_post = curl_easy_init();
        if(curl_post){
            curl_easy_setopt(curl_post, CURLOPT_URL, url);
            res = curl_easy_perform(curl_post);

        }
        curl_easy_cleanup(curl_post);

        //dando get nos comandos
        curl = curl_easy_init();
        init_string(&s);
        if(curl) {
            curl_easy_setopt(curl, CURLOPT_CUSTOMREQUEST, "GET");
            curl_easy_setopt(curl, CURLOPT_URL, "https://api.thingspeak.com/channels/1610089/fields/1.json?api_key=IMEJ81H8EYTMTL5U&results=1%0A");
            curl_easy_setopt(curl, CURLOPT_FOLLOWLOCATION, 1L);
            curl_easy_setopt(curl, CURLOPT_DEFAULT_PROTOCOL, "https");
            curl_easy_setopt(curl, CURLOPT_WRITEFUNCTION, writefunc);
            curl_easy_setopt(curl, CURLOPT_WRITEDATA, &s);
            res = curl_easy_perform(curl);
        }
        curl_easy_cleanup(curl);

```

```
        //tratando os comandos
        parsed_json = json_tokener_parse(s.ptr);
        json_object_object_get_ex(parsed_json, "feeds", &feeds);
        n_feeds = json_object_array_length(feeds);
        for(i=0;i<n_feeds;i++) {
            feed = json_object_array_get_idx(feeds, i);
            json_object_object_get_ex(feed, "field1", &field1); // campo do comando
            json_object_object_get_ex(feed, "entry_id", &entry_id); // campo da contagem de entradas, essa varialvel é
                                                                    // que garante que não fiquemos presos no mesmo co
        }
        entry = json_object_get_int(entry_id);
        c = json_object_get_int(field1);

    if(entry == old_entry) {
        // esse if é para não ficar repetindo o mesmo comando
        continue;
    } else {
        switch (c)
        {
            case 1:
                goLeft();
                old_entry = entry;
                break;
            case 2:
                goRight();
                old_entry = entry;
                break;
            case 3:
                goForward();
                old_entry = entry;
                break;
            case 4:
                goBackward();
                old_entry = entry;
                break;
            case 5:
                stopRover();
                old_entry = entry;
                break;
        }
    }

    if (halfdelay(5) != ERR) {
        while(getch() == c)
            if(halfdelay(1) ==ERR) break;
    }

    stopRover();
    cbreak();
    }
    endwin();
    return 0;
}

```

Program that establishes the UART communication between the Labrador and Pulga core.

```
#include <ncurses.h>
#include <wiringPi.h>
#include <string.h>
```

```
#include <curl/curl.h>
#include <json-c/json.h>
#include <unistd.h>
#include <time.h>
#include <stdio.h>
#include <stdlib.h>
#include <termios.h>
#include <fcntl.h>
#include <sys/select.h>
#include <sys/types.h>
#include <sys/ioctl.h>

//Structure of the string sent by the Pulga: <sv1,v2,v3>

int serial_open(const char *device, const int baud, int bytes_to_trigger)
{
    struct termios options; //default termios for inspire
    speed_t myBaud;
    int status, fd, ret = 0;
    unsigned int non_standard_baud = 0;
    switch (baud)
    {

    case 50:
        myBaud = B50;
        break;
    case 75:
        myBaud = B75;
        break;
    case 110:
        myBaud = B110;
        break;
    case 134:
        myBaud = B134;
        break;
    case 150:
        myBaud = B150;
        break;
    case 200:
        myBaud = B200;
        break;
    case 300:
        myBaud = B300;
        break;
    case 600:
        myBaud = B600;
        break;
    case 1200:
        myBaud = B1200;
        break;
    case 1800:
        myBaud = B1800;
        break;
    case 2400:
        myBaud = B2400;
        break;
    case 4800:
        myBaud = B4800;
        break;
    case 9600:
        myBaud = B9600;
        break;
    case 19200:
        myBaud = B19200;
        break;
    case 38400:
        myBaud = B38400;
        break;
```

```
    case 57600:
        myBaud = B57600;
        break;
    case 115200:
        myBaud = B115200;
        break;
    case 230400:
        myBaud = B230400;
        break;

    default:
        /*non default values*/
        non_standard_baud = 1;
        break;
    }

    /*open file descriptor*/
    fd = open (device, O_RDWR | O_NOCTTY | O_NDELAY | O_NONBLOCK);
    if (fd < 0)
        return -1;

    fcntl (fd, F_SETFL, O_RDWR);

    // Get and modify current options:
    tcgetattr (fd, &options) ;

    cfmakeraw(&options);
    if(non_standard_baud == 1){
         /*just set to 115200, but there is no use*/
         cfsetispeed (&options, B115200);
         cfsetospeed (&options, B115200);
     }else{
         cfsetispeed (&options, myBaud);
         cfsetospeed (&options, myBaud);
     }
     options.c_cflag |= (CLOCAL | CREAD);
     options.c_cflag &= ~PARENB;
     options.c_cflag &= ~CSTOPB;
     options.c_cflag &= ~CSIZE;
     options.c_cflag |= CS8;
     options.c_iflag &= ~(IXON | IXOFF | IXANY);
     options.c_lflag &= ~(ICANON | ECHO | ECHOE | ISIG);
     options.c_oflag &= ~OPOST;

     options.c_cc [VMIN]  = bytes_to_trigger; //check when have at least 6 bytes in serial
     options.c_cc [VTIME] = 0;

     ret = tcsetattr (fd, TCSANOW | TCSAFLUSH, &options) ;
     if(ret != 0){
         printf("\n ERROR ! in Setting attributes in %s\n", device);
         return -3;
     }

     tcflush(fd, TCIFLUSH);

     ioctl (fd, TIOCMGET, &status);

     status |= TIOCM_DTR ;
     status |= TIOCM_RTS ;

     ioctl (fd, TIOCMSET, &status);

     //uart_set_custom_baudrate(fd, baud);
     //delay(10);

     return fd ;
}
```

```

char buffer_global[1000];
int serial_pulga;

void serial_rx(){
    char serial_rx_buffer[1000];
    int i = 0, ret;
    int bytes;
    bytes = read(serial_pulga, &serial_rx_buffer, 100);
    printf("rx %d bytes from pulga\n", bytes);
    serial_rx_buffer[bytes] = '\0';
    printf("Data received: %s\n", serial_rx_buffer);
        }

int main() {
    struct timeval tv;
    int ret;
    fd_set rfds;
    int maxfd;     /* maximum file descriptor used */

    serial_pulga = serial_open("/dev/ttyS0", 115200, 8);
        if(serial_pulga < 0){
            printf("ERRO /dev/ttyS0\n");
            return -1;
   }

    FD_ZERO(&rfds);
    FD_SET(serial_pulga, &rfds);
    maxfd = serial_pulga + 1;

    ret = write(serial_pulga, "a", 2);
    if(ret <= 0){
         printf("Erro write\n");
    }

    tv.tv_sec = 0;
    tv.tv_usec = 100000;
    while(1){
    /*set serial to be read on select call*/
    FD_SET(serial_pulga, &rfds);

    ret = select(maxfd, &rfds, NULL, NULL, &tv);
    if(ret == -1 ){
        printf("There are error in Select() call\n");
    }else{
            if (FD_ISSET(serial_pulga, &rfds)){         // input from source 1 available
                serial_rx();
            }

      }

   }
return 0;
 }
```

APPENDIX E - ASSEMBLING INSTRUCTIONS OF THE VEHICLE

This appendix summarizes the steps followed for assembling the structure of the smart vehicle.

The chassis of the OSEPP Tank Kit comes ready to be used. It has multiple holes where control boards, sensors, and other components can be attached using spacers or screws. Developers can adapt the structure to create different configurations easily. The vehicle structure was assembled using the following components:

- Chassi OSEPP Tank Kit.
- Labrador 32-bits.
- Dual H-bridge motor driver.
- Lead-acid battery.

The vehicle is controlled by a control board, which is the Labrador 32-bits in this research work. The following connections are made to the board:

- Power supply: It is connected directly to the output of the battery.
- Control signal: Arbitrary GPIO pins can be selected to connect the H-bridge motor driver to the control board.
- 5V signal: The 5-volt pin is connected to the H-bridge motor driver on the reference port.

The dual H-bridge motor driver has the following connections:

- DC motors: The DC motors are connected one on each side of the H-bridge motor driver.
- Power supply: It is connected directly to the output of the battery.
- Voltage reference: It is gathered from the control board.
- Control signal: It is used for controlling the state, rotation, and speed of the DC motors.

Figure 26 describes the GPIO configuration of the Labrador 32-bits. GPIO are pins in which it is possible to send and receive data. Labrador boards adopt the standard userspace interface for embedded Linux and use the library *wiringK9*, which is based on the *wiringPi*.

Sensors are connected to the Labrador board using the GPIO pins, which can be selected arbitrarily in accordance with the configuration shown in Figure 26.

Figure 26 - GPIO Labrador 32-bits

FUNC	SODIMM	HEADER		SODIMM	FUNC
3.3V	N/C	1	2	N/C	5V
GPIOE3/TWI_SDATA	41	3	4	N/C	5V
GPIOE2/TWI2_ SCLK	43	5	6	N/C	GND
GPIOB18/OAP/TS_CLK/LCD0_D19	134	7	8	17	**GPIOC27**/SPI1_SS/I2C0_SCLK/SPDIF/UART0_TX
GND	N/C	9	10	19	**GPIOC26**/SPI1_MISO/I2C0_SDATA/UART0_RX
GPIOC0/DSI_DP3/SD1_CLK/LCD0_D16	161	11	12	34	**GPIOB8**/PWM3/SD0_CLK/KS_OUT1
GPIOC1/DSI_DN3/SD1_D3/LCD0_D9	163	13	14	N/C	GND
GPIOC4/DSI_CP/SD1_D1/LCD0_D1	167	15	16	103	**GPIOA25**/SIRQ1
3.3V	N/C	17	18	149	**GPIOC6**/DSI_DP0/UART2_RX/SPIO_MISO
GPIOC25/TWI3_SDATA/PCM0_SYNC/SPI0_MOSI	53	19	20	N/C	GND
GPIOC24/I2S_MCLK1/PCM0_IN/SPI0_MISO	55	21	22	169	**GPIOC5**/LCD0_D0/DSI_CN/SD1_D0
GPIOC22/TWI3_SCLK/PCM0_CLK/SPI0_SCLK	47	23	24	51	**GPIOC23**/I2S_LRCLK1/PCM0_OUT/SPI0_SS
GND	N/C	25	26	136	**GPIOB19**/OAN/TS_START/LCD0_D15
GPIOB16/OBP/TS_IN1/LCD0_D21	140	27	28	146	**GPIOB14**/OCP/TS_IN0/LCD0_D23
GPIOB15/OCN/TS_IN2/LCD0_D22	148	29	30	N/C	GND
GPIOB10/OEP/TS_IN7/LCD0_DCLK0	158	31	32	154	**GPIOB13**/ODN/TS_IN4/LCD0_VSYNC0
GPIOB0/PCM0_OUT/I2S_BCLK1	9	33	34	N/C	GND
GPIOB1/PCM0_CLK/I2S_LRCLK1	13	35	36	7	**GPIOA28**/PCM0_IN/I2S_BCLK0
GPIOB2/PCM0_SYNC/I2S_MCLK1	15	37	38	5	**GPIOA31**/I2S_D1
GND	N/C	39	40	3	**GPIOA27**/I2S_D0

Default Function	Header Pin		Default Function
VCC	1	2	5V
GPIOE3	3	4	5V
GPIOE2	5	6	GND
GPIOB18	7	8	UART0_TX
GND	9	10	UART0_RX
GPIOC0	11	12	GPIOB8
GPIOC1	13	14	GND
GPIOC4	15	16	GPIOD30
VCC	17	18	GPIOC6
TWI3_SDA	19	20	GND
GPIOC24	21	22	GPIOC5
TWI3_SCK	23	24	GPIOC23
GND	25	26	GPIOB19
GPIOB16	27	28	GPIOB14
GPIOB15	29	30	GND
GPIOB10	31	32	GPIOB13
GPIOB0	33	34	GND
GPIOB1	35	36	GPIOA28
GPIOB2	37	38	RESERVED
GND	39	40	RESERVED

Source: CANINOS LOUCOS (2022)