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From Expert Computational Knowledge to Interdisciplinary Communication

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ABSTRACT

In the contemporary landscape, the fields of cybernetics, artificial intelligence, and digital technology significantly impact society, reshaping production processes, decision-making frameworks, and human behaviors. Training engineers with transversal skills becomes imperative to navigate workflow complexities and communicate across these disciplines. We propose a new learning approach structured around expert prerequisites, integrating AI principles dedicated to Embedded Systems engineering track. Our module focuses on creating an autonomous driving vehicle using an autonomous robot kit, fostering interdisciplinary learning. Real-time demonstrations assess learning outcomes, emphasizing problem-solving skills. Inspired from recent evaluation concept of interdisciplinary assessment. Our evaluation criteria emphasize functionality, integrated idea defense, and written reports. The defense organization scheme fosters positive perceptions of interdisciplinary links.

Keywords: Interdisciplinarity, Embedded Systems, Artificial Intelligence, Autonomous Robot.

1. INTRODUCTION

In the contemporary landscape, the fields of cybernetics, artificial intelligence, and digital technology are deeply impacting society, reshaping production processes, decision-making frameworks, and human behaviors. Each field requires specialized knowledge and vocabulary, yet they converge at the application level, driving significant trends in product innovation. However, deep expertise in each area often leads to communication issues [1], hampering the efficiency of manufacturing processes. Recognizing this, it is imperative to train a new generation of engineers with transversal skills, enabling them to navigate the complexities of workflow management and communicate seamlessly across disciplinary boundaries.

This imperative is particularly evident in the domain of embedded systems. From the mobile, wearable, and smart devices of today to the transformative Artificial Intelligence (AI), 5G-powered Internet of Things (IoT), and Edge Computing, embedded systems are the fundamental building blocks of our connected and automated world. As we transition from billions to trillions of intelligent, connected devices, the next generation of engineers must possess a thorough understanding of how to build and deploy modern embedded system solutions, along with the ability to communicate efficiently in this multidisciplinary domain [18].

For over 20 years, ESIEE Paris has specialized in embedded systems education, preparing students with in-depth and comprehensive knowledge to design, build, and program intelligent software and hardware that comply with strict requirements concerning time latency, power consumption, reliability, and cost efficiency. In the two-year track program, students develop practical skills and theoretical knowledge in embedded systems engineering.

In response to the imperative of training engineers with interdisciplinary skills, we propose introducing a new learning approach aimed at students in the embedded systems program. This approach is strategically structured around the hierarchy of expert prerequisites from multiple domains, encompassing control theory, real-time embedded systems, communications, robotics, perception, and system coding. Additionally, we integrate fundamental artificial intelligence and its computational principles from learning to application. Thus, the interdisciplinary learning process can benefit from the interactions among AI techniques and its applicative fields [17].

This article introduces this new teaching module designed with the main goal of creating a fully autonomous driving vehicle using an existing autonomous robot kit. From design to implementation, different expert domains are integrated, and the system's behavior is rigorously evaluated. Constraints related to the quality of scene analysis based on AI, real-time performance, precise control strategy, and the modularity/generality of the software architecture that integrates the system's cybernetic features are considered.

Through a combination of ad-hoc expert courses providing cross-disciplinary perspectives and a supervised project, student teams delve into the intricacies of optimizing autonomous systems based on artificial intelligence. Through this experiential learning approach, students are exposed to real-world situations that require a circular process of interaction and interpretation across cybernetics, artificial intelligence, and digital technologies. The teams work concurrently, and experience sharing occurs throughout the project. By engaging in collaborative efforts, students not only gain a nuanced understanding of the inherent complexities in these domains but also engage in interdisciplinary research and communication to identify and integrate the expected solution.

The assessment of learning outcomes involves real-time demonstrations conducted simultaneously for all groups in a competitive manner. The validation of the module's success depends not only on the satisfaction of specific constraints adapted to each domain but also on the ability to link disciplinary issues and defend the chosen solution. The audience is invited to witness and interact with the teams, fostering a collaborative environment for the exchange of knowledge and exploration of different approaches. This approach not only bridges the communication gap between fields but also equips the next generation of engineers with the interdisciplinary prowess needed to advance the convergence of cybernetics, artificial intelligence, and digital technologies.

The paper is organized as follows: the second section discusses the role of interdisciplinary communication acquisition in the context of engineering education, the third section briefly outlines the current curriculum in terms of acquiring expert skills, the fourth section introduces our new module and the expected learning outcomes, the fifth section analyzes its pedagogical contributions, and finally, we conclude in the last section.

2. EXPERT KNOWLEDGE VERSUS INTERDISCIPLINARITY IN SCIENCE

In the field of embedded system engineering, there exists a notable contradiction between the demand for expert knowledge and the critical necessity for interdisciplinary communication skills [8, 9]. This contradiction stems from the complex nature of embedded systems and the diverse range of domains they intersect with.

Firstly, embedded system engineering requires a deep understanding of hardware and software integration, real-time operating systems, low-level programming languages, and electronic components. Engineers need to possess expert knowledge in areas such as microcontroller architectures, circuit design, firmware development, and optimization techniques to ensure the efficient running of embedded systems. These technical competencies are essential for designing and implementing complex applications [7].

However, despite the emphasis on technical expertise, the success of embedded system projects often hinges on effective interdisciplinary communication. Embedded systems typically operate within larger systems or applications and can be seen as cyber-physical systems. They involve collaboration with professionals from diverse fields such as computer science, electrical engineering, mechanical engineering, and industrial design[14]. Communicating effectively with specialists from these different disciplines is crucial for integrating embedded systems seamlessly into broader contexts.

Furthermore, embedded systems are increasingly integrated within IoT ecosystems, smart devices, and cyber-physical systems, which demand an integrated approach to design and development[5, 6]. As the complexity and interconnectedness of embedded systems continue to grow, specific domain application overlaps, and the ability to communicate and collaborate across disciplines are becoming increasingly mandatory for engineers in this field [8]. Thus, it becomes evident that multidisciplinary issues should be properly addressed in the academic context[11]. The interdisciplinary understanding and synergy achieved should be a part of the learning outcomes [9, 13].

However, despite the critical importance of interdisciplinary communication skills, they are often overlooked or undervalued in traditional engineering education programs. It is important to remove the methodological and conceptual barriers to working across disciplinary boundaries. Indeed, as shown in[12, 14], there are cognitive barriers linked to highly domain-specific scientific practices, which can limit the potential for interdisciplinary work. Thus, balancing the acquisition of expert knowledge with the development of interdisciplinary skills is paramount for preparing engineers to thrive in the dynamic and interdisciplinary domain of embedded systems [7].

3. EXPERT SKILLS OF EMBEDDED SYSTEM ENGINEERING TRACK

In response to the increasing demands for embedded systems expertise, our Embedded System track program is tailored to equip students with the requisite skills and knowledge essential for addressing complex challenges in the field. In general, the program of this course relies on the overall learning outcomes framework, shared among all the programs offered by this institution (Fig. 1).

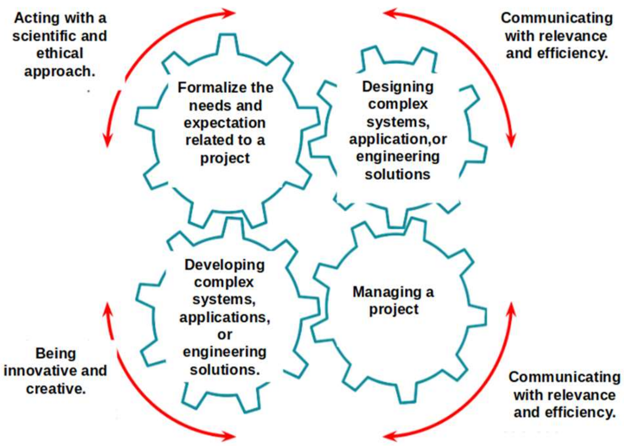


Figure 1: The eight main skill sets upon which the construction of the curriculum of engineering specializations at ESIEE Paris (an engineering school of University Gustave Eiffel) is based [13].

As industries increasingly rely on embedded systems for critical functions, the program emphasizes the development of robust solutions that adhere to stringent requirements concerning time latency, power consumption, reliability, and cost efficiency. The scientific curriculum of the Embedded Systems track is designed to cultivate proficiency across a spectrum of domains within embedded systems engineering.

Recognizing the interdisciplinary nature of the field, courses integrate principles from computer science and electrical engineering, encompassing vital areas such as hardware design, real-time embedded development, signal processing, and control. Moreover, the program underscores the necessity for expertise in Model-Based Systems Engineering with SysML methodology, enabling students to conceptualize system models and articulate high-level behavioral specifications of control system components using state charts [4], fostering a holistic understanding of system dynamics and feedback mechanisms.

In Figure 2, we can see that the space dedicated to interdisciplinarity is condensed within the slots allocated to projects or internships. The advantage of this organization is that it allows for the mixing of audiences from different fields and the development of professional interactions. The disadvantage is that it remains an uncontrolled mechanism, and the cognitive aspect is not always positively encouraged.

We have therefore decided to take advantage of the introduction of a new teaching module to incorporate this interdisciplinary aspect into a controlled and explicit pedagogical process. Thus, in the 'Advanced Sciences and Techniques' block, we introduce the fundamentals of artificial intelligence while managing the learning process in a context that requires a critical integration of knowledge from other very specific domains (such as automation, real-time systems, and electronics). Our teaching module aims to enable students to deeply understand the opportunities and challenges presented by the convergence of these domains.

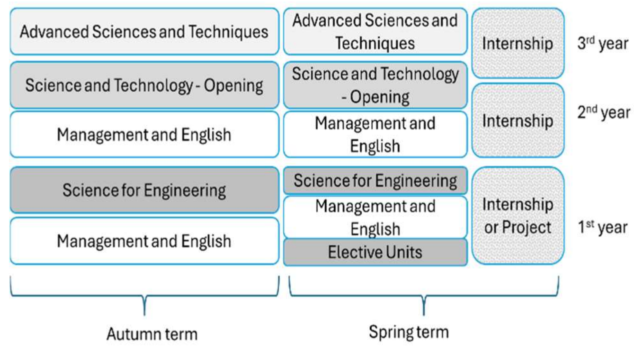


Figure 2: Classic organization of teaching domains. The space dedicated to multidisciplinarity is located within the projects and internships slots.

4. ARTIFICIAL INTELLIGENCE AND EMBEDDED SYSTEMS

As mentioned, the module entitled "Artificial Intelligence for Embedded Systems" is taught in the final year of the engineering program. It consists of 30 hours of scheduled in-person instruction, distributed as follows: 10 hours of lectures, 6 hours of supervised practical work, and 14 hours of supervised projects. The lectures and practical work are intended to build new knowledge and skills not yet developed in previously completed modules. Meanwhile, the project, centered around robotic applications, serves as an interdisciplinary playground [7-9].

Figure 3 illustrates the construction of the course organization, which follows a classical approach in the transmission of fundamentals. It starts with the introduction of computational models, moves through the analysis of optimization techniques and the construction of deep neural networks, and finally delves into state-of-the-art DNNs, applications, and constraints. Each set of theoretical knowledge is accompanied by a practical session aimed at building specific and strictly defined outcomes and standard evaluation.

After this condensed learning of the basics of AI, 40% of the allocated time is dedicated to the completion of a project where interdisciplinary collaboration is supervised by two teachers specialized in two different fields: AI and real-time systems. The application project relies on the creation of an autonomous robot (representing an example of an autonomous vehicle) that utilizes an onboard color camera for perceiving its environment. This allows us to construct a cybernetic study object as it implements the action-perception cycle in the context of action-oriented perception [5], with the possibility to dynamically modify motor behavior based on sensing [6].

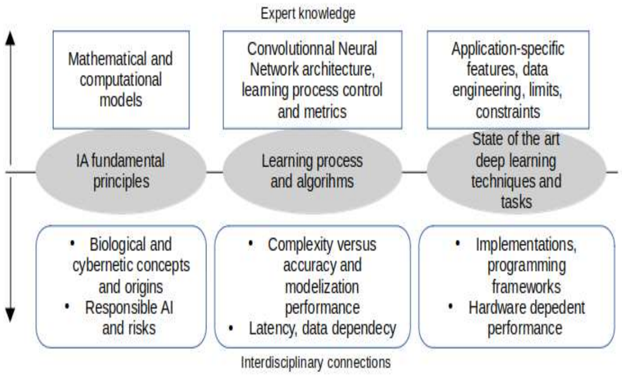


Figure 3: Course program and the covered topics

The project specifications are to create a robot that moves autonomously on a model city layout. It must detect not only the information necessary to maintain its trajectory but also detect obstacles, road signs, the presence of intersections, the opportunity to change direction, etc. The specifications are accompanied by implementation constraints, such as the computation board, the electronic motor control board, and the camera's position. Students are required to use the knowledge building blocks learned previously: artificial intelligence in this module, ROS (Robot Operating System) [15], and control theory (Figure 4).

Thus, the success of the project relies on balancing the domain-specific system components: model complexity and execution time performance (AI domain) versus control computing (control theory) and real-time execution (ROS running and motors steering).

The computation board (like Raspberry Pi 4, 4GB of RAM) limits the available computing power without the possibility to exploit a graphics card due to the lack of development tools. This necessitates students to implement system optimization by striking a balance between latency, precision, and real-time requirements. Naturally, this will involve iterative experimentation and modification, delving into the intersection of parallel improvements in AI implementation and dynamic control by confronting them with the physics of motion, perception, and their uncertainties.

The students work in teams (a maximum of three students) in a laboratory equipped with TurtleBot-type robots [16] and a shared city model platform (Figure 5). Thus, teams can communicate with each other, observe the progress and bottlenecks of others. Teacher supervision focuses on coaching, enabling exchanges on observed problems by interconnecting the specificities of each scientific domain. For instance, poor trajectory tracking can result in a connection between data engineering and the consequences on control in case of inaccuracies, or on the adaptation of control parameters relative to the image acquisition frequencies and scales in perception data. The interdisciplinary collaboration is driven by the need for an effective problem-solving method, stimulated by real-world experiences, thereby forming a closed loop of development-observation-action.

The project evaluation is organized in the presence of all teams, where each demonstrates their solution efficiency and the implementation functioning on the robot, detailing the functional and non-functional aspects to improve. Emphasis is given to each team's individual contribution and an innovative aspect of the solution to meet or even exceed the specifications.

5. INTERDISCIPLINARY COMMUNICATION

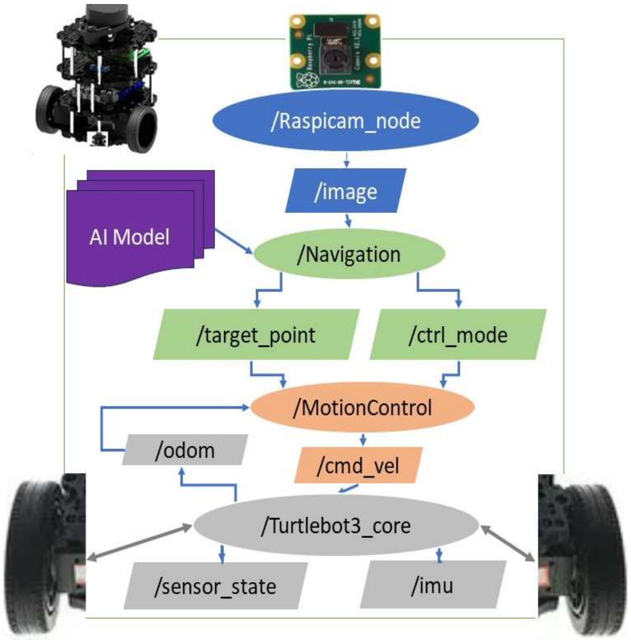
Measuring, quantifying, or evaluating interdisciplinarity can be challenging due to its complex and subjective nature. Here are some reasons why it can be difficult. Similarly, measuring interactions between disciplines remains challenging. However, through mentoring and evaluation techniques, interdisciplinarity can be highlighted along with the ability to establish effective communication in this context.

In [14], Wang and Schneider highlight the utility of using a real-life object for integrating knowledge from different domains to enable an evaluation process. Since we are in an educational environment, this concept is particularly interesting because traditional measurement metrics such as references are not applicable. Conversely, we can implement the evaluation of the integration of ideas from different domains, which is examined by hand, i.e., cognitively. This evidence can be the strongest. Thus, we have established three evaluation criteria for the project presented above:

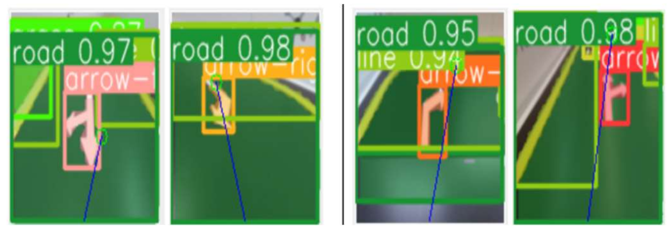
Demonstration of functionality with an objective quality assessment of execution and compliance with specifications.

Public defense of integrated ideas from the scientific domains applied to the project, including an evaluation of their contributions to project solving.

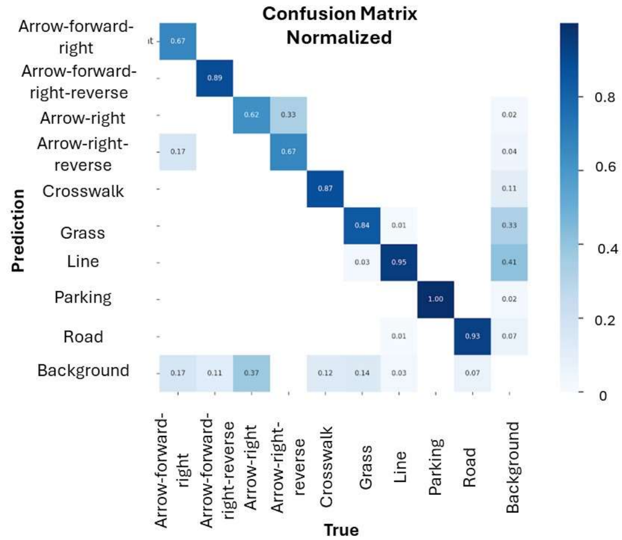
Written report highlighting the solutions of each disciplinary component of the project and their integration.



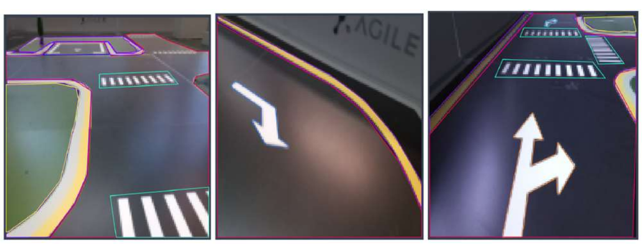
(a) The embedded controller architecture: it is composed of two ROS nodes, "navigation" and "motion control", communicating through topic-based messaging, according to the publish-subscribe model. The navigation node listens to the topic /image received from the Raspicam_node at the frequency of 5 FPS. This node then uses the onboard AI model and the object detection and segmentation to do the navigation decision and to construct the target trajectory (topic /target_point). The motion control node uses the coordinates of the trajectory and the localization of the robot (topic /odom) to control the kinematic and the velocity of the robot (topic /cmd_vel).



(c) Learning process control and evaluation.



(d) Control command estimation (blue line).



b) Data engineering

Model	Size (pixels)	mAPval 50-95	Engine	FPS CPU	FPS RPI 4	NB params
YOLOv8n	640	37.2	PyTorch	48.78	1.6	8.7 M
YOLOv8n	640	37.2	ONNXRuntime	46.00	2.1	
YOLOv8s	640	44.6	PyTorch	31.95	1,47	28.6 M
YOLOv8s	640	44.6	ONNXRuntime	30.83	n.c.	

(e) Confrontation of computing performance available and needed by the AI model.

Figure 4: Examples of students work outputs from intermediate steps of the project.

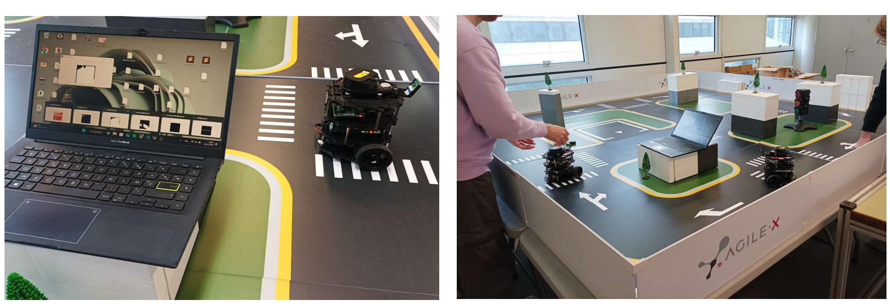


Figure 5: In situ validation and tests of system behavior. The robot must perform autonomous navigation task in hard lighting conditions making IA model road recognition complex problem requiring a deep neural network challenging computing resources as well as system robustness.

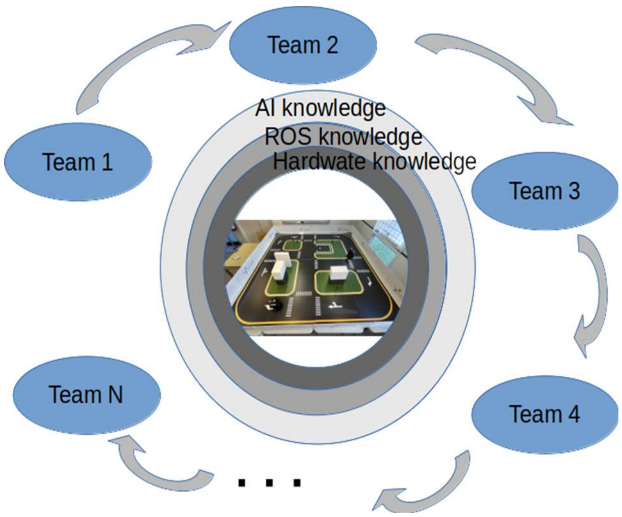


Figure 6: Project evaluation organization scheme

Figure 6 presents the progress of the defense, which indeed allows for 2 hours of communication and exchanges with the student teams, during which the disciplinary knowledge integrated into the projects is discussed at an expert level and interactions take place. This results in communication with a positive perception of interdisciplinary links by the learners.

6. CONCLUSIONS

The interdisciplinary nature of fields such as embedded systems engineering necessitates a balance between expert knowledge acquisition and effective communication across disciplines. While technical expertise is crucial for the successful implementation of embedded systems projects, effective interdisciplinary communication is equally important.

ESIEE's approach to training engineers in embedded systems reflects a commitment to addressing the complexities of interdisciplinary collaboration. By integrating AI principles into the curriculum and emphasizing experiential learning through projects such as autonomous driving vehicle creation, ESIEE prepares students to thrive in dynamic and interdisciplinary environments.

Furthermore, the evaluation criteria outlined in this paper emphasize the importance of functionality demonstration, multi-domain integrated idea defense, and written reports in assessing students' interdisciplinary skills.

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