A FRAMEWORK FOR THE TEACHING OF AUTONOMOUS MOBILE ROBOTICS

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ABSTRACT

A framework for teaching Autonomous Mobile Robotics is presented. The activity is part of the Bachelor's program in Artificial Intelligence at the Federal University of Goiás, Brazil. The program runs over four years, and the framework was built as a design-implement experience for a course module in autonomous mobile robotics in the fourth year. The first years of the program contain mandatory course modules in entrepreneurship, mathematics, and computer science, and the course module in robotics is the second one where students are introduced to a design-implement experience based on the CDIO framework. The course module was designed in collaboration with engineers from Synkar Autonomous in Brazil to validate the design process. The course framework consisted of software and hardware resources, such as container virtualization to run repeatable test cases, ROS2 for developing robotic software and applications, project management using kanban to suit the lifecycle of robotic prototyping (i.e., hardware-based software development), and the "AIbot" customized robot designed for the practical experiences. As a result, we created a first design-implement experience in robotics, that was able to match basic professional skills demanded by industry, such as agile development, reproducibility, and software modularization. The framework also served to train the students with the best practices and modern methodologies used by leading companies in robotics. Finally, some reflections and lessons learned were pointed out to further improve the course module in future.

KEYWORDS

Design-implement experience, robotics, project-based learning, Standards: 2, 4, 5, 11.

INTRODUCTION

A key aspect of the CDIO framework is closing the gap between higher education programs and professional work in terms of the competences and skills required of graduates (CDIO Initiative, 2025). With the rapid growth of robotics and artificial intelligence applications, the use of standardized software development tools and agile methods for project management became crucial for companies to deliver scalable robotic products and services. The key to this is to work on standardized methods and professional practices. The present is a follow-up on prior work of the authors, where they introduced a first CDIO design-implement experience at the Computer Vision course module of the Bachelor's in Artificial Intelligence program, at the Federal University of Goiás in Brazil (Gunnarsson & Díaz-Salazar, 2023).

Although design-implement experiences represent a vital component of the CDIO framework (see Standard 5), there is a lack of approaches designed in actual collaboration with the industry. Numerous examples of design-implement experiences have been presented within the CDIO community, and many of them can be accessed through the CDIO website (CDIO Initiative, 2025). For instance, a successful example was presented in (Svensson & Gunnarsson, 2012). For the specific topic presented herein, *i.e.* design-implement experiences within robotics, artificial intelligence, and software development carried out in close collaboration with start-up companies, it is difficult to find examples of design-implement experiences connected to the CDIO framework. Hence the paper has potential to be a contribution to the CDIO community.

BACKGROUND INFORMATION

The CDIO framework

While the idea of sharing our world with robots that cooperate smoothly with us humans is exciting, training undergraduate students with the competences required by the robotics industry is more than challenging. For instance, one of the major issues relies on the high costs of implementing a robotics laboratory and training people for teaching, which means having access to open-source hardware and resources that, more than often, are not publicly available. Today, the integration of a professional robotics curriculum into an educational setting demands access to proprietary tools, and without the direct support of industry in the integration process, it will remain prohibitive for most institutions. In addition to this, bridging the gap between theory and practice is always a challenge for educators: How to teach robotics effectively? How to set up a working framework for robot operation? How to evaluation the learning outcomes during examinations?

In an approach to address part of the challenges, in this work we proposed a first design-implement experience in robotics based on the CDIO framework. The key to success in this case was the establishment of a strategical partnership with the Synkar Autonomous company (Synkar Autonomous, 2024), to explicitly involve them during the design process, lectures and evaluation of the course module. Synkar is a robotics company working with autonomous last-mile delivery of products and services in Brazil and abroad. The partnership with Synkar allowed us to propose a design-implement framework for the teaching of robotics with a strong focus on best practices and skills required from professionals in robotics. We believe that such methodology will allow us to succeed in delivering graduates to society, who are not only technically competent, but also possess experience in problem-solving and communication, as described in (Mezilov *et al*., 2024).

The CDIO framework in Brazil

The CDIO framework is receiving considerable attention in Brazil, starting with the adoption by the Military Engineering Institute (IME). Several universities have joined the CDIO Initiative with increasing contributions to the CDIO literature describing the implementation of the CDIO framework in the Brazilian context. Examples of the latter are (Lourenco & Veraldo, 2015), (Neto *et al.,* 2019), (Passos *et al*., 2019), and (Rezende *et al.,* 2022). Moreover, CDIO can be instrumental towards implementing the Brazilian national guidelines for engineering education, as pointed out in (Rezende *et al.,* 2022). However, stronger connections of the CDIO International community with the Latin American region can be further improved by promoting interactions during the regional meetup events, as observed at the CDIO Conference in Trondheim 2023, where a lack of participants was noticed during the Latin American meetup.

THE CONTEXT OF THE DESIGN-IMPLEMENT EXPERIENCE

The Federal University of Goiás

The Federal University of Goiás (UFG) is the largest public university in the Central-West region of Brazil and is in the city of Goiânia. In numbers, the university has 60 years of history, with 104 undergraduate schools, 78 post-graduate programs, and approximately 22,000 students distributed across four campuses. The module in Autonomous Mobile Robotics is taught in the fourth year of the program in Artificial Intelligence, which is run by the Institute of Informatics.

The Bachelor's Program in Artificial Intelligence

The Bachelor's program in Artificial Intelligence (BIA) at UFG is the first undergraduate program in Artificial Intelligence launched in Brazil and started the activities in March 2020. The entrance examination is run yearly through a nation-wide evaluation, with 30 new students entering the program in every class. The first class concluded activities in February of 2024 and, by January of 2025, there are five classes running courses simultaneously.

The BIA is a four-year program composed of eight semesters corresponding to 3,200 hours. The first three years include course modules in Entrepreneurship, Mathematics, Computer Science, Machine Learning, and Deep Learning. The module in Autonomous Mobile Robotics runs in the seventh semester, with 96 hours of credits in total, and it is the second course module where students are introduced to a design-implement experience according to the CDIO framework, the first course being Computer Vision taught at the fifth semester. The fourth year includes course modules on specialized topics, such as Natural Language Processing, Reinforcement Learning, Robotics and Big Data. The program concludes with the Residence in Artificial Intelligence, which is a course module of 320 hours where students elaborate a capstone project and present it publicly, as part of the requirements for graduation.

A FRAMEWORK FOR TEACHING ROBOTICS

The main contribution of this work to the CDIO community is the proposal of a framework for the teaching of robotics that was defined in close collaboration with an industrial partner (Synkar Autonomous) to train practitioners with modern hardware and software tools that are used in actual professional robotic products and services. The partnership with Synkar has a successful history of recent cooperations, since they are a former spinoff of the local hub of entrepreneurship at the Federal University of Goias and received financial support from the research group on five projects already through the EMBRAII program of innovation (a governmental initiative in Brazil). More specifically, the authors worked together with engineers from Synkar in tasks such as the choice of lecture topics to be discussed, the design of practical laboratories and the proposal of benchmarks for evaluations.

In sum, the proposed framework includes tools such as Docker, ROS2, and Agile development, which are all part of the regular workflow of world-class companies in robotics, such as Tesla, Boston Dynamics, and Synkar on itself. These tools allow companies to deploy products and services that have reproducible results and that can be verified and tested in controlled environments of operation. The educational framework proposed in this work incorporates adapted versions of such tools to cope with specific robotic equipment of the course module. For instance, we adopt Turtlebot as the main platform for teaching, but we also have projects using quadrotors and quadrupeds.

Docker

Docker is a virtualization tool that allows us to develop fully functional work environments in software development (Docker, 2025). Docker is extensively used in modern robotics development due to the use of containers, which are software-defined machines that encapsulate the specifications of a particular software stack, allowing for a controlled operation of the robot's software and the interaction with its low-level hardware interfaces and sensors. The containers enable development of modules of individual features and functionalities of a robot, making it easy to test and debug before going to production. Particularly, we adopted Docker as a strategy to bring the educational context of learning robotics closer to the skills demanded in professional software and hardware services.

ROS2

ROS2 is an open-source robotic framework for the development of applications and services. ROS2 facilitates the design of robotic hardware and software and its simulation in realistic scenarios of operation. Compared to the first version, the architecture of ROS2 is based on the concepts of nodes and topics that make the integration of hardware and software easier and that also facilitates operating robots in swarms of networked environments for Industry 4.0 applications. In this work, we adopted ROS2 for the practical laboratories, giving special attention to the creation of ROS packages, which are customized software modules developed by the students to achieve specific robot tasks. Examples of such tasks are teleoperation and robot localization by fusion of lidar and wheel encoders. The ROS2 setup used in our framework also included the CAD model of a differential robot called "Albot", that was designed for the course module and that can operate in different virtual work environments. From the educational perspective, ROS2 has the additional benefits of being industrial-grade and well documented (Bonci *et al*., 2023).

Agile development

We adopted the agile methodology for the execution of the course module's laboratories. The laboratories consisted of developing software modules that incrementally enabled features of the robot, such as teleoperation or localization. The deliveries were submitted using GitHub Classroom repositories, to control the software versioning and documentation. On a typical repository workspace, the students received basic software templates to startup and a kanban board for monitoring the activities of their projects. The kanban board allowed them to map the lifecycle of a project using a simple strategy based on three stages: "to do", "doing", and "done". The students were evaluated according to the completion of the tasks allocated on each of the stages. The kanban model also allowed them to measure the time execution of the tasks. When performing work in groups, the student's teamwork was supervised through the assignment of the tasks to the individuals of a group and making it easier to follow-up. Agile development is the current standard for project management in modern IT companies and was also adopted in the robotics industry due to its effectiveness (Cao *et al*., 2009).

Albot

Albot is a differential-drive robot designed for the course module in collaboration with (Pequi Mecanico, 2025) and was designed to serve as a platform for the laboratories. Albot is a two-wheel drive robot with a castor wheel and a size of 544x455x413 millimeters. The robot hardware consists of sensors, such as 2D lidar, IMU with 3-axis accelerometers, gyroscopes and magnetometers, wheel encoders, and a camera. Figure 1 shows the schematic of the robot and its operation in a simulated warehouse environment using a vision sensor. The robot model was released under the open-source license and the source code for the simulation can be found on (Albot, 2025).

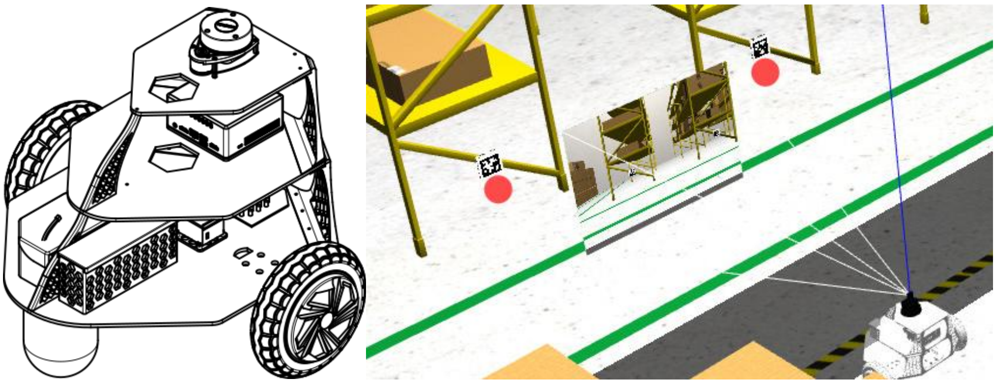

Figure 1. Left: The robot Albot. Right: Simulation of Albot in a warehouse performing localization with known correspondences using AprilTag fiducial markers. A visualization of the forward-looking camera is displayed and highlighted in white rays.

Structure of the course module and learning goals

The course module in Autonomous Mobile Robotics runs over 16 weeks and corresponds to approximately 4 ECTS credits (60 ECTS credits correspond to one year of full-time studies), which means the students are expected to spend 96 hours on the module.

The learning outcomes contain goals related to:

- (Unsupervised) Explain the basic concepts involved in robotic perception and action.
- (Supervised) Apply computer vision techniques to robotic solutions.
- (Following instructions) Apply localization and mapping techniques.
- (Following instructions) Design robot perception and action solutions.

The text in parentheses refers to the levels of incremental learning outcomes of a student towards reaching a goal and they are specified in the Study Plan document of the bachelor's program. These levels serve as checkpoints for the instructor to measure the learning process throughout the course progress. For instance, in the "Unsupervised" level, the students are expected to reach a goal independently without the support from the instructor. On the contrary, at the "Supervised" level, the instructor acts as a guide to help students to reach a goal in a less independent approach. In the "Following instructions" level, the students are expected to execute procedures and methods adequately as specified by the instructor.

Work process and assessment

Twenty-two students attended the lectures and laboratories. When running practical activities, the class was divided into five teams, with an average of five students per team. The teams were sorted out by the students, and each team was required to have a leader who handled the team's management and communication with the instructor.

Four laboratories of three-weeks in duration were performed. They involved the topics of teleoperation, Kalman filtering (KF), Extended Kalman filtering (EKF) and Simultaneous Localization and Mapping (SLAM). The deliveries were performed via incremental submissions through repositories for version control and documentation. As stated by the students, the course in Autonomous Mobile Robotics is both theoretically and practically demanding. Thus, the laboratories were fundamental to drive the learning process of assimilating complex theoretical aspects into actual robotic applications. The challenge was always to motivate the students towards gaining confidence with the implementation of difficult tasks such as robot localization and mapping.

Three evaluations were applied to the students, covering topics such as kinematic modeling of the robot, robot localization with KF and EKF, and SLAM using a combination of lidar and wheel encoders. Each evaluation consisted of a practical challenge designed as a problem-solving scheme that addressed a specific robot task, for instance, controlling the robot with operation from a distance, or mapping and recovering the robot position within an environment that was completely new to it. The assessment was performed in terms of the level of completion of the tasks and some algorithm-specific metrics, such as the total error in odometry or the stability of a localization filter over time. Additional evaluation criteria were focused on the students' design process in terms of prototyping and building the required software packages. The final grade was complemented by an examination that included a written technical report and an oral presentation.

Examples of project tasks and results

The students were introduced to the fundamentals of probabilistic robotics during the lectures, which is the basis of autonomous robot tasks, such as locomotion, kinematics, perception, and localization. Learning robotics in a probabilistic manner enables students to deal with robotic algorithms that can handle uncertain and dynamic scenarios typical of real-world problems, as required in professional services. At the center of probabilistic robotics is the idea of estimating the position and orientation of a robot from sensor data, which in turn deals with the problem of estimating quantities that are not observable directly, but that can be inferred, such as determining the localization of a robot from the set of images of a camera in combination with odometrical data from wheel encoders.

The laboratory sessions focused on solving the previous theoretical problems through the implementation of algorithms in practice. One of the first methods in autonomous robotics is the Kalman filter because it is at the core of many localization problems and, and it provides a convenient setup for discussing some of the key aspects that occur in practice. For instance, the students had the opportunity to experience how to deal with the uncertainty present in the actuators and sensor data by implementing a Kalman filter and were also introduced to the vocabulary and terminology used in modern robotic projects. At the end, three evaluations were applied covering the aspects of kinematic modeling, robot localization and SLAM, as detailed below.

Assessment 1: Kalman filter with constant velocity model

In the first assessment, the participants had to implement a Kalman filter to determine the localization of a vehicle driving through a tunnel without the support from GNSS signals. The only data provided was the velocity in the driving direction from which the students were required to infer the position of the vehicle. Additionally, they had to perform a statistical analysis of the system by corrupting the input data and tuning the covariance matrix of the Kalman filter to keep the filter stability. The experience was implemented with focus on the "Following instructions" learning goal, which means that the instructor provided a template code with guidelines and steps to help the students to develop and customize a first localization filter.

Assessment 2: Extended Kalman filter localization

In the second evaluation, the students implemented a more advanced localization algorithm using the extended Kalman filter. The scenario was a robot moving with constant turn rate in a circular trajectory. In this case, the input data included the velocity of the vehicle, its 2D position and orientation and the goal was to localize the robot on a map. The students were instructed to perform statistical analysis of the data and the system, as in the first assessment, but taking acquaintance of new problems such as the non-linearities present in the design of the filter models. The learning outcome covered in this case was the "Supervised" level, in which the students proposed solutions that were discussed and validated with the instructor.

Assessment 3: EKF-SLAM with known correspondences

The third assessment aimed to evaluate competences in simultaneous localization and mapping (SLAM), which is a fundamental problem in autonomous navigation and mobile robotics. In this case, the students were required to calculate the position of a robot and, at the same time, generate a map of the environment with the coordinates of visual markers encountered along the robot path. This is a problem that is common in scenarios where a robot moves in an environment that is totally new and without previous knowledge of it, such as in robot exploration, search and rescue missions, or last-mile delivery of products, as performed by Synkar. The students already had a solid basis for building own solutions at this stage of the course module, so the "Unsupervised" learning goal was committed in this case.

Observations and student feedback

Some observations and lessons learned can be summarized by the end of the learning activity:

- We used state-of-the-art hardware and software resources used by industry, but those are computationally demanding and, due to this, they could not run efficiently on the computers we had at the local facility. For instance, we needed to swap the ROS2 simulation of the TurtleBot4 robot platform, that was intended to be used originally, with the simulation of the Albot robot because it was a much lighter model to use. This change caused a delay during the preparation of the course activities, which needed to be reformulated to meet the expected duration.
- A second thought is related to the time required to build a first functional framework. This was a hard challenge due to the limited infrastructure we received, which made it difficult to prepare the coursework. Most of the course preparation hours were allocated into

building a working container image, integrating the framework parts (Docker, ROS2, Agile), and designing the Albot robot.

- A third consideration is that the students receive additional follow-up supervision from the teaching assistant weekly. This was an important service that was made available for extra class support and that helped students to reach the learning goals, especially during the execution of practical experiences.

At the completion of the course module, twenty-one students passed (95%), with only one student failing (5%) due to absence during the evaluation process. In general, the overall feedback from the participants concerning the design-implement experience was positive. As feedback for future, the students suggested incorporating more challenges into the framework involving machine learning and artificial intelligence methods, as revealed by the class survey results in Table 1. See (SIGAA, 2023).

Table 1. Results of the teaching evaluation by the class

N	Suspensions	Dimension 2		Dimension 3		Total Avg. [1]	Total Std. [1]
		Avg.	Std.	Avg.	Std.		
22	0	6.35	3.78	9.77	0.60	6.35	3.51

[1] Total Average and Total Standard Deviation are calculated from Dimension 1 -"Institution by the Student" and Dimension 2 - "Instructor by the Student", which are metrics calculated from an institutional survey that UFG applies to the students at the end of each semester, with a maximum of 10.00 points. Dimension 3 is another metric, entitled "Self-assessment by the student", which is also calculated from the same survey.

CONCLUSIONS

In this work we described a framework for the teaching of Autonomous Mobile Robotics that has, as a main contribution, the collaboration of a key industrial partner in robotics. The course module was structured as a design-implement experience in the Bachelor's program in Artificial Intelligence at the Federal University of Goiás in Brazil. We made use of professional tools, such as Docker, ROS2, and Agile methodology that were customized in cooperation with the Synkar company to strengthen the skills and knowledge required in professional robotic products and services. Moreover, the course was designed on top of three learning goals covering unsupervised, supervised and following instructions levels of accomplishment. A first take-home message to the CDIO community is to incorporate local industries in the design-implement processes. The students appreciated the proposed framework from a professional and technical perspective. As shown by the results, the course helped them to incorporate basic professional skills required to develop robotic applications in industry and to put project management abilities in practice. A second contribution to the CDIO community would be to use open-source resources for teaching as much as possible. In case of financial restrictions, the use of customized robot simulation in ROS was key. Finally, the main concern of the class was not related to the proposed framework itself, but to a special request, in which they were asked to incorporate more practical activities involving machine learning methods.

In future, we can also incorporate more individual evaluation methods, such as interviews to have student feedback with finer granularity.

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