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Programming Mobile Robots in an Educational Context: a Hardware-in-the-loop Approach

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***Abstract*— In this paper it is presented a Hardware-in-the-loop (HIL) mobile robot programming approach, to be applied in a robotics educational context. The motivation to apply this approach is the fact that students can program the robots without access to the robot hardware, but still maintain some important closed loop control critical features, such as a realistic lag time and the possibility for a larger number of students to program at the same time. Therefore, the developed software is applied to the real hardware without any change. The HIL approach was applied to provide a simulation close to reality, once the processing occurs in the real robot processor and the actuation and sensorization inside the simulation, adding to the advantage to test the firmware avoiding damage in the physical robot.**

I. INTRODUCTION

According to the growing of mobile robotics technologies in today's society, whether in industries, or in service robotics, there is a necessity to train good professionals qualified for such activities [1]. In this context, STEM areas have been included inside the educational context as a top priority, in order to encourage, attract and motivate young students and researchers to these field [2].

The area of robotic systems covers many of the STEM concepts such as science, engineering, electronics, programming, mechanics, and it can also be applied to develop problem solving and critical thinking skills. Besides that, generates another benefits such as social, emotional, as well as research and development skills. Currently, mobile robots are used as a teaching aid tool from primary schools to universities, undergraduates and post-graduates, providing an excellent way to teach multidisciplinary skills [3].

Applying mobile robots in schools and/or universities most often requires the purchase of equipment, which unfortunately can be expensive, becoming something limited. In recent years, mainly during and after the COVID-19 pandemic, studies have been searching for alternatives for the traditional teaching and learning process. In this case, new education models have been implemented such as remote laboratories, simulations, videoconferences, virtual applications, etc. All these techniques have been provided to be beneficial in many aspects and are increasingly being used in classes [2], [3], [4].

Nowadays, for the design and development of a modern systems by industries, it is required to perform several tests in order to validate the final product, for this reason, simulations and also techniques like Hardware-in-the-loop (HIL) are widely applied. The HIL approach has many benefits, not only in industries, but also inside educational contexts. In comparison with traditional testing and development methods, HIL technique provides the reduction of development time and costs, detection and correction of possible fails in a initial phase of the development, etc [5], [6], [7], [8], [9].

Applying HIL inside an educational context can provide the opportunity to students test the control algorithm in the real hardware, even if the equipment are scarce. Usually classes encompass an amount of students and there is not enough equipment for everyone. In this case, firstly they work in a safe environment, avoiding damages in the equipment and then test their works in real conditions [7], [10].

The students learn concepts through practical experience and interaction with real physical systems beyond simulation and dealing with problems in a practical context [11], [12], [13]. In this context, Hardware-in-the-loop (HIL) is relevant, since the same development board is applied to execute the controller in the real robot, as well as in the simulated one, as illustrated in Figure 1.

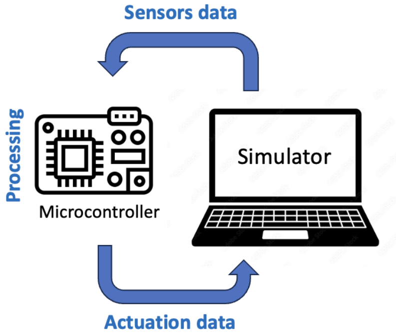

Fig. 1. Hardware-in-the-loop (HIL) architecture

In this approach the physical robot is connected to the virtual robot, therefore the simulator provides the sensor's data acquired to the real embedded controller, which executes

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the processing and control the simulated robot. Through this technique it is possible to deal with the real limitations of hardware, reducing development time, avoiding possible errors in the firmware, which can be tested without hardware damage and also the reduction of costs and risks in experimental tests [1], [14], [6].

This paper has the objective to present the design, prototyping and development of mobile robots for educational classes, by applying HIL approach, proving that this method has benefits inside the robotics educational context.

This paper is structured as follows, in the next section, the developed mobile robot prototype is described in detail, both the mechanical part, as well as the development of its firmware. Then, it is presented a description about the technique Hardware-in-the-loop and how it was applied in this work. Afterwards, the obtained results are shown, followed by the conclusions and future work.

II. MOBILE ROBOT PROTOTYPE

In this section, the mobile robot prototype developed to be applied in the robotics classes is presented. The mechanical design and its data acquisition and processing are shown and discussed, being a detailed description of its kinematics and controller presented in [15]. A total of four mobile robots were assembled, since the students will be divided in several work groups, being each one a team that will participated in a competition.

A. Design and prototyping

The designed mobile robot has a differential kinematics, composed by two wheels where the motors are fixed, a chassis capable to load all the components, including the microcontroller and two frontal pieces, in which the line and distance sensors are attached. All the structure was printed applying 3D technology, as shown in Figure 2. The final robot prototype assembled with all the components is shown in Figure 3.

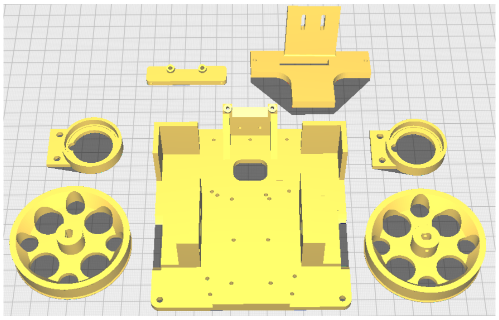


Fig. 2. Mobile robot 3D printing model

The robot was developed with components that allow the robot to be able to follow a line and avoid obstacles. The wheels are composed by two DC motors, controlled by a drive board FIT0450, being responsible for the robot locomotion. The motors have built-in encoders, which enable closed-loop speed control and robot odometry estimation.

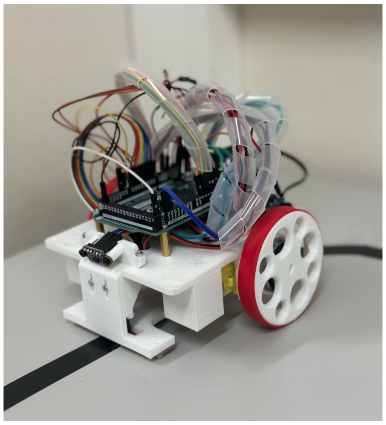


Fig. 3. Mobile robot prototype

The sensors used are a line sensor QTR-8A to acquire data related to the black line and a Time of Flight distance sensor VL53L0X for obstacle avoidance. The data processing is performed by an Arduino Mega, the power source is supplied by two rechargeable Lithium Ion 3.7V batteries and an auto power off system to prevent damage to batteries. Figure 4 illustrates all the components included in the mobile robot and the respective data flow.

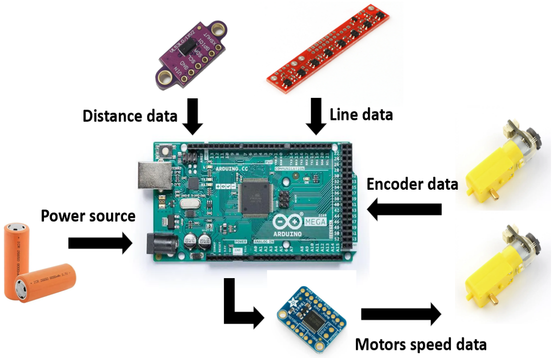


Fig. 4. Mobile robot components

B. Algorithm for line center calculation

In order to the robot be able to follow a line, the error in relation of the line center was calculated. The sensor applied to detect the line was the QTR-8A Reflectance Sensor, an module composed by 8 infrared LED/phototransistors, which provides different reflections based on the surface color [16].

The values provided by the 8 phototransistors are analog, therefore it was established a threshold for the detection of a black line. By this way, the values below this threshold are considered actives and the others inactives. An weighted average is calculated based on the number of active phototransistors (over the black line).

The module was positioned in the central front part of the robot. Therefore, in order to obtain the error in relation of line center, the average is subtracted from the value 4.5, which is a value that represents the center of the 8 phototransistors, that is, the target value that the robot should have as reference, when moving forward, as shown in Figure 5.

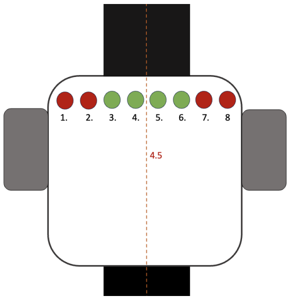


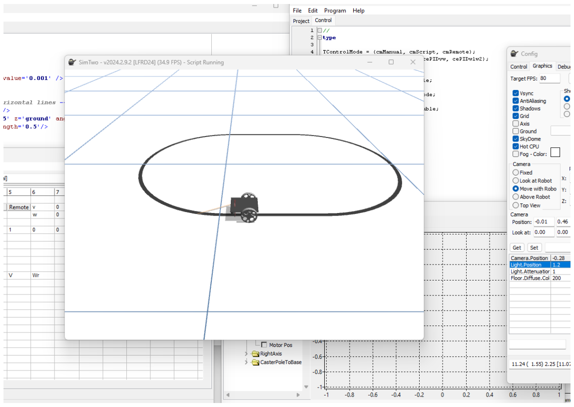
Fig. 5. Line sensing by the reflectance sensor

III. HARDWARE IN THE LOOP APPROACH

In this section the HIL approach applied to an educational robot is described. It was applied the SimTwo simulator, which is an open source software for realistic simulation. Several kind of robots can be used with this simulator, the physical characteristics can be included to obtain dynamics realism, such as shape, mass, elasticity, moments of inertia or parameters like resistance, inductance, etc [1], [14], [17].

A. Scenario

Figure 6 shows the SimTwo simulator environment with a scenario created to test the mobile robot performance while following a line. For this purpose, two straight lines and two arcs were created and positioned in order to form a path inside the SimTwo, totalizing a length of 1.94m.



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//
type

TControlMode = (cmManual, cmScript, cmRemote);
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Fig. 6. SimTwo simulator environment

B. Virtual mobile robot

Firstly, a virtual robot was created inside the simulation environment, with the same dimensions and components of the real robot. The virtual model is composed by solids like cuboids and cylinders connected by articulations like hinge joints, allowing the objects to move through an axis. Figure 7 shows the virtual robot created.

In the virtual robot, it were included 8 phototransistors that represent the line sensor. In the simulation it was not necessary to establish a threshold to detect the black line, therefore digital values were obtained from these 8 sensors, being 1 if it is over the black line and 0 if it is outside the line. The parameters of the motors and encoders were also included in order to make the robot close to the reality.

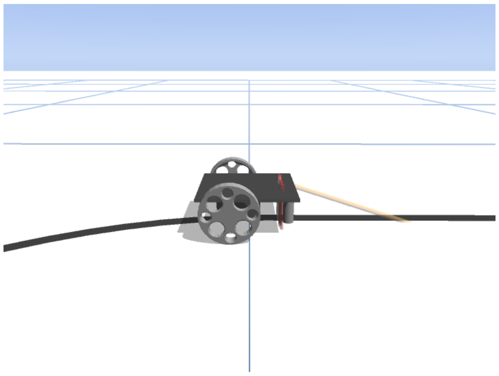

Fig. 7. Virtual robot

In relation of the distance sensor, the papers [18] and [19] already presented a modeling of the Time of Flight distance sensor applied in SimTwo, therefore this model was also included in the simulation.

C. Hardware-in-the-loop

In the Hardware-in-the-loop (HIL) approach the virtual robot created inside the simulator communicates with the real robot through serial communication, being the way to exchange data. By this way, it is possible to test and validate the robot controller based on a realistic simulation, since the processing is performed in the real hardware conditions and the actuation is performed inside the SimTwo simulator, without damage the hardware. Figure 8 illustrates this method.

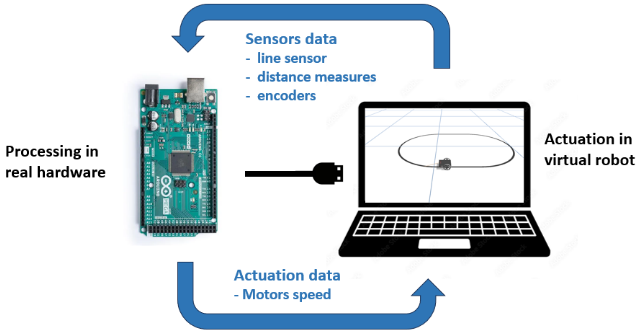

Fig. 8. HIL simulation diagram

In this technique the simulator provides the sensors data, such as line sensor data, distance measures and encoders value for the embedded system, which is responsible to perform the processing and send to the simulator the values related to the motors speed, controlling the actions of the virtual robot.

IV. RESULTS

This section presents the results related to the application of HIL in the development and validation of educational mobile robots firmware. In order to test the robot following a line, a path was created inside the SimTwo simulator with the same dimensions of a real path, as shown in Figure 9, with a total length of 1.94m. The path is composed by two straight lines with a length of 0.5m and separated by a distance of 0.3m, as well as two arcs in both sides with 0.15m of radius. It was measured the time that each robot performed the path, obtaining close values of nearly 27s, providing both the simulation as well as the real robot different values for each one, since it are stochastic processes.

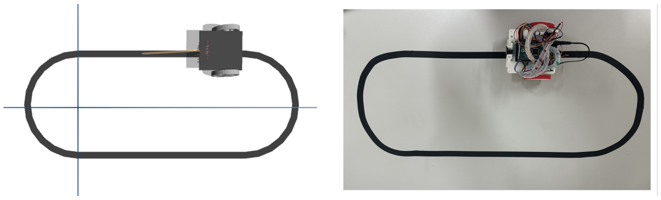

Fig. 9. Simulated and real path

Figure 10 represents the trajectory performed by the virtual robot, that is, the positions X and Y in meters during the execution of the path and having HIL approach running, being the start point and direction of movement also presented in the figure. The results proved that the controller algorithm is controlling well the virtual robot, which performed, in a satisfactory manner, the scenario trajectory illustrated in Figure 6. Therefore, in this validation, the simulator sends the data acquired from reflectance sensor to Arduino MEGA that performs all the necessary processing and send back to the simulator the reference voltage related to the speed in each one of the motors.

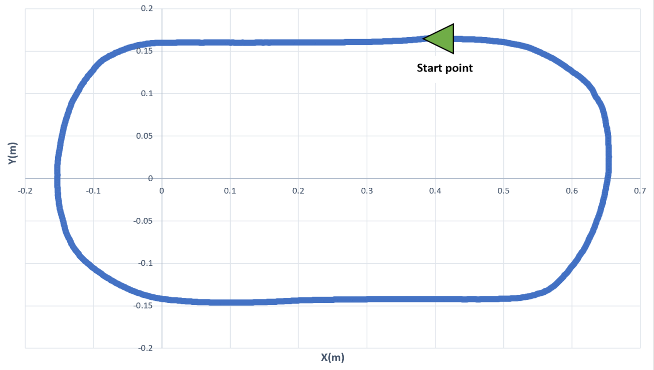

Fig. 10. Results of the path performed by the virtual robot

The variation of virtual robot position can also be analyzed in Figure 11, which represents the behavior of X and Y positions in function of the time. Then, it can be observed how the X values starts decreasing and Y values remained constant until the beginning of the first curve, when X cross the origin axis, and then Y values starts to decrease. When X cross the origin for the second time, represents the end of the first curve in the path of Figure 10, and the beginning of a straight line again, where X increases and Y keeps constant. The beginning of the second curve is marked by the increase of Y and the end by decrease of X. Therefore, the behavior of the curves coincides with the path taken by the virtual robot.

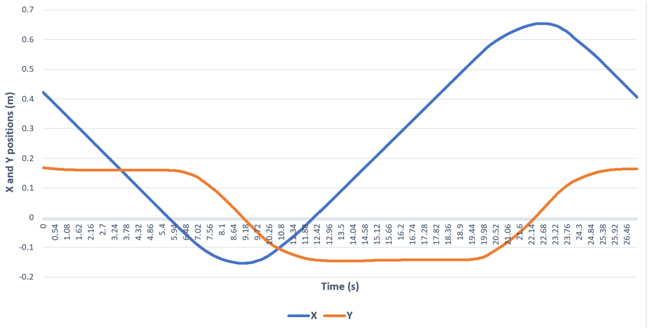

Fig. 11. Behavior of positions X and Y in function of the time

V. CONCLUSION AND FUTURE WORK

This paper addressed the prototyping, development and validation of mobile robots for application in educational context using the Hardware-in-the-loop (HIL) approach. Through this technique, it was possible to use the real embedded system to control a virtual robot, being the processing performed in the real hardware. The simulation was very close to the reality, because the controller algorithm was tested in real conditions of the hardware memory and processing time. The results were satisfactory, proving that the virtual robot could be controlled by the real hardware.

The HIL technique provides many advantages, not only in industry but also in educational context. Such benefits include the reduction of development time, costs reduction, correction of fails in initial phases, to test and validate the algorithm and controller in dangerous and/or extreme conditions, a realistic processing time, because the processing is being performed inside the real hardware. Inside an educational context, HIL approach allows students to test their controller algorithms in the real hardware conditions of processing time and memory, learning in a safe environment, avoiding damages in the equipment and also in situations where the hardware is limited for the number of students in the class. Besides that, this method has been implemented in industries for a long time, therefore, applying this approach inside the classrooms prepare the students to job market, developing their professional skills that industries needs.

As future work, the obstacle avoidance algorithm will be implemented and validated, as well as a case study of the application of these mobile robots in robotics classes.

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