Proposal of a low cost educational mobile robotics experiment: an approach based on hardware and simulation

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***Abstract*—In this paper it is presented an educational mobile robotics experiment based on a low cost mobile robot prototype and its simulation. The chosen educational robot challenge is a classical introductory experiment, that consists in following a line with a mobile robot based on the differential kinematics. The presented experiment has as goal to introduce students to the challenges of mobile robotics, initially programming a simulated robot, building a real robot and finally testing the developed code in a real robot. The robot was simulated using SimTwo, which is a realistic simulation software that can support several types of robots. Having as base the proposed challenge, a mobile robot competition was conducted as a part of the evaluation of the curricular unit of "Systems Based on Micro-Controllers" of the "Electrotechnical and Computer Engineering" course of the Faculty of Engineering of the University of Porto.**

I. Introduction

In this paper it is presented an educational mobile robotics experiment based on a low cost mobile robot prototype and its simulation. The mobile robot, consists in a 3D printed small prototype, that uses inexpensive hardware, such as servo motors, an Arduino Uno platform and an infra-red detector array. For the proposed robot, continuous rotation is necessary, so the servo motors must be modified. This modification consists in disconnecting the position potentiometer from the gear train, setting the potentiometer to a fixed position, and removing the angle stops from the motor shaft. The robot is also equipped with the Zumo reflectance sensor, providing an easy way to add line sensing or edge detection. The chosen challenge is a classical introductory mobile robotics experiment, that consists in following a line with a mobile robot based on the differential kinematics [2] [3] [7] [14]. The presented experiment has as goal to introduce students to the world of mobile robotics, initially programming a simulated robot and finally testing the developed code in a real robot. The robot was simulated using SimTwo, shown in Figure 1, which is a realistic simulation software that can support several types of robots. Its main purpose is the simulation of mobile robots that can have wheels or legs, although industrial robots, conveyor belts and lighter-than-air vehicles can also be defined. Basically any type of terrestrial robot definable with rotative joints and/or wheels can be simulated in this software [1] [8] [13] [15].

Having as base the proposed challenge, a mobile robot competition was conducted as a part of the evaluation of the curricular unit of "Systems Based on Micro-Controllers" of the "Electrotechnical and Computer Engineering" course of the Faculty of Engineering of the University of Porto. It was received feedback from the students, concerning the success of the mobile robotics experiment, based on that feedback some reflections were made. The students that participated in the referred robot competition are shown in Figure 2.

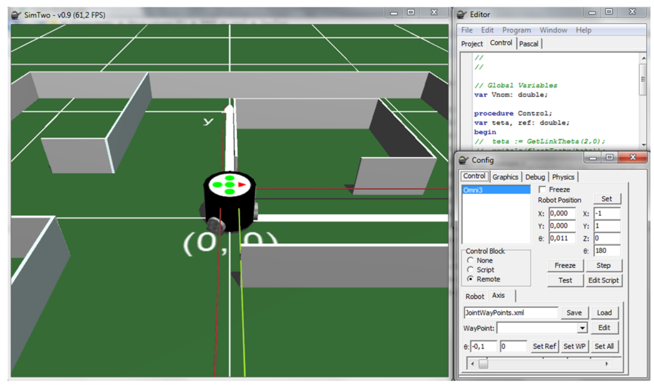

Fig. 1. SimTwo 3D View.

Fig. 2. Students at the mobile robot competition.

The paper is organized as follows: After a brief introduction it is described the robot prototype and its model, then the mobile robotics experiment is introduced and finally some conclusions and future work are presented.

II. Robot Prototype Description

The prototyped mobile robot consists in a 3D printed small prototype, being presented in Figure 3, that uses inexpensive hardware, such as servo motors, an Arduino Uno platform and an infra-red detector array. The 3D printer models that were developed, in order to prototype the robot, are presented in Figure 4, where it can be seen the 3D models for the robot chassis and wheels 3D models. In the next subsections it will be introduced the prototype sensors and actuators description and their modeling.

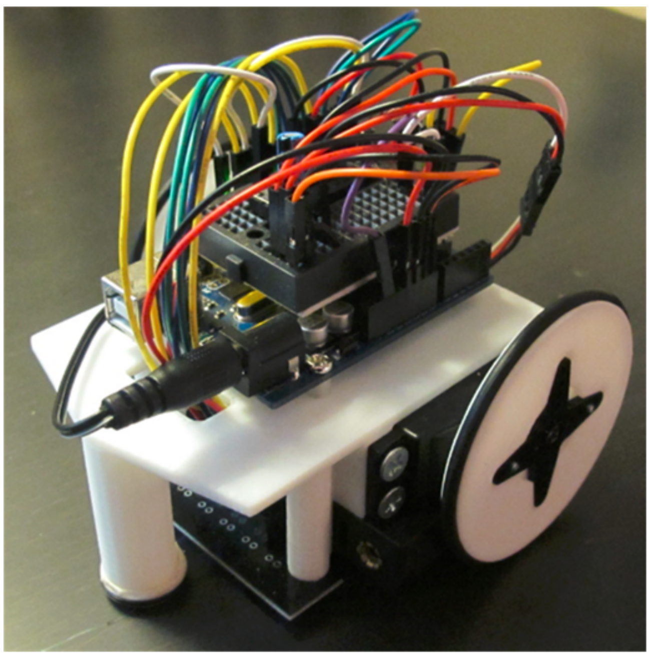

Fig. 3. Robot prototype.

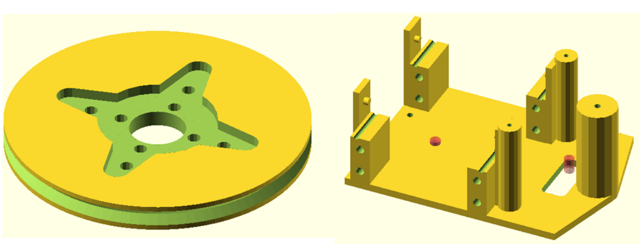

Fig. 4. Robot prototype 3D printer models.

A. Sensors

The robot is equipped with the Zumo [4] reflectance sensor, providing an easy way to add line sensing or edge detection. It features six separate reflectance sensors, each consisting of an IR emitter coupled with a phototransistor that responds based on how much emitter light is reflected back to it. The purpose of using the referred sensor is to sense and follow a line. A Zumo reflectance sensor array with labeled sensors and dimensions is shown in Figure 5. More information about this sensor can be found in [4]. The simulated model of the sensor returns binary information, it is assumed that if the sensor is above a black line it returns 1 and if not 0.

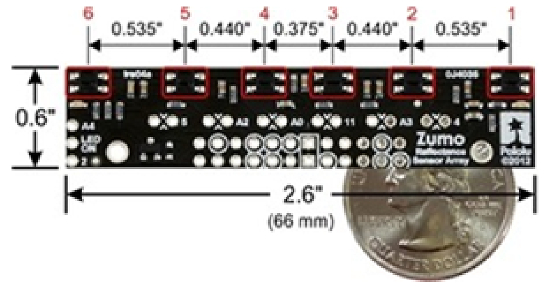

Fig. 5. Zumo reflectance sensor [4].

B. Actuators

The robot actuator is the Futaba S3003 Servo. A servo motor is a complete assembly made of a small high RPM motor, gear reduction, H-Bridge and position control circuitry. If the servo is not modified it is used to produce a rotational position based on a Pulse Width Modulated (PWM) signal. The Futaba S3003 servo motor has three inputs: PWM (white), power (red), and ground (black). Based on the PWM signal the servo will turn its shaft to a position within a range of approximately 200 degrees. When a PWM command is given to the circuitry an error signal is produced. This error signal turns the motor in the appropriate direction. The motor gearing turns a position potentiometer, which gives a feedback signal to the position control circuitry. When the correct position is indicated by the potentiometer, the error signal becomes small enough, so the motor stops turning. For the proposed robot, continuous rotation is necessary, so the servo motors must be modified. This modification consists in disconnecting the position potentiometer from the gear train, setting the potentiometer for a known PWM signal and removing the angle stops from the motor shaft. Some offset developed by software is necessary to get the two motors to turn at the same speed. More detailed information of the Futaba S3003 servo motor and its modification can be found in [5].

In order to obtain the actuator model it was necessary to know for each control signal the output velocity of each modified servo-motor, incremental encoders were used for that purpose. The use of incremental encoders, as shown in Figure 6, is only necessary to obtain the actuator model. The used incremental encoders are an expensive piece of hardware that would increase considerably the cost of the robot prototype. A tachometer was used in order to convert the measured transitions per sample time to Rad/s. In order to measure the motor angular velocity with the tachometer, a printed black and white pattern with transitions was attached to a robot wheel.

The control signal is the same as for a standard servo, only this time the length of the on time pulse will affect the speed and directions. For a certain pulse width the servo will stop. Values above or below will make the servo rotate faster in either direction. The signal (d), depicted in Figure 7, is the difference for the stopping pulse width. This value must be divided by 40000, in order to obtain the time in seconds. As there is a gearbox with an high ratio, the dynamic response

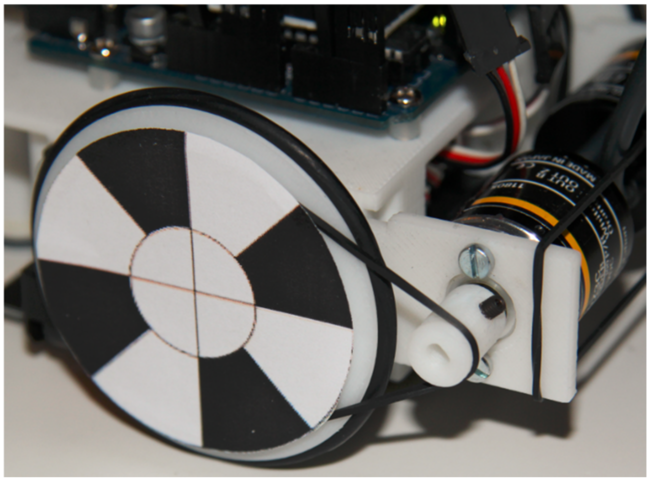

Fig. 6. Robot with encoders.

is very fast. The most important aspect of the model is the non linearity introduced by the modified controller. This non linearity can be seen in Figure 7 where the steady state speed for a certain pulse width has a small dead zone and a non linear behavior as it approaches the maximum speed. In order to model these non linearities, equation 1, saturated for values inferior to zero, was estimated. Using the experimental speed measures the best fit was found by optimizing the values of $a_2..a_0$, $b_2..b_0$. The total error, being the sum of the absolute differences, was used as the target function [6]. The estimated values can be seen in Table I.

$$\omega(d) = \frac{a_2.d^2 + a_1.d + a_0}{b_2.d^2 + b_1.d + b_0} \tag{1}$$

Parameters	Value
a_1	-34.760E-6
a_2	-69.581E-3
a_3	488.777E-3
b_1	-29.663E-6
b_2	2.278E-3
b_3	-1.964

TABLE I. ESTIMATED PARAMETERS.

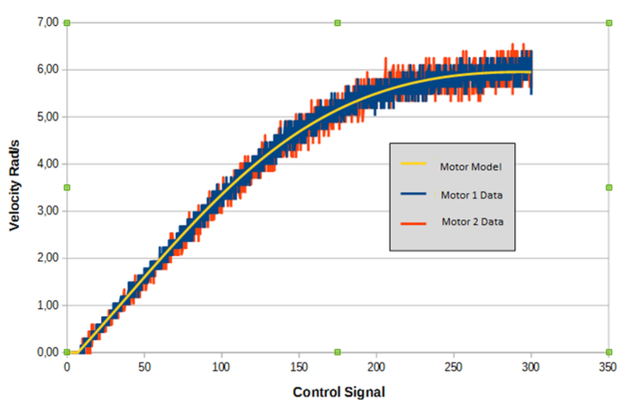

Fig. 7. Futaba S3003 Model.

In order to invert equation 1, equation 2 can be obtained. The solution for equation 2, corresponds to equation 3, resulting in a function with its domain from 0 to 5.955 Rad/s, that has as input a velocity and as output the servo control signal.

$$(\omega b_2 - a_2)d^2 + (\omega b_1 - a_1)d + \omega b_0 - a_0 = 0 \tag{2}$$

$$d = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{3}$$

where:

- $a = \omega b_2 - a_2 <$
- $b = \omega b_1 - a_1$
- $c = \omega b_0 - a_0$

For an input inside the referred function's domain, equation 3 returns two values, the chosen value must be equal or greater than 7 and less or equal than 293. Values from 0 to 6 are inside the dead zone and values superior to 293 correspond to the saturation zone.

III. MOBILE ROBOTICS EXPERIMENT

Following a line with a robot based on the differential kinematics is a classical introductory experiment that allows students to be introduced to the challenges of mobile robotics. Understanding the concepts of sensor, actuator and locomotion are the primary goals of this experience based on the control of a reactive robot [14].

Initially the students develop the robot control using simulation, as shown in Figures 8 and 9. The simulator (SimTwo) sends the sensor data, at each sampling time, to a remote c standard application and the remote application returns the velocity that each robot wheel must have in order to perform its tasks, as shown in Figure 9. Finally the students can test the control algorithm just by compiling the program to be flashed on the microcontroller, as shown in Figure 9. The control function is a c standard function, being used either in the simulated as well as in the real environment.

The presented approach is very useful, whenever reducing costs is a primary goal, because several student groups can develop robot code simultaneously, using simulation, and then test the robot code in a prototype that can be shared by several groups of students, although in this competition each group had its own prototype.

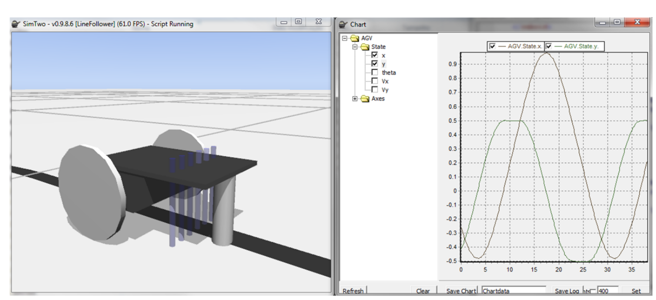

Fig. 8. Simulated Robot Experiment.

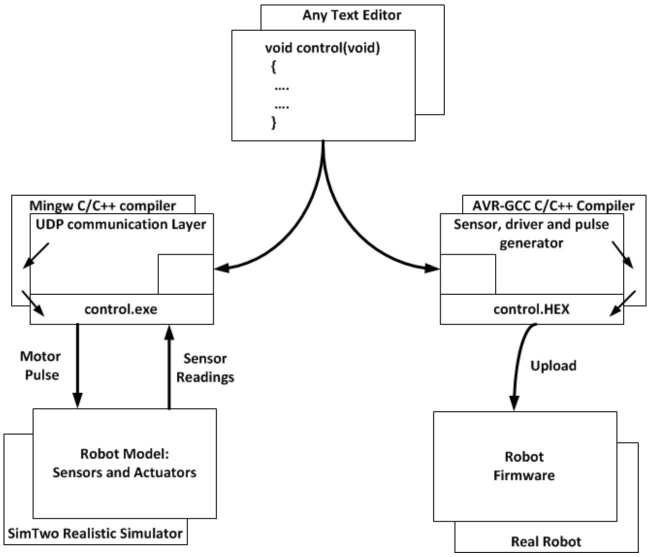

Fig. 9. Robot experiment software development block diagram.

In order to calculate the pulse width for the desired servo speed, a lookup table can be applied. On the other hand a more experienced programmer can use a more complexe approach. The previously presented equation model for the Futaba modified servo can be inverted, having in mind that the servo speed will saturate for nearly 5.955 Rad/s, for an input of 293. The input increase beyond this value wont produce a higher speed value. The programmer must also take in account that the inverted equation is valid only for inputs superior or equal to 7, due to the servo dead zone. The pulse value in seconds is calculated dividing the input value by 40000, finally this value is summed to the stopping pulse width for a positive speed rotation, and subtracted for a negative speed.

Each student group had 10 minutes to participate in the competition, making as many attempts that they like to make. Their robot has to complete the circuit three times, if the robot stops after completing this task a 10 % bonus is subtracted from the time spent. That can be done by counting laps, using a special marker present on the track. The winning team is the one that spends the lowest time to complete the challenge. Some students and their supervisors, preparing their robots for the competition, are shown in Figure 10.

IV. Student Feedback

In order to receive feedback regarding the effectiveness of the mobile robotics experiment an inquire was made to the students that participated in the mobile robots competition. The inquire was performed by 24 Students, having for each question the option to answer from 1 to 5, where 1 is "I totally disagree", 3 is "I am neutral" and 5 is "I totally agree". Bellow the inquire results can be found, where the average results and the standard deviation (STDV) of the students answers are presented.

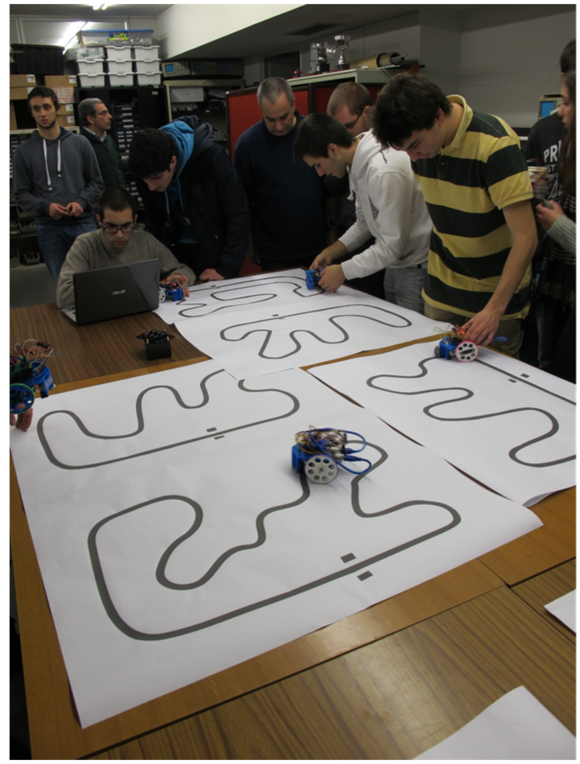

Fig. 10. Students and their supervisors at the robot competition

Question:	Average	STDV
The theoretical classes were important for the curricular unit learning process?	3.3	1.3
Practical classes were important for the curricular unit learning process?	4.5	0.8
Were you able to chose the practical work?	4.6	0.7
Laboratory classes were useful for the curricular unit learning process?	4.1	1.0
Do you prefer to be evaluated by laboratory works?	4.5	0.7
The laboratory work is useful for the curricular unit learning process?	4.7	0.6
Would you like to have more laboratory works?	3.6	1.1
Would you like to have complexer laboratory works?	3.3	1.0
The work with the robot was useful for the curricular unit learning process?	4.6	0.5
The participation in the robot competition generated more motivation?	3.9	1.1
Would you like to work again with robots in different curricular units?	4.5	0.7
Working with robots is important to motivate yourself to other curricular units?	4.0	1.1
Working with robots was important to understand the curricular unit contents?	4.0	0.9
Would you like to spend more time working with robots?	4.0	0.8
Simulation was important for the code development?	4.0	0.8

It was concluded from the inquire results that students were substantially motivated for the curricular unit study, mainly because the laboratory work involved mobile robots. The fact that the results of the laboratory work were applied in a final robot competition was an extra motivation, because students like to compete [9][10][11][12]. It was also observed that the students were happy with the fact that the laboratory work reflected almost all the contents of the curricular unit, helping them to be better prepared for the individual written evaluation. It was also concluded that the presented laboratory work was a first option for the major part of the students, there were different options for the practical evaluation and the competition was not mandatory.

V. Conclusions and Future Work

In this paper it is presented an educational mobile robotics experiment based on a low cost mobile robot prototype and its simulation. The mobile robot consists in a 3D printed small prototype, that uses inexpensive hardware, such as servo motors, an Arduino Uno platform and an infra-red detector array. The robot was simulated using SimTwo, which is a realistic simulation software that can support several types of robots.

The chosen educational robot challenge is a classical introductory experiment, that consists in following a line with a mobile robot based on the differential kinematics. The presented experiment has as goal to introduce students to the challenges of mobile robotics, initially programming a simulated robot and finally testing the developed code in a real robot.

The presented approach is very useful, whenever reducing costs is a primary goal, because several student groups can develop robot code simultaneously, using simulation, and then test the robot code in a prototype that can be shared by several groups of students. This approach is very convenient, for example, for schools of developing countries that usually have reduced budget.

The modeling and simulation information of a modified Futaba S3003 Servo-Motor, presented in this paper, is a relevant information, mainly for teams that use this servo in robot competitions, allowing them to learn how to modify it, to understand in detail the servo internal controller and also how to simulate it, testing robot controllers without accessing to hardware.

It was concluded from the inquire results that students were substantially motivated for the curricular unit study, mainly because the laboratory work involved mobile robots. The fact that the results of the laboratory work were applied in a final robot competition was an extra motivation, because students like to compete. It was also observed that the students were happy with the fact that the laboratory work reflected almost all the contents of the curricular unit, helping them to be better prepared for the individual written evaluation. Overall it was observed that students like laboratory works, robots, competitions and stated that simulation can also be a good help to develop robot code without access to hardware.

As future work the authors would like to organize another editions of the robot competition and to evolve the available robot prototypes.

Acknowledgment

The authors would like to thank all the persons involved in the robot competition, to the students for their effort while participating in the robot competition, making it competitive and fun, to the referees, that supervised the competition, and also to the team mentors, that helped and inspired the participating teams.

This work is financed by the ERDF European Regional Development Fund through the COMPETE Programme (operational programme for competitiveness) and by National Funds through the FCT Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) within project FCOMP-01-0124-FEDER-037281

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