

# Using educational robotics to teach fundamental feedback control concepts

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**Abstract.** This work examines the role of educational robotics towards teaching high-school children basic automatic control concepts including feedback, the structure and the differences between open- and closed-loop control systems, the basic elements of a closed-loop system, the effect of external disturbances, the tracking error, as well as practical issues concerning control hardware implementation. The ideas are exemplified with hands-on exercises and experiences from a STEM summer school based on educational robotics.

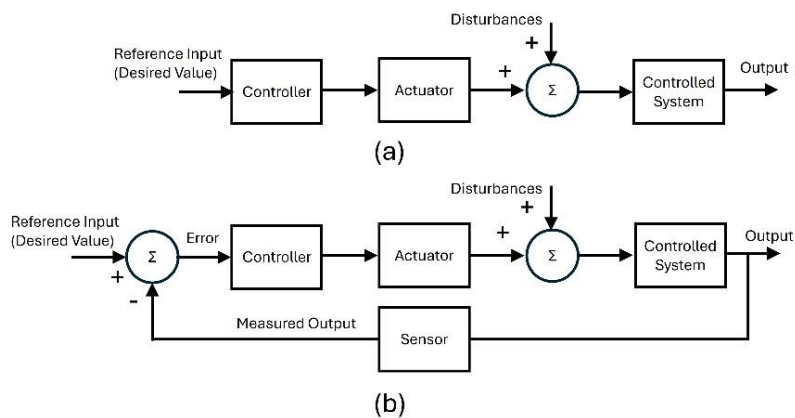
**Keywords:** Educational robotics, STEM Education, Feedback control, Open-loop systems, Closed-loop systems, Control hardware

## 1 Introduction

The role of educational robotics in STEM (Science, Technology, Engineering, and Mathematics) education has been widely acknowledged in literature [1]. Robotics is an exciting area with a rich content and provides a comprehensive framework for teaching the above topics as part of a systematic and integrated approach. It also presents unique opportunities for hands-on activities to better motivate children and help them to understand theoretical concepts within the STEM context. Moreover, students can develop a set of important skills including communication, collaboration, critical thinking etc., which are often referred to as 21<sup>st</sup> century skills [2]. Educational robotics has become popular across every level of the educational system [3], while robotics competitions provide an additional stimulus [4-6]. Various commercial educational robotics products exist [7] but building custom hardware using off-the-shelf components is also common. In terms of engineering content, a most important topic that becomes relevant is control systems. Dynamic systems including robots require control to perform motions and execute useful tasks. Feedback control is a fundamental element of robotic systems to continuously monitor actions and make real-time adjustments based on sensory information. Admittedly, advanced classical control concepts are complex and depend on mathematics. However, fundamental ideas, such as open- and closed-loop

control structures, are intuitive and can be conveyed to students through educational robotics.

Educational robotics mostly concern mobile robots which typically integrate all the basic elements of a feedback control system: controlled system, controller, sensors and actuators. The general structure of an open-loop and a closed-loop (feedback) control system is shown in Figure 1. The former approach can be appropriate for well-defined and isolated systems (i.e., with minimal external disturbances). The latter uses sensory feedback information and allows the system to deal with external disturbances and unmodelled dynamics, leading to superior performance [8].



**Fig. 1.** General control system setup, components and signals.  
(a) Open-loop system; (b) Closed-loop system.

Control is an integral part of many engineering systems and mostly concerns closed-loop configurations (e.g., room temperature control, automobile cruise-control, robot motion control). The purpose of the control system is to have the output (controlled variable) of a dynamic system track the reference input (or equivalently, drive the error signal to zero). It is important for students to realize that closed-loop feedback processes are common in nature even though they tend to be invisible, as for example the regulation of vital human body functions, including the control of breathing and body temperature. In fact, a direct analogy exists between the operation of a robotic system and a human being or animal, which uses sensory information (sight, smell, hearing, taste, touch) to control its actions. For example, when a human is walking, sensory information is used to monitor and correct motions.

In educational robotics exercises it is common that when students are confronted with a motion control problem, they find more intuitive to apply open-loop control approaches, and the programming of timed motions. Upon testing their systems they realize that this approach does not work well as the battery level drops but also when other effects become significant (assembly inaccuracies, asymmetries, etc.). In [9], it is claimed that the technical solution of certain commercial robotics kits to integrate an encoder into the motor assembly makes “driving straight a primitive” and the user only needs to define the desired velocity and number of rotations. This way students may

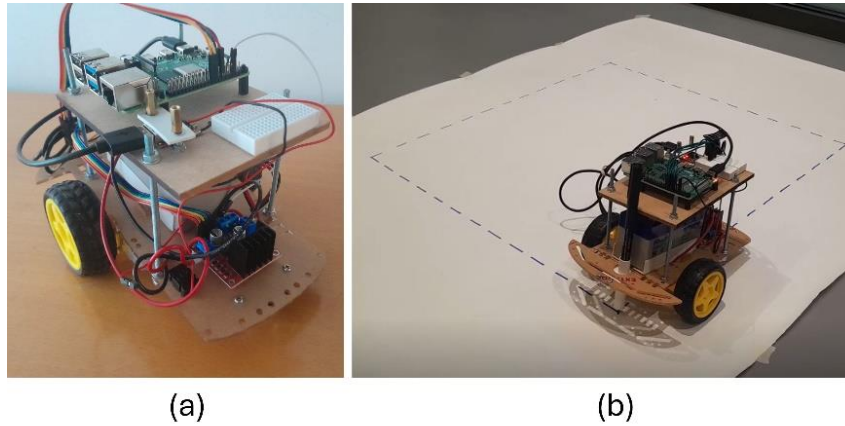
miss an important lesson that “real robots don’t drive straight”. Of course, it is up to the educator to use such kits productively and present the material in a way that will prevent any misconceptions about technology. When projects are based on custom robots with off-the-shelf components, students need to think in more generic terms. This provides them with a more realistic picture of the underlying engineering problems.

In typical educational robotics exercises and competition challenges, a robot is often required to follow a path (e.g., line-following) or move along a wall (e.g., maze solving). The basic feedback control concept is simple. In the case of line-following: if too far on the right, then turn left; if too far on the left, then turn right; otherwise, keep going straight.

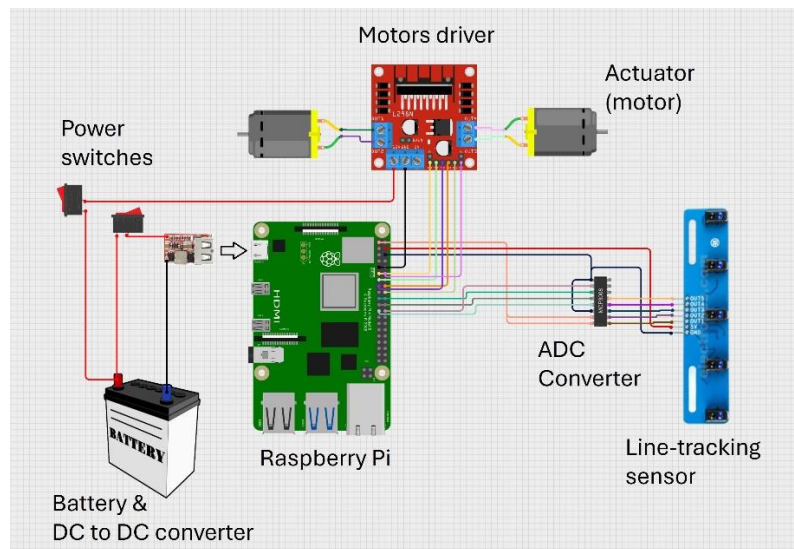
In this paper, it is described how educational robotics activities were used to teach high-school students (aged 12-14 years old) basic control concepts, such as open- and closed-loop systems, the basic elements of a feedback control system, the effect of external disturbances and evaluation of system performance. These activities were part of a STEM education summer school.

## **2 Robot hardware**

There exist various commercial educational robotics products, but projects can also be designed and built using off-the-shelf components and programmable controllers. The latter require more skill and experience but provide more realistic engineering experiences as well as more opportunities for creativity. In terms of mechanical hardware, the differential drive robot was selected for our exercises (see Figure 2). This configuration has two individually driven wheels on both sides of the robot plus a caster wheel to prevent tilting. It is controlled using two electric motors allowing the system to move in the forward/backward direction and turn: spinning in place, turn about one wheel or take wide turns. The speed and direction of motion for the robot depends on the rate and direction of rotation of the two driven wheels. A distinct feature of the robots which were assembled by the students, is the integration of an accessory that includes a pencil/marker placed inside a vertical holder that is dragged with the robot. The marker draws a trace of the actual path over the floor surface, on which the desired path is printed for comparisons. Any deviation between the desired and the actual path corresponds to error. System control is implemented using a Raspberry Pi single-board computer (SBC). This system allowed the students to familiarize themselves with the hardware implementation of the control system, the ideas of controller inputs and outputs, as well as basic programming of the control algorithm. The electronics diagram is shown in Figure 3. The electrical and control electronics system comprises the Raspberry Pi (control unit), the infrared line tracking sensor (5 Channels TCRT5000L), an Analog-to-Digital converter (ADC) that changes the sensor’s analog signal to digital, and two DC motors (actuators) corresponding to each wheel. The motor driver (L298N) allows speed and direction control of the two DC motors. The system is powered by a 12V rechargeable lead-acid battery. A DC-to-DC converter circuit is used to power the Raspberry Pi with the required 5V voltage.



**Fig. 2.** The differential drive robot assembled by the students. (a) Overview of mechanical configuration. (b) Pencil/marker holder accessory at the rear of the robot to draw the actual path (a continuous line) for comparisons with the desired one (dashed line).



**Fig. 3.** Electrical and electronics hardware system of the robot used in the exercises.

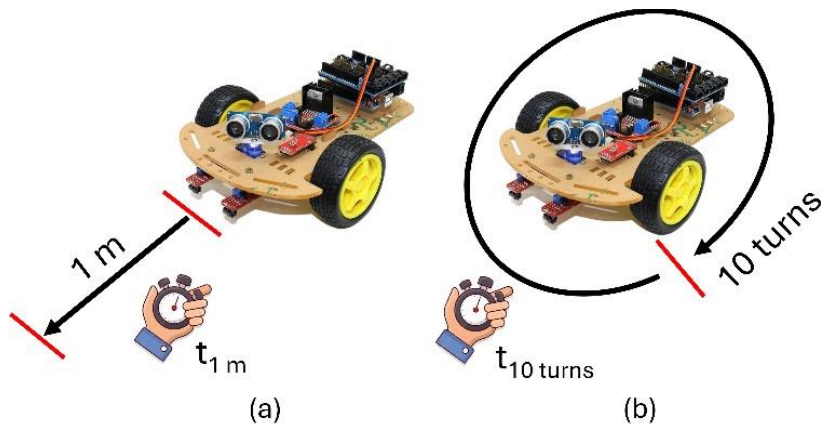
### 3 Methodology and Exercises

As part of a STEM summer school on educational robotics, students were introduced to basic control aspects of robotics. Key concepts, including the open- and closed-loop control (shown in Figure 1), were discussed with the participants along with familiar examples of controlled systems. The basic robot platform was assembled by the stu-

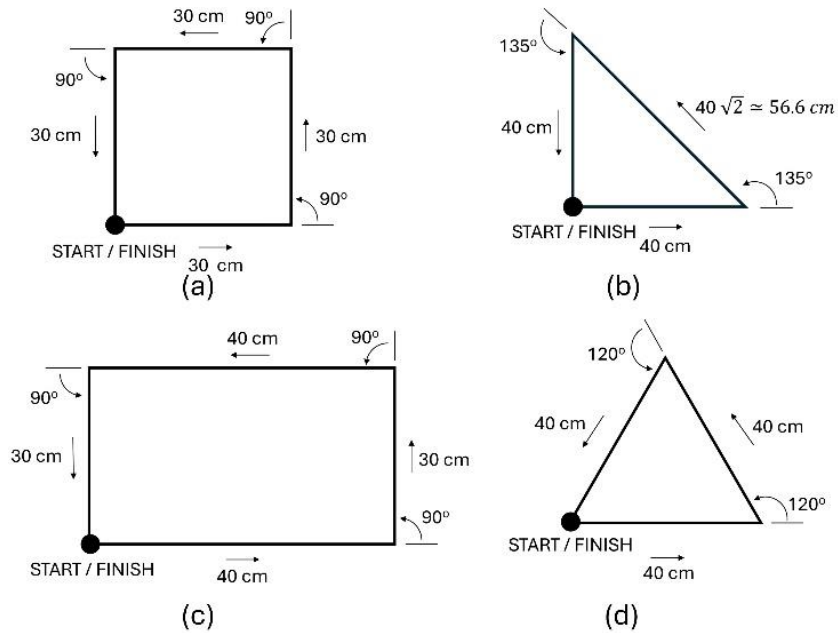
dents (mechanical, electrical and electronics hardware) while working in teams. Students were introduced to basic programming of the system using examples before proceeding with the designed hands-on exercises.

### 3.1 Open-loop control

Before proceeding with the open-loop control exercises, the time constants corresponding to the straight and the turning motion were calculated (see Figure 4). For this purpose, the time required for the robot to cover a 1m distance was measured ( $t_{1m}$ ). Likewise, the time for the robot to spin 10 times about itself was also measured ( $t_{10\text{ turns}}$ ). Then, the time for the robot to cover a 1cm distance will be  $t_{1cm} = \frac{t_{1m}}{100}$ , and the time corresponding to one degree rotation will be  $t_{1deg} = \frac{t_{10\text{ turns}}}{10 \times 360}$ . To experiment with open-loop control the students programmed the robots to follow certain geometrical shapes, as shown in Figure 5, which include straight line segments and turns.



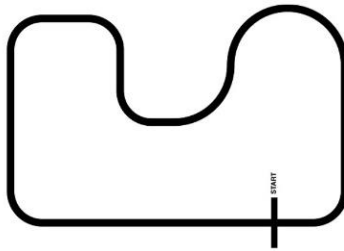
**Fig. 4.** Finding the time constants for the open-loop control implementation.  
(a) Linear motion; (b) Turning (spinning) motion.



**Fig. 5.** Desired path for open-loop testing. (a) Square; (b) Right triangle; (c) Rectangle; (d) Equilateral triangle.

### 3.2 Closed-loop path-following control

The objective of the closed-loop exercises was for the robot to follow the desired path and complete the closed track as fast as possible, using the line-tracking sensor installed at the front of the robot. The shape of the test track is shown in Figure 6. The width of the dark line was 20 mm and its overall length was 3.5 m. It includes both straight and curved parts requiring both left and right turns for the robot.

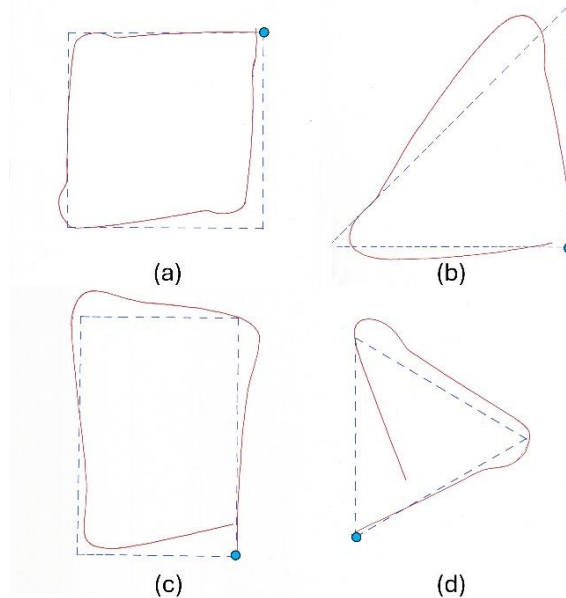


**Fig. 6.** The line-following track for the closed-loop robot control exercises.

## 4 Experimental testing results

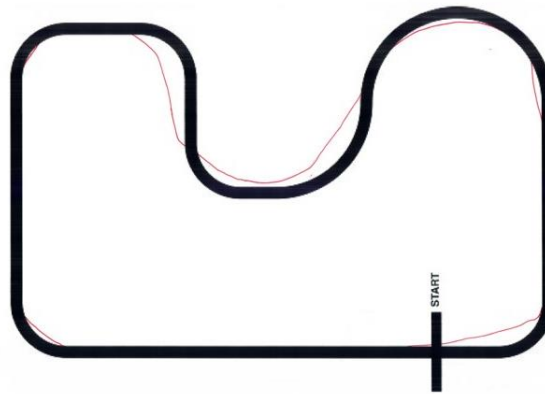
The students worked in teams of 4 children and following the open-loop control procedure described above tried to follow each path shown in Figure 5. Indicative results for the open loop experiments are shown in Figure 7, which includes scans of the test papers for the given paths. The desired path is the blue dashed line, and the actual path is drawn by the marker with a continuous red line. Upon examining the results, students realized that open loop path following was not accurate and kept worsening while the battery's voltage dropped. From the results it becomes apparent that this control method is not adequate for the given task for several reasons that the students identified: components manufacturing and assembly inaccuracies, weight distribution, dropping battery level, floor condition, etc. The results were discussed with the instructors to understand the performance limitations of open-loop control. Notice that while the robot turns the path that is drawn on the paper is curved because the marker is not pointing in the middle of the wheels axis and an offset exists.

To demonstrate the effect of external disturbances the students were asked to perform the same exercises with the robot having to go uphill/downhill by changing the inclination of the table surface. The control programme was exactly the same as before. In that case path-following was dramatically worsened because of the external disturbance (floor slope). In fact, one motivation for using feedback control is to deal with external disturbances. The results were discussed with the students and it was explained to that in practical applications the control objective is to have the system output closely follow the reference input in the presence of external disturbances.



**Fig. 7.** Examples of open-loop tracking of each given path. (a) Square; (b) Right triangle; (c) Rectangular; (d) Equilateral triangle (---: desired path, —: actual path, •: start point).

The second set of exercises involved the use of feedback so that the robot can follow a dark line printed on the floor as fast as possible. A basic line-following approach was programmed so that the robot uses a line-tracking sensor to monitor its position in relation to the line and adjust its direction accordingly. Simple if/then programming statements were used, and minimal effort was devoted towards optimizing performance. Representative results are shown in Figure 8 with the actual path marked with a thin red colour line, confirming the effectiveness of the approach. Even though the control parameters were not optimized, the tracking performance is reasonably good and if the system deviates from the desired path, it automatically corrects itself. To evaluate performance, students measured the time to complete the track and the maximum error (deviation between desired and actual path), realizing the extra difficulty when trying to increase the speed of the robot.



**Fig. 8.** Example of closed-loop line-following exercise (—: desired path, —: actual path).

## Conclusions and discussion

Educational robotics also provide opportunities for students to learn fundamental concepts in control and hardware implementations. This was demonstrated through basic exercises performed as part of a STEM summer school. The exercises were designed to teach students how control systems are implemented, both in terms of software and hardware, and highlight the differences between open- and closed-loop control. The hands-on exercises allowed them to understand the need for sensory feedback towards implementing an effective closed-loop robot control system.

The basic robotic hardware that was used is low-cost and comprises off-the-shelf components. The system is versatile and allows the integration of extra sensors and programming to expose students to more advanced topics in control. For example, the hardware may be adapted to support the implementation of well-established control schemes including the PID (Proportional-Integral-Derivative) controller. These controllers can be designed to meet specific performance specifications by selecting appropriate sets of feedback gains.

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