Teaching analog Line-Follower (LF) robot concept through simulation for elementary students

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Abstract. At present, almost all modern industries utilize robots to increase production efficiency and effectiveness. Students’ competencies must be prepared appropriately by educators. Accordingly, in the future, they have qualified technical-skills when dealing with the fully-supported robot in their job. These supporting competencies are involved in extracurricular subjects. Robotics is one of several subjects taught at the elementary level; simple robots like analog Line-Follower (LF) robots are very suitable for elementary school students’ teaching topics. Using proper strategies, the elementary students will learn simple robotics comprehensively with mentoring assistance by STEM Teachers. This paper presents a teaching material on how a simple robot (i.e., LF robot) can be introduced to elementary students. The Circuit Wizard\textsuperscript{TM} simulator was chosen as a teaching tool because it offers a virtual world, good animation, and user-friendly software. Therefore, the elementary student will understand the basic concept and apply their constructed knowledge in real robot hardware. Teaching materials are entirely taught in the simulation domain, consisting of several contents starting from the introduction of electronic components to DC motor drivers. This paper can be used as a supplementary reference (source) for STEM teachers in teaching the fundamental of analog LF robots to elementary students.

1. Introduction
The rapid development of software and hardware technology affects several aspects of life, such as education. In the hardware aspect, as we can see, it will continue to evolve (including robotics). Thus, there will be a need for human resources who have skills in robotics, mechatronics, and automation in the future [1]; this is possible because robots almost replace human jobs in the future. This condition can stimulate several other elementary schools to introduce robots in their curriculum through extracurricular programs with the Lego Robot medium or simple Line Follower (LF) robots. In Indonesia, many robot competitions for elementary school students are starting to be held [2,3]. Elementary school students can be trained in creative thinking and problem-solving skills with robots [4]. Whereas in the software aspect, as we can see, the education sector can benefit from the availability of learning tools and resources such as smartphones, tablets, and PCs, which can then introduce augmented reality technology so that learning becomes more attractive [5,6]. With smartphones, tablets, and PCs, we can also replace physical tools in practicum learning with virtual ones so that virtual laboratories can represent expensive practicum tools [7,8].
Robotics that only exist in universities can now be taught from kindergarten to high school children [9]. But unfortunately, the robotics extracurricular is still considered too expensive by the community because robot modules on the market are still challenging to find in stores and the country, especially for the elementary school level [10]. For this reason, learning media can be a solution to introduce a simple robot concept, such as the Line Follower (LF) Robot, to elementary students. The trainer kit approach can be chosen [11], but it still involves real hardware. A virtual approach using simulation is an option; it can also help them to understand the basic concept better.

Based on the problem mentioned earlier, this paper aims to utilize software technology to explain hardware technology (robotics) through EDA-based simulations. Because the “strong concept” is more emphasized than only “robot assembly,” a breakthrough is needed to create a set of materials that specifically address a robot's concept. There are two types of LF Robot, i.e., Digital [12] and Analog. For this case, we select an analog type because it is straightforward for elementary school students. Figure 1 shows the part of the analog LF Robot consisting of sensors, electronic drivers (Operational Amplifier-based Comparator, Switch-based driver, or H-Bridge driver), DC motors.

Using this curriculum design will provide understanding to elementary school students, especially for grade 6 (approximately 12 years of age), about the basics of robotics, starting from sensors, actuators to their integration. Y-H Ching proposed a similar curriculum with a total of twelve sessions [13], but the approach is hardware. Meanwhile, this paper uses a software (virtual world) approach with five teen sessions. The wide selection of tools offered can make students interested in learning robotics; in this course, we chose the Circuit Wizard™ simulator because it provides complete components and exciting interactions.

2. Methods
Table 1 represents a set of proposed courses. It consists of fifteen learning activities where the arrangement of this table is derived from Figure 1. A simple robot LF analog is assembled from several electronic components: twelve BJT transistors, two DC motors and gear-box (left and right), one free-wheel placed on the front of the LF robot, three DC sources or batteries (for the left sensor supply, right sensor, and electronic driver), four LEDs - four sensors (in this case, we used a Light Dependent Resistor), four IC Op-Amp model LM741, and four resistors.

From the first to the second sessions, elementary school students will be introduced to the LF robot and Circuit Wizard by STEM teachers. In 4.0 industry, the robotics engages STEM; it means STEM
teachers have a significant share as tutors in this course. Through this session, students will understand the LF Robot, which is a robot that works by distinguishing colors between the background and lines through sensors in a voltage divider circuit. Then, the value representing the binary logic sequence will be obtained and processed by the Op-Amp-based comparator circuit from this difference.

At the 3rd and 4th sessions, elementary students were introduced to the LDR sensor circuit using the voltage divider principle and simulated with the Circuit Wizard™. Then at the 5th and 6th sessions, the Op-Amp and its configuration as a comparator were introduced and demonstrated. The principle is to compare the input voltage and reference voltage of the Op-Amp. The output voltage of the comparator results in logic “1” or logic “0”.

The BJT transistor is a crucial component in the LF robot; it will control the DC motor to rotate or not with the given input conditions. There are two types of drivers introduced to elementary school students at the 5th and 6th sessions, namely switches and H-Bridge. Switch topology, the wheels only rotate clockwise (CW) and cannot rotate counterclockwise (CCW) so that the LF robot cannot move backward. Meanwhile, the LF robot can move backward on the H-Bridge if the line tracing process goes wrong. After each block (sensors, comparators, and drivers) are taught at the previous meeting. The integration of each of these blocks is integrated and described, and simulated at the 11th and 12th meetings. At the last session, which is the 13th to 15th, students were given a project related to the LF robot simulation using Circuit Wizard™. Due to the page limitation for this paper, we only discuss the 5th to 15th sessions. Each session has a duration of 6 hours of study.

Table 1. Proposed robotic curriculum for extracurricular programs in the Elementary school (sixth grades or about 12 years old children).

| Sessions | Subtopic/Activities                                                                 | Duration |
|----------|-------------------------------------------------------------------------------------|----------|
| 1-2      | Introduction of LF Robot, Basic Electronic Components to build the LF robot & Circuit Wizard™ | 6 hours  |
| 3-4      | Sensors & Voltage Divider Principles, simulation demo with Circuit Wizard™          | 6 hours  |
| 5-6      | Comparator Principles, simulation demo with Circuit Wizard™                         | 6 hours  |
| 7-8      | Switch Driver (ON/OFF) Principles, simulation demo with Circuit Wizard              | 6 hours  |
| 9-10     | H-Bridge Driver (CW & CCW Rotation) Principles, simulation demo with Circuit Wizard™ | 6 hours  |
| 11-12    | How to integrate the LF control? 1) Sensor – Comparator – Switch Driver, 2) Sensor – Comparator – H-Bridge Driver | 6 hours  |
| 13-15    | Project                                                                             | 6 hours  |

3. Results
This course contains lab experiments conducted in a practicum using Circuit Wizard. After previously, students understand the theory (the LF Robot and its construction using electronic components) and how to operate Circuit Wizard™; it required practice to prove the fundamental theory. When the initial step is understood, the students are already to practice, as described in the technical arrangements (Section 3.1. to 3.4).

3.1. Op-Amp-based comparator principles
The comparator circuit compares the magnitudes of two voltages inputted to the Op-Amp IC (LM741 type). The key is to understand positive input voltage (denoted as Vin +) and negative input voltage (denoted as Vin –) on the Op-Amp (Figure 2a). There are two output conditions: when the positive input (Vin +) greater than or equal to the negative input (Vin –), the result is a positive voltage. While the positive input (Vin +) smaller than the negative input (Vin –), the result is a negative voltage. Practically, it can be expressed as Equation (1) and Equation (2),

$$\text{When } Vin(+) \geq Vin(-), \text{ thus } Vout = V +$$  \hspace{1cm} (1)

$$\text{When } Vin(+) < Vin(-), \text{ thus } Vout = V -$$  \hspace{1cm} (2)

In this session, the elementary students were assigned to simulate a comparator circuit on the circuit wizard™ where Vin+ and Vin– use batteries varied according to experiment (Figure 2b). The op-amp is rated at 12V. The output of the Op-Amp is connected to the voltage meter. Elementary school students
observe how the comparator circuit's output if \( V_{\text{in}+} \) is higher than \( V_{\text{in}-} \) or vice versa, whether it corresponds to equations (1) and (2) or not. The result of students’ observation is shown in Table 2.

**Figure 2.** (a) Op-Amp as a comparator configuration; (b) a schematic for practicum

As seen in Table 2, the Circuit wizard\textsuperscript{TM} simulates an output voltage that is not equal to zero volts and \( V_{\text{sat}+} \) is not equal to 12V, which is exactly 892.24 mV and 11.11 V, respectively. Therefore, it is considered 0V when \( V_{\text{in}+} < V_{\text{in}-} \), and \( V_{\text{sat}+} \) is equal to 12V when \( V_{\text{in}+} \geq V_{\text{in}-} \).

| No | \( V_{\text{in}+} \) | \( V_{\text{in}-} \) | Theory | Vout | Simulation |
|----|----------------|----------------|--------|------|------------|
| 1  | 6V            | 1V             | \( V_{\text{in}+} \geq V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = V_{\text{sat}+} \). 6V \( \geq \) 1V \( \rightarrow \) 12V | 11.11 V |
| 2  | 6V            | 2V             | \( V_{\text{in}+} \geq V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = V_{\text{sat}+} \). 6V \( \geq \) 2V \( \rightarrow \) 12V | 11.11 V |
| 3  | 6V            | 3V             | \( V_{\text{in}+} \geq V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = V_{\text{sat}+} \). 6V \( \geq \) 3V \( \rightarrow \) 12V | 11.11 V |
| 4  | 6V            | 4V             | \( V_{\text{in}+} \geq V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = V_{\text{sat}+} \). 6V \( \geq \) 4V \( \rightarrow \) 12V | 11.11 V |
| 5  | 6V            | 5V             | \( V_{\text{in}+} \geq V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = V_{\text{sat}+} \). 6V \( \geq \) 5V \( \rightarrow \) 12V | 11.11 V |
| 6  | 6V            | 6V             | \( V_{\text{in}+} \geq V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = V_{\text{sat}+} \). 6V \( \geq \) 6V \( \rightarrow \) 12V | 11.11 V |
| 7  | 6V            | 7V             | \( V_{\text{in}+} < V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = 0 \text{V} \). 6V \( < \) 7V \( \rightarrow \) 0V | 892.24 mV |
| 8  | 6V            | 8V             | \( V_{\text{in}+} < V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = 0 \text{V} \). 6V \( < \) 8V \( \rightarrow \) 0V | 892.24 mV |
| 9  | 6V            | 9V             | \( V_{\text{in}+} < V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = 0 \text{V} \). 6V \( < \) 9V \( \rightarrow \) 0V | 892.24 mV |
| 10 | 6V            | 10V            | \( V_{\text{in}+} < V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = 0 \text{V} \). 6V \( < \) 10V \( \rightarrow \) 0V | 892.24 mV |
| 11 | 6V            | 11V            | \( V_{\text{in}+} < V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = 0 \text{V} \). 6V \( < \) 11V \( \rightarrow \) 0V | 892.24 mV |
| 12 | 6V            | 12V            | \( V_{\text{in}+} < V_{\text{in}-} \) \( \rightarrow \) \( V_{\text{o}} = 0 \text{V} \). 6V \( < \) 12V \( \rightarrow \) 0V | 892.24 mV |

3.2. Electronics driver principles: Switch topology and H-Bridge

Figure 3 is a series of drivers with a switch topology. Elementary students are given knowledge about the BJT transistor, which consists of three legs (collector, emitter, base) and its fundamental principles, namely in saturation conditions (if the input voltage is much greater than 0.7) and cut-off (input voltage <0.7). The practicum components are one transistor, two batteries as the base input and the collector input, and one LED as an indicator. Figure 3 (a) is the transistor state when “active”, as seen from the LED light that turned “on” \textsuperscript{[14]}. Whereas Figure 3 (b) is the transistor state when it is “inactive” so that the LED is turned “off” because there no current flows from the Collector pin to the Emitter pin; this condition can be expressed as Equation (3) and Equation (4),

\[
\text{When } V_{BE} < 0.7, \text{ thus } V_{CE} = -0V, \text{ the LED turns off}
\]

\[
\text{When } V_{BE} >> 0.7, \text{ there is a number of current flowing from the collector to the emitter, the LED turns on}
\]

The next driver is the H-Bridge, which consists of four transistors assembled like a bridge connection, as shown in Figure 3 (c). Unlike the switch configuration that has one input, the H-Bridge driver has two inputs (denoted as \( V_{in1} \) and \( V_{in2} \)). The difference between the two input voltages results in two conditions: the DC motor that rotates clockwise (CW) and counterclockwise (CCW) \textsuperscript{[15]}. Elementary school students perform observations on how the DC motor rotates with a given input variation. The
experimental results of elementary school students who took this course program are presented in Table 3.

![Transistor switch topology](image1)
![Inactive topology](image2)
![Schematic for H-Bridge](image3)

**Figure 3.** (a) Transistor switch topology is active; (b) inactive (c); a schematic for H-Bridge practicum.

**Table 3.** Result of the H-Bridge driver practicum.

| No | V\text{in} 1 | V\text{in} 2 | Motor DC conditions |
|----|-------------|-------------|---------------------|
| 1  | 0V          | 0V          | Not spinning        |
| 2  | 6V          | 6V          | Non spinning        |
| 3  | 12V         | 12V         | Not spinning        |
| 4  | 0V          | 12V         | Fast CW             |
| 5  | 12V         | 0V          | Fast CCW            |
| 6  | 12V         | 6V          | Slow CCW            |
| 7  | 6V          | 12V         | Slow CW             |

As shown in Table 3, if the two input values are the same, then the DC motor condition will not rotate. If one input has a range that is more than twice the other input, it can be shown as follows: If V\text{in} 1 is greater than V\text{in} 2, the DC motor condition will quickly rotate counterclockwise. Conversely, if the V\text{in} 1 is smaller than V\text{in} 2 input, the DC motor condition will rotate clockwise quickly. If V\text{in} 1 is twice greater than V\text{in} 2, then the DC motor will slowly clockwise. Conversely, if V\text{in} 1 is almost half of V\text{in} 2, then the DC motor condition will rotate slowly counterclockwise. Figure 4 depicts the results of student experiments under the Circuit Wizard™ simulation.

3.3. Integration

At this session, students integrated the sensor block into the switch driver (Figure 5a) and the sensor to the comparator H-bridge driver (Figure 6a). The first step that must be done by elementary school students is to create a circuit based on Figure 5 (b), then connected the Op-Amp output to the switch transistor circuit. The LED is placed on the Emitter pin of the NPN transistor. In the Circuit Wizard™, conversion of the schematic to PCB layout is carried out; the “Double-sided option; thin tracks” is selected and checked on “Allow me to customize the PCB layout.” The “Next” button is then pressed until the customization process is finished. The PCB result is shown in Figure 5(b). In the next step, students connect three digital multimeters to measure three variables: 1) op-amp’s output voltage; 2) the LDR sensor voltage; and 3) the voltage from the voltage divider circuit as V\text{in} (-). Students then vary the LUX value on the LDR according to the provided experimental table. LDR sensors are used to change the resistance value based on the intensity of light received. The resistance value when it is dark is 10 MΩ and 1 kΩ when it is bright. Table 4 is the result of student observations, and Figure 6 is a sample of student experiments.
Figure 4. The screen shot of the student’s experiment results captured on Circuit Wizard™.

Figure 5. Block diagram of sensor – comparator – switch driver integration; (b) schematic of practicum; (c) PCB layout of the complete driver circuit using transistor switch.

Table 4. Practicum results.

| No | Lux | V_{out} of LDR Sensor | V_{out} of Voltage Divider circuit | Theory | Simulation | LED condition | Does V_{out} fit in theory? |
|----|-----|-----------------------|-----------------------------------|--------|------------|----------------|--------------------------|
| 1  | 10  | 5.99 V                |                                   | 5.99 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes (almost 6V)          |
| 2  | 100 | 5.99 V                |                                   | 5.99 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 3  | 200 | 5.98 V                |                                   | 5.98 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 4  | 300 | 5.98 V                |                                   | 5.98 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 5  | 400 | 5.96 V                |                                   | 5.96 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 6  | 500 | 5.95 V                |                                   | 5.95 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 7  | 600 | 5.92 V                |                                   | 5.92 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 8  | 700 | 5.87 V                | 3 V                               | 5.87 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 9  | 800 | 5.71 V                |                                   | 5.71 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 10 | 850 | 5.43 V                |                                   | 5.43 V ≥ 3 V → 6 V               | 5.11 V     | On            | Yes                     |
| 11 | 900 | 1.71 V                |                                   | 1.71 V < 3 V → 0 V               | 0.89 V     | Off           | Yes (almost 0V)          |
| 12 | 925 | 1.71 V                |                                   | 1.71 V < 3 V → 0 V               | 0.89 V     | Off           | Yes                     |
| 13 | 950 | 1.71 V                |                                   | 1.71 V < 3 V → 0 V               | 0.89 V     | Off           | Yes                     |
| 14 | 975 | 1.71 V                |                                   | 1.71 V < 3 V → 0 V               | 0.89 V     | Off           | Yes                     |
| 15 | 1000| 1.71 V                |                                   | 1.71 V < 3 V → 0 V               | 0.89 V     | Off           | Yes                     |
At this session, elementary students are expected to understand the concepts of LF robot sensors, Op-Amp-based comparators, and electronic drivers. Afterward, the block diagram of Figure 5(a) is integrated into the H-Bridge circuit. Since there are two inputs from the H-Bridge, block diagram in Figure 5(a) is copied twice. To be precise, as the block diagram in Figure 1. Later, $V_{in1}$ and $V_{in2}$ are connected to the H-Bridge circuit via a transistor switch (Emitter pin to $V_{in}$ H-Bridge). The voltage for the two comparator circuits is set to 6V. The voltage for the switch transistor circuit and the H-Bridge are set to 12V. Each block is given Ground. The elementary student adjusts the lux level for each comparator. The DC motor is set to 1.5V. The circuit is then converted to PCB (Figure 7). The DC motor’s speed is changed to 500 RPM. Therefore, the its rotation can be seen clearly. Table 5 shows the practicum done by elementary school students.

![Figure 6](image1.png)  
**Figure 6.** Sample of practicum result: (a) first test, when sensor is set to 10 Lux; (b) five tenth test, when sensor is set to 1000 Lux.

![Figure 7](image2.png)  
**Figure 7.** (a) Circuit for sensor – comparator – H-Bridge driver integration; (b) virtual practicum for one wheel of LF robot (left wheel).

| No | LDR of the 1st Comparator | LDR of the 2nd Comparator | DC Motor conditions |
|----|--------------------------|---------------------------|---------------------|
| 1. | 1000 lux                 | 10 lux                    | Slow CW             |
| 2. | 10 lux                   | 1000 lux                  | Slow CCW            |
| 3. | 10 lux                   | 10 lux                    | Not spinning        |
| 4. | 1000 lux                 | 1000 lux                  | Not spinning        |
3.4. Project
At this session, students can do more exercises by designing various modifications to components and circuits. Steps 3.1 to 3.4 of this paper are for one side of LF robot’s wheel. To make a complete analog LF robot through simulation, elementary school students must apply two wheels (two H-Bridge drivers, two DC motors, and four comparators). STEM teachers assess students throughout the project.

4. Conclusion
Robotics has become popular among children and is being taught to elementary school students through robotic extracurricular activities. Generally, most institutions use the LF robot, a robot that can cross a black or white line. Analog LF robot training to elementary school students uses a software approach (simulation) to learn basic theory visually. It is hoped that students will find it easier to understand the concept of a simple LF robot. Each training stage in this paper can be used as a reference for STEM teachers to teach elementary school students the concept of simple robot LF robots, starting from the voltage dividers principle, the main circuit block in LF robotics, and its integration. This paper can be used besides the LF robot assembly practice. Hence, those elementary students can assemble a robot and perform analysis because they have understood the basic concepts before.

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