

## Integrated Analog-Digital Robotics Learning System to Improve Elementary Students Computational Thinking

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**Abstrak.** Penelitian ini mengeksplorasi penerapan model pembelajaran robotika analog-digital terpadu untuk meningkatkan kemampuan berpikir komputasi pada siswa sekolah dasar. Kegiatan pembelajaran disusun secara progresif, dimulai dari eksperimen robotika berbasis sensor analog dan dilanjutkan dengan pengendalian robot digital yang dapat diprogram. Sebanyak 30 siswa kelas lima berpartisipasi dalam program intervensi empat minggu yang melibatkan aktivitas robotika langsung. Kemampuan berpikir komputasi siswa dievaluasi melalui empat dimensi: dekomposisi, pengenalan pola, abstraksi, dan berpikir algoritmik. Temuan ini menunjukkan adanya perbaikan pada seluruh indikator yang dinilai. Nilai rata-rata meningkat dari 61,3 pada pretest menjadi 82,7 pada posttest, dengan gain ternormalisasi sedang (*N-gain*) sebesar 0,55. Analisis statistik menggunakan uji-*t* berpasangan juga menunjukkan perbedaan yang signifikan antara skor pretest dan posttest ( $p < 0,05$ ). Hasil tersebut menunjukkan bahwa pembelajaran robotika terpadu dapat memberikan dukungan yang berarti bagi pengembangan keterampilan berpikir komputasi pada pendidikan dasar.

**Keywords:** Sistem Robotika Pendidikan, Robot Digital Analog, Berpikir Komputasi

**Abstract.** This study explores the implementation of an integrated analog-digital robotics learning model to improve computational thinking skills among elementary school students. The learning activities were arranged progressively, starting from analog sensor-based robotics experiments and continuing to programmable digital robot control. A total of 30 fifth-grade students participated in a four-week intervention program involving hands-on robotics activities. Students' computational thinking abilities were evaluated through four dimensions: decomposition, pattern recognition, abstraction, and algorithmic thinking. The findings revealed improvements in all assessed indicators. The average score increased from 61.3 on the pretest to 82.7 on the posttest, with a medium normalized gain (*N-gain*) of 0.55. Statistical analysis using a paired-sample *t*-test also showed a significant difference between pretest and posttest scores ( $p < 0.05$ ). These results indicate that integrated robotics learning can provide meaningful support for developing computational thinking skills in primary education.

**Keywords:** Educational Robotics System, Analog Digital Robots, Computational Thinking

### 1. Introduction

Digital transformation in the world of education encourages the need to change learning approaches that focus not only on mastering material, but also on developing higher-order thinking skills. One of the skills that is of primary concern is Computational Thinking (CT), namely the ability to solve problems systematically through a process of decomposition, pattern recognition, abstraction, and algorithm development.

The introduction of CT from the elementary school level is considered important because it can form a logical, critical, and adaptive mindset towards technological developments. However, the implementation of CT in elementary schools still faces various obstacles. The learning that takes place tends to be theoretical and not fully supported by media that is able to connect abstract concepts with students' real experiences [1]. The use of software based on visual programming has indeed been widely applied, but this approach emphasizes the logical aspect without providing an adequate understanding of how a system works physically. As a result, students can follow programming instructions, but do not fully understand the relationship between input, process, and output in a technological system.

One approach that is considered capable of answering this problem is robotics-based learning. Educational robotics provides a direct learning experience (hands-on learning), so that it can increase student involvement and motivation. In addition, robotics also allows for more contextual integration of STEM concepts through the activities of designing, assembling, and operating simple technological systems. However, the implementation of educational robotics so far still tends to focus on microcontroller-based digital robots. This approach is effective in training algorithmic skills but does not provide a basic understanding of the working principles of the hardware.

On the other hand, learning analog robots that utilize simple circuits such as sensors and transistors is still limited to component recognition and has not been directly linked to the development of computational thinking capabilities. This condition shows that there is a gap in robotics learning, where analog and digital approaches are still treated separately. In fact, the integration of the two has the potential to provide a more complete and meaningful learning experience. Therefore, this study introduces an innovative robotics learning framework that gradually combines analog circuit robots with programmable digital robots in one integrated instructional model. In contrast to earlier approaches that typically use analog and digital robotics as separate learning tools, this system links fundamental sensor-response concepts, hardware logic comprehension, and block-based coding through a step-by-step learning sequence aimed at strengthening computational thinking skills among elementary school students. While many robotics studies focus on technical design and programming outcomes, fewer studies explain how robotics activities can be systematically connected to computational thinking dimensions for younger learners. Therefore, this study positions the robotics platform as a pedagogical tool rather than solely a technological product.

## **2. Literature Review**

Computational thinking (CT) is an important competency in modern education, which focuses on the ability to solve problems systematically through decomposition processes, pattern recognition, abstraction, and algorithms. In recent years, CT is no longer viewed as part of computer science alone, but as an interdisciplinary skill that needs to be instilled from elementary education [2]. Recent studies show that strengthening CT at the K-6 level has a significant impact on students' critical thinking and problem-solving abilities [3].

Various approaches have been developed to integrate CT in learning. One commonly used approach is block-based visual programming, which is considered capable of making it easier for students to understand algorithmic concepts without having to deal with syntactic complexity [4]. However, this approach has limitations because it does not provide real experience regarding how computational logic is implemented in physical systems [5]. As an alternative, educational robotics is starting to be widely used as a learning medium to support CT development. Robotics allows students to learn directly through interaction with physical devices, thereby creating a more contextual and meaningful learning experience [6]. Research shows that the use of robotics in learning can significantly increase student engagement and strengthen understanding of CT concepts.

In practice, educational robotics is generally divided into two main approaches, namely analog robots and digital robots. Analog robots use simple electronic circuits such as sensors and

transistors without involving programming, making them suitable for introducing basic electronics concepts [7]. Meanwhile, digital robots use microcontrollers and programming to control systems in a more complex and flexible manner [8]. These two approaches have their respective advantages in supporting learning.

Existing educational robotics studies mainly emphasize either programming-oriented digital robots or component-oriented analog robots. Digital robot platforms are effective for teaching algorithms and coding logic, while analog robots are useful for introducing sensors and basic electronics [9]. However, limited studies have combined both approaches into a continuous pedagogical model that links physical circuit behavior with programmable computational logic [10]. This gap becomes more critical at the elementary level, where students require gradual transitions from concrete experiences to abstract reasoning.

Several recent studies have begun to lead to the integration of various approaches in robotics learning. This integration is considered capable of providing a more comprehensive learning experience because it connects concrete concepts with abstractions in stages [11]. In addition, an integrated approach can also help students build a deeper understanding of the technology system as a whole.

On the other hand, research regarding the implementation of CT and robotics in elementary schools still shows that there are challenges, especially in terms of the availability of learning models that are structured and appropriate to student characteristics [12]. Apart from that, teacher readiness factors and the choice of learning media are also important aspects in the successful implementation of CT and robotics in schools [13]. Without appropriate media support, CT learning tends to be suboptimal and difficult for students to understand [14]. Therefore, innovation is needed in developing learning media that are not only interactive but also able to bridge abstract and concrete concepts simultaneously.

Based on this study, it can be concluded that educational robotics has great potential in supporting the development of computational thinking. However, there is still a need to develop learning models that can integrate analog and digital robotic approaches in one structured system. This integration is expected to provide a more complete learning experience, so that students not only understand programming concepts, but also the working principles of the system as a whole [15].

Another problem that is often found is the unavailability of learning models designed systematically to develop CT through robotics, especially those adapted to the characteristics of elementary school students [16]. Many implementations are still partial and not equipped with measurable evaluation mechanisms [17][18]. This has an impact on the less-than-optimal development of students' CT abilities as a whole.

Based on this description, this research aims to develop a microcontroller-based educational robotics system through the integration of analog and digital robots as learning media to improve elementary school students' computational thinking abilities. The system being developed is designed in the form of gradual learning, starting from the introduction of basic concepts through analog robots, then continuing with the implementation of programming logic on digital robots [19].

The use of educational robotics continues to evolve toward more integrative system designs that combine analog and digital approaches in a single learning platform [20]. A robot model that merges these two paradigms, such as a line tracer equipped with obstacle avoidance and activation based on human detection using a Passive Infrared (PIR) sensor, can serve as an effective medium to support conceptual and practical understanding. In this configuration, analog circuits are responsible for immediate sensor responses, while digital control systems manage logical processing and behavioral decisions. This combination enables learners to explore how autonomous systems operate through the interaction of sensing, processing, and actuation components [21].

Line-following robots are commonly implemented in robotics learning environments because they provide a clear illustration of how sensors and actuators can be coordinated to achieve a specific task [22]. Through direct experimentation, students can observe how variations

in sensor input influence movement patterns, thereby strengthening their reasoning and analytical skills. Expanding this basic model with obstacle avoidance features introduces additional system complexity, requiring the integration of multiple sensors and conditional control strategies. This progression encourages learners to think more critically about system design and real-time decision-making processes [23].

The addition of a PIR sensor as a trigger mechanism further enhances the functionality of the robot by enabling it to respond selectively to human presence. This approach not only introduces the concept of environmental awareness but also reflects practical implementations found in automated and energy-efficient systems. By activating only when needed, the robot demonstrates how sensing technologies can be utilized to optimize system performance [24].

The key innovation of this research is not simply the integration of analog and digital robots, but the creation of an organized two-phase learning framework. In the first phase, students learn how sensors and actuators interact directly through analog circuits. In the next phase, they build on that understanding by applying programmable digital control with microcontrollers. This step-by-step instructional transition has seldom been explored in earlier robotics education studies, especially for learners at the elementary school level. Moreover, the platform combines line tracking, obstacle detection, and PIR-based motion activation in one modular system, allowing several computational thinking skills to be developed at the same time.

### **3. Research Methodology**

This research applied a Research and Development (R&D) method to create and assess an educational robotics system that combines analog and digital robots to enhance computational thinking skills among elementary school students. The study took place at a public elementary school in Surabaya, Indonesia.

The participants were 30 fifth-grade students chosen through purposive sampling. This class was selected because the students already had basic exposure to science and technology activities and matched the intended age group for beginner robotics education.

The program was implemented over a period of four weeks and included eight instructional sessions, with two meetings each week. Every session was conducted for approximately 90 minutes.

The learning intervention was organized through four interconnected stages that gradually introduced students to increasingly complex robotics tasks while deliberately fostering core computational thinking competencies. During the first stage, students explored the main components of a robot, including sensors, motors, power sources, and control units. They were guided to examine the role of each part and how individual elements contribute to overall system performance. This activity was intended to strengthen decomposition skills by helping learners break a complex system into smaller and more understandable functional units.

In the second stage, students worked with an analog line-following robot and repeatedly observed how different sensor inputs produced immediate movement responses. Through direct experimentation, they compared robot behaviors under varying light conditions, track positions, and surface contrasts. These repeated observations encouraged students to identify regularities, similarities, and recurring response patterns, thereby supporting the development of pattern recognition skills.

The third stage introduced digital control through block-based programming. Students were asked to convert the physical behaviors previously observed in the analog robot into programmable instructions that could be executed by a microcontroller-based robot. In this process, they learned to simplify real-world actions into logical commands, select relevant variables, and arrange command sequences systematically. Such activities were designed to strengthen abstraction and algorithmic thinking in a form appropriate for elementary learners.

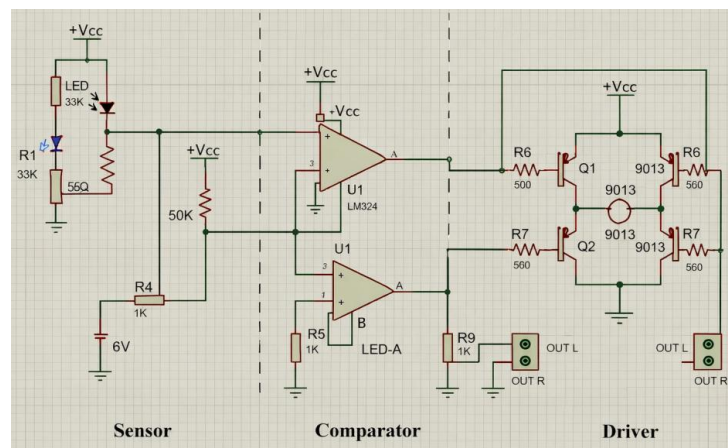
In the final stage, students participated in collaborative mission-based challenges that required the robot to complete tasks such as line tracking, obstacle avoidance, and motion-triggered activation. To solve these problems, students needed to plan strategies, test solutions, identify errors, and refine their programs through repeated trials. This concluding stage integrated

all computational thinking dimensions in an authentic learning context, allowing students to apply decomposition, pattern recognition, abstraction, and algorithmic reasoning simultaneously while working in teams.

Improvement in students' computational thinking was examined through a validated pretest–posttest instrument specifically designed for elementary school learners. The assessment consisted of contextual and scenario-based tasks that matched the learning activities carried out during the robotics program, allowing students to demonstrate their reasoning in situations that were familiar and age-appropriate. Four core dimensions were measured, namely decomposition, pattern recognition, abstraction, and algorithmic thinking.

Items related to decomposition asked students to separate a robotic task into smaller functional steps or identify the role of individual components within a system. Pattern recognition tasks required learners to observe repeated behaviors, detect regular sensor responses, or recognize similarities across different movement situations. Abstraction items focused on the ability to select important information, ignore irrelevant details, and represent problems in a simpler form. Meanwhile, algorithmic thinking was assessed through activities that required students to arrange commands logically, determine action sequences, and predict the outcomes of programmed instructions. By using problem situations closely connected to the robotics experience, the instrument was intended to capture not only factual understanding but also students' ability to apply computational thinking skills in practical contexts. Pretest scores were used to describe students' initial competencies, while posttest results reflected the extent of improvement after completing the intervention program.

System usability was evaluated using the System Usability Scale (SUS) questionnaire distributed after the learning program. In addition, student engagement and collaboration were observed using structured observation sheets during all sessions. Quantitative data were analyzed using descriptive statistics and normalized gain (N-gain), while observational results were interpreted qualitatively to support the findings.



**Figure 1. Schematic of an Analog Line Tracer Robot**

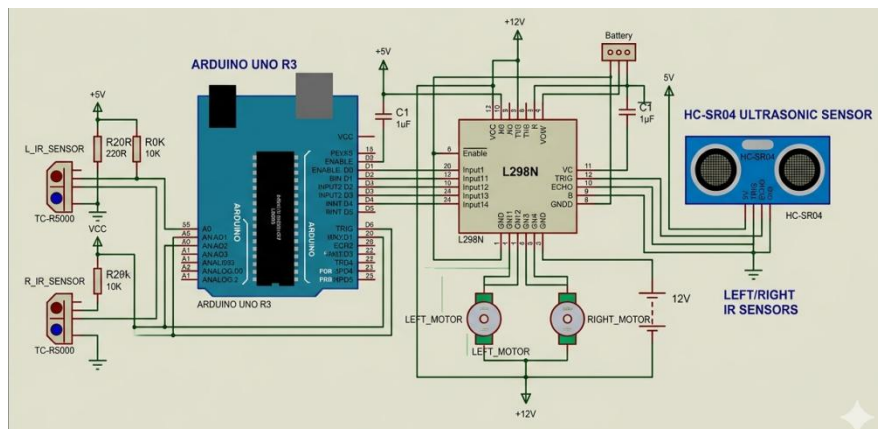
The implementation phase was carried out on class V students at one of the state elementary schools in the city of Surabaya. Learning activities are carried out in several meetings with a practice-based approach (hands-on learning). In Figure 1, the analog robot was used as an introductory learning medium that allowed students to directly observe how variations in sensor input produced different movement responses. By examining these cause-and-effect relationships, students were guided to break down the robotic system into simpler functional parts and identify recurring response patterns, thereby supporting the development of decomposition and pattern recognition skills.

The robotics platform was designed with integrated sensing, control, and actuation modules that allowed students to engage in a range of interactive learning tasks, including line following, obstacle avoidance, and motion-triggered activation. Through these activities, learners

were able to observe how sensor input was processed into control decisions and then translated into mechanical movement. This structure provided a concrete learning environment in which students could explore the relationship between input, process, and output while developing problem-solving and computational thinking skills through direct experimentation.

From a learning perspective, the system design supports the development of computational thinking through direct interaction with hardware and software components. The decomposition of the system into functional modules enables students to understand complex robotic behavior as a combination of simpler processes. Pattern recognition is reinforced through sensor-based line detection, while abstraction is introduced by separating control logic from hardware execution using the motor driver. Furthermore, algorithmic thinking is emphasized through conditional programming structures that govern decision-making based on sensor input.

The learning program was intentionally structured to strengthen four computational thinking dimensions. Decomposition was trained through robot component analysis and system breakdown tasks. Pattern recognition was developed through repeated sensor-response observation activities. Abstraction was supported by selecting relevant inputs and simplifying control conditions. Algorithmic thinking was strengthened through block-based programming and navigation challenges. By referencing the implementation shown in Figure 2, the study highlights how integrated robotics design can effectively bridge fundamental electronic concepts with programmable control, supporting the development of computational thinking in primary education.



**Figure 2. Schematic Line Follower and Avoiding Obstacle Circuit**

In Figure 2. The digital robot was employed to help students transform previously observed physical behaviors into structured programmable commands. Through block-based coding activities, learners practiced selecting relevant variables, organizing logical sequences, and designing control instructions, which contributed to the improvement of abstraction and algorithmic thinking skills. The evaluation stage aimed to measure the effectiveness of the developed system. Computational thinking abilities were assessed using a researcher-developed test instrument consisting of 20 items, including multiple-choice and short problem-solving questions. The instrument was designed based on four main indicators: decomposition, pattern recognition, abstraction, and algorithmic thinking, with five items representing each indicator.

Decomposition items measured students' ability to divide complex problems into smaller tasks. Pattern recognition items evaluated the ability to identify repeated structures or similarities in robotic movement scenarios. Abstraction items assessed students' ability to focus on relevant information while ignoring unnecessary details. Algorithmic thinking items measured the ability to arrange logical step-by-step solutions. Each item was scored on a scale of 0–5, resulting in a maximum total score of 100. Higher scores indicated better computational thinking performance. Content validity was evaluated through expert judgment involving three specialists in robotics education and instructional design. The instrument was revised based on their recommendations.

A pilot test involving 15 students outside the main sample produced a Cronbach's alpha value of 0.82, indicating good reliability. The test used a pretest-posttest design to determine the improvement in students' abilities after participating in the learning program. The test result data were analyzed using normalized gain (N-gain) calculations.

## 4. Result and Discussion

### 4.1. System Development Results

The results of this research are a microcontroller-based educational robotics system that integrates analog robots and digital robots in one gradual learning scenario. The developed educational robotics platform integrates analog and digital robots within a progressive learning framework. Functional testing shows that both modules can run well and in accordance with the learning scenarios that have been designed. Integration between the two modules allows students to understand the relationship between sensor input, signal processing, and actuator output more concretely.

### 4.2. Computational Thinking Ability Test Results

Measurement of computational thinking abilities was carried out through a pretest and a posttest on 30 class V students. The test results are presented in Table 1.

**Table 1. The Result of Pretest and Posttest Computational Thinking**

No	CT Indicator	Pretest (Mean)	Posttest (Mean)	N-Gain	Category
1	Decomposition	62.1	80.5	0.48	Medium
2	Pattern recognition	60.4	84.2	0.60	Medium
3	Abstraction	59.8	81.3	0.54	Medium
4	Algorithm	62.9	85.0	0.59	Medium
	Mean	61.3	82.7	0.55	Medium

A paired-sample t-test was conducted to compare students' computational thinking scores before and after the learning intervention. The analysis revealed a statistically significant difference between pretest and posttest results ( $p < 0.05$ ), indicating that the improvement observed after participation in the robotics program was unlikely to have occurred by chance. These findings suggest that the implemented learning model contributed positively to the development of students' computational thinking skills. Table 1 shows the improvement in decomposition scores, indicating that students became more proficient in separating robotic tasks into smaller and more manageable elements, such as sensing, decision-making, and movement functions. This suggests that learners developed a clearer understanding of how complex systems can be organized into interconnected components. Growth in pattern recognition appears to be closely related to repeated experimentation during line-following activities, where students observed consistent relationships between sensor input and robot responses. Through these experiences, they became more capable of identifying regularities and using previous observations to predict future behavior. The gains recorded in abstraction imply that students increasingly understood how to focus on essential information while filtering out details that were not relevant to problem solving. This ability was particularly visible when learners selected key variables needed to control robot movement and simplified practical situations into workable logic models. Meanwhile, the stronger performance in algorithmic thinking reflects students' successful involvement in programming activities that required ordered sequencing, conditional commands, and error correction. Repeated testing and debugging sessions likely helped learners build a more systematic approach to constructing step-by-step solutions.

### 4.3. System Usability Test Results (SUS)

Evaluation of system usability was carried out using the System Usability Scale (SUS) instrument. The results of data processing are presented in Table 2.

**Table 2. System Usability Scale (SUS) Test Results**

Aspects of Average	Score Average
Ease of use	82.5
System efficiency	80.3
User convenience	81
Total SUS Score	81.2

Based on these results, the SUS score of 81.2 indicates that the system is in the good category (acceptable). This indicates that the system is easy to use by elementary school students and supports the learning process effectively.

#### 4.4. Observation Results of Student Activities

Observations are made during the learning process to measure the level of student involvement. The observation results are summarized in Table 3.

**Table 3. Observation Results of Student Activities**

Observation Aspect	Percentage (%)
Active participation	88%
Group collaboration	85%
Enthusiasm for learning	90%
Solution to problem	84%

Data shows that the level of student engagement is relatively high, with an average of 87%. This shows that a robotics-based learning approach is able to increase student interaction and participation significantly. The study shows that integrating analog and digital robots improves computational thinking. Analog robots help students grasp basic input–output concepts through hands-on experience, while digital robots introduce programming logic gradually, enhancing algorithmic and pattern recognition skills. High usability scores indicate the system is suitable and easy for elementary students, supported by increased engagement and enthusiasm. Overall, this approach effectively strengthens computational thinking and creates a more meaningful learning experience.

The results show that the proposed integrated model offers benefits that go beyond conventional single-mode robotics learning. Earlier studies commonly emphasize only coding activities or basic hardware assembly, while this system allows students to understand both physical sensing processes and logical decision-making within a unified learning sequence.

## 5. Conclusion and Suggestion

The study indicates that integrated robotics learning can serve as a meaningful instructional medium for introducing computational thinking in elementary education. The findings indicate that the proposed system has the potential to support the development of computational thinking skills, as reflected by improvements in posttest scores across all assessed indicators. Moderate gains were observed in decomposition, pattern recognition, abstraction, and algorithmic thinking, suggesting that gradual transitions from concrete circuit-based activities to programmable digital control may provide meaningful learning benefits. In addition, the usability results show that students responded positively to the learning platform and were able to interact with the system comfortably. However, these findings should be interpreted with caution because the study involved a limited sample size and did not include a comparison group. Therefore, the results cannot yet be generalized as conclusive evidence of effectiveness across broader educational contexts. Future research is recommended to involve larger participant groups, apply experimental or quasi-experimental designs, and compare this model with other robotics learning approaches. Further development may also explore integration with IoT, artificial intelligence,

and collaborative learning environments to examine wider impacts on creativity, teamwork, and advanced problem-solving abilities.

This research shows positive results but still needs development through expanding the number and variety of subjects, as well as using more complex experimental methods. System development can also be directed at integrating technologies such as IoT and AI, as well as examining their impact on creativity, collaboration, and advanced problem-solving capabilities. With continuous development, this system has the potential to become an innovative solution in transforming learning into the digital era.

Suggests that analog–digital educational robotics may provide an interactive alternative to conventional instruction and may help integrate computational thinking into elementary STEM learning.

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